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# Estimation of Safety Benefits for Heavy-Vehicle Crash Warning Applications Based on Vehicle-to-Vehicle Communications

# Disclaimer



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13. ABSTRACT

This report presents a general methodology to estimate the crash avoidance effectiveness of vehicle-to-vehicle (V2V) safety applications for heavy vehicles and project their potential annual safety benefits. The report also describes the application of this methodology and the results for three selected crash warning applications: intersection movement assist, forward crash warning, and blind spot/lane change crash warning. The safety benefits are projected in terms of annual reductions in the number and comprehensive cost of police-reported crashes that involved multiple vehicles, including at least one heavy vehicle. The methodology relies on target baseline crash populations obtained from the 2011-2013 General Estimates System crash database; driver/vehicle/application performance data from a National Advanced Driving Simulator study; naturalistic driving data from the Integrated Vehicle-Based Safety System field operational test; and on the Safety Impact Methodology tool that simulates the basic kinematics of driving conflicts and driver/vehicle response. In applying this methodology, it is assumed that all heavy vehicles are equipped with the three selected V2V safety applications and that all other motor vehicle body types (e.g., passenger cars, motorcycles, etc.) are equipped with V2V vehicle awareness devices that transmit basic safety information to heavy vehicles.

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## SI* (MODERN METRIC) CONVERSION FACTORS

| APPROXIMATE CONVERSIONS TO SI UNITS | | | | |
|---|---|---|---|---|
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| **in** | inches | 25.4 | millimeters | mm |
| **ft** | feet | 0.305 | meters | m |
| **yd** | yards | 0.914 | meters | m |
| **mi** | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| **$in^2$** | square inches | 645.2 | square millimeters | $mm^2$ |
| **$ft^2$** | square feet | 0.093 | square meters | $m^2$ |
| **$yd^2$** | square yard | 0.836 | square meters | $m^2$ |
| **ac** | acres | 0.405 | hectares | ha |
| **$mi^2$** | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| **fl oz** | fluid ounces | 29.57 | milliliters | mL |
| **gal** | gallons | 3.785 | liters | L |
| **$ft^3$** | cubic feet | 0.028 | cubic meters | $m^3$ |
| **$yd^3$** | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | **NOTE: volumes greater than 1000 L shall be shown in $m^3$** | | |
| | | **MASS** | | |
| **oz** | ounces | 28.35 | grams | g |
| **lb** | pounds | 0.454 | kilograms | kg |
| **T** | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| **oz** | ounces | 28.35 | grams | g |
| | | **TEMPERATURE (exact degrees)** | | |
| **°F** | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |

| APPROXIMATE CONVERSIONS FROM SI UNITS | | | | |
|---|---|---|---|---|
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| **mm** | millimeters | 0.039 | inches | in |
| **m** | meters | 3.28 | feet | ft |
| **m** | meters | 1.09 | yards | yd |
| **km** | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| **$mm^2$** | square millimeters | 0.0016 | square inches | $in^2$ |
| **$m^2$** | square meters | 10.764 | square feet | $ft^2$ |
| **$m^2$** | square meters | 1.195 | square yards | $yd^2$ |
| **ha** | hectares | 2.47 | acres | ac |
| **$km^2$** | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| **mL** | milliliters | 0.034 | fluid ounces | fl oz |
| **L** | liters | 0.264 | gallons | gal |
| **$m^3$** | cubic meters | 35.314 | cubic feet | $ft^3$ |
| **$m^3$** | cubic meters | 1.307 | cubic yards | $yd^3$ |
| **mL** | milliliters | 0.034 | fluid ounces | fl oz |
| | | **MASS** | | |
| **g** | grams | 0.035 | ounces | oz |
| **kg** | kilograms | 2.202 | pounds | lb |
| **Mg (or "t")** | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| **g** | grams | 0.035 | ounces | oz |
| | | **TEMPERATURE (exact degrees)** | | |
| **°C** | Celsius | 1.8C+32 | Fahrenheit | °F |

***SI is the symbol for the Internat'l System of Units. Make appropriate rounding to comply with Section 4 of ASTM E380. (Revised March 2003)**

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# List of Acronyms

| | |
|---|---|
| **AIS** | Abbreviated Injury Scale |
| **BSW/LCW** | Blind Spot Warning/Lane Change Warning |
| **ER** | Exposure Ratio |
| **FARS** | Fatality Analysis Reporting System |
| **FCW** | Forward Crash Warning |
| **GES** | General Estimates System |
| **HV** | Host Vehicle |
| **HW** | Highway |
| **IMA** | Intersection Movement Assist |
| **IMA-M** | IMA - Moving |
| **IMA-S** | IMA - Stop/Proceed |
| **IVBSS** | Integrated Vehicle-Based Safety System |
| **LCL** | Lane Change Left |
| **LCR** | Lane Change Right |
| **LVD** | Lead Vehicle Decelerating |
| **LVM** | Lead Vehicle Moving |
| **LVS** | Lead Vehicle Stopped |
| **MAIS** | Maximum Abbreviated Injury Scale |
| **MPH** | Miles Per Hour |
| **NADS** | National Advanced Driving Simulator |
| **NASS** | National Automotive Sampling System |
| **NHTSA** | National Highway Traffic Safety Administration |
| **PDO** | Property Damage Only |
| **PR** | Prevention Ratio |
| **RV** | Remote Vehicle |
| **s** | Second |
| **SCP** | Straight Crossing Paths |
| **SCP-M** | Straight Crossing Paths - Moving |
| **SCP-S** | Straight Crossing Paths – Stop/Proceed |
| **SIM** | Safety Impact Methodology |
| **TTI** | Time-to-Intersection |
| **V2V** | Vehicle-to-Vehicle |

# List of Equation Variables

| | |
|---|---|
| $B_A$ | Reduction in annual baseline target crashes in a scenario by an application |
| $CP_{with}$ | 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 |
| $E_A$ | Crash avoidance effectiveness of an application in its target scenario |
| $EM_{with}$ | Exposure Measure to a driving conflict corresponding to a target scenario in treatment condition |
| $EM_{without}$ | Exposure Measure to a driving conflict corresponding to a target scenario in baseline condition |
| $N_C$ | Annual number of baseline target crashes in a scenario |

# Preface

Volpe, The National Transportation Systems Center is supporting the National Highway Traffic Safety Administration under a multi-year, multi-task intra-agency agreement, by estimating the safety benefits of crash warning applications for heavy vehicles based on vehicle-to-vehicle communications (V2V). This agreement includes additional tasks to conduct an independent evaluation of the heavy-truck crash warning applications from the Safety Pilot Model Deployment, conduct root cause analysis of false alerts, and analyze driver behavior at intersections to better understand the performance of V2V-based intersection crash warning applications.

This report describes the methods, data sources, and results of the safety benefit estimation task for heavy vehicles. In addition to this report, there are companion reports on V2V crash warning applications for light vehicles that document the approach and results of characterization test procedures, performance measures, safety impact methodology tool; and an independent evaluation of the Safety Pilot Model Deployment for light vehicles, heavy trucks [1], and transit buses.

# Executive Summary

Volpe, The National Transportation Systems Center (Volpe), is supporting the National Highway Traffic Safety Administration by developing a general methodology for projecting the potential safety benefits of motor vehicle crash warning applications. Volpe applied this methodology to crash warning applications that use vehicle-to-vehicle (V2V) communications for heavy vehicles (e.g., medium and heavy trucks, as well as buses, with gross vehicle weight rating over 10,000 pounds). V2V communications is the term used to describe how vehicles communicate basic safety information with other nearby vehicles using the dedicated short-range communication link at 5.9 GHz. The safety applications on these vehicles, in turn, use the information received to determine whether and when to warn drivers about potential imminent crash risk. The benefits of V2V come from those safety application warnings and the extent to which they help drivers avoid crashes.

This report describes Volpe's methodology for projecting safety benefits associated with those crash warning applications, and applying the methodology to estimate those benefits. Safety benefits are expressed in terms of the number of heavy-vehicle, police-reported crashes that might be avoided, comprehensive costs saved, and equivalent lives saved. For this analysis, Volpe assumed that all heavy vehicles are equipped with the selected V2V safety applications and all other motor vehicle body types (e.g., passenger cars, motorcycles, etc.) are equipped with vehicle awareness devices that communicate their basic safety messages to heavy vehicles. Note that other assumptions could be made about the penetration rates of the technology in the fleet, which would have different implications for benefits estimates, but the methodology used to calculate benefits would be the same.

The selected V2V crash warning applications for this analysis are:

1. *Intersection Movement Assist (IMA),* which warns drivers of vehicles approaching from a lateral direction at an intersection (or any road junction).
2. *Forward Crash Warning (FCW),* which warns drivers of stopped, slowing, or slower vehicles ahead in the same lane.
3. *Blind Spot Warning/Lane Change Warning (BSW/LCW),* which alerts drivers to the presence of vehicles approaching or in their blind spot in the adjacent lane.

Prototypes of these crash warning applications were tested on several heavy vehicles that participated in the Safety Pilot Model Deployment field test.

Ideally, the safety benefits from motor vehicle safety technology are measured from field crash data by comparing the crash experience between equipped and non-equipped vehicles. However, when a crash-avoidance technology is new and not yet widespread (or even present) in the on-road fleet, there is no actual crash data from real-world driving because crashes have not yet occurred and cannot occur without equipped vehicles on the roads. In addition, crash data are rare or non-existent during the conduct of naturalistic driving tests since widespread exposure is required to ensure adequate crash data. The scope of field operational tests is typically limited to a few instrumented vehicles driven by volunteer subjects for a relatively short period of time. Finding a way to assess the safety benefits of emerging crash avoidance technologies is vital to government efforts to promote their emergence, but the catch-22 of their newness must be overcome. To estimate the crash avoidance benefits of the V2V applications, this report describes a methodology that relies on several sources:

1. National crash databases, which provide statistics on the target baseline (non-equipped vehicles) crash populations and information about the driving conditions of the various target pre-crash scenarios for computer simulations.

2. Integrated Vehicle-Based Safety System field operational test ( and a National Advanced Driving Simulator study, which generate data about driver/vehicle performance and system capability in target driving conflicts addressed by the applications.
3. Safety Impact Methodology (SIM) tool, which is used to incorporate data from all the data sources and to estimate the probability of a crash in baseline and treatment conditions (i.e., without and with the assistance of the V2V-based safety applications), using the Monte Carlo technique to simulate the basic kinematics of driver/vehicle response to driving conflicts. Results from the SIM tool directly support the estimation of crash avoidance effectiveness for the selected safety applications.

Volpe queried baseline crash data from the 2011-2013 General Estimates System (GES) crash databases to obtain the target crash population for each safety application. The GES database was selected since it contains representative national statistics of all police-reported crashes for all severities. The data query was performed using the following criteria:

1. Multi-vehicle pre-crash scenarios potentially addressable by the selected V2V safety applications
2. Involvement of at least one heavy vehicle in the crash
3. No control loss by the heavy vehicle
4. No impaired heavy-vehicle drivers
5. Vehicle maneuver initiated by the heavy vehicle (where applicable), such as changing lanes or turning left

Table ES- 1 provides a breakdown of the target crash statistics, based on 2011-2013 GES statistics, which could potentially be addressed by the three selected V2V safety applications. As shown in Table ES- 1, the annual target crash population is 92,875 police-reported crashes, while the annual comprehensive cost is approximately $14,275M. This cost corresponds to about 1,561 equivalent lives lost annually.

**Table ES- 1. Breakdown of Target Crash Statistics by V2V Applications**

| Application | Number of Crashes | Comprehensive Cost ($M) | Equivalent Lives Lost |
|---|---|---|---|
| **IMA** | 35,517 | 8,568 | 937 |
| **FCW** | 33,025 | 4,685 | 512 |
| **BSW/LCW** | 24,333 | 1,022 | 112 |
| **Total** | 92,875 | 14,275 | 1,561 |

Based on the safety benefits estimation methodology presented in this report, the three selected V2V crash warning applications have an estimated 45-49 percent crash avoidance effectiveness that results in a reduction of between 41,638 and 45,775 police-reported crashes annually. Table ES- 2 breaks down these safety benefit statistics by each of the three applications in terms of crashes avoided, cost saved, and equivalent lives saved. These applications could save between $7,674M and $7,848M annually in target crash comprehensive cost. This cost benefit translates into between 838 and 857 equivalent lives saved.

**Table ES- 2. Breakdown of Safety Benefits by V2V Applications**

| Application | Number of Crashes Avoided | Cost Saved ($M) | Equivalent Lives Saved |
|---|---|---|---|
| **IMA** | 22,744 | 5,528 | 604 |
| **FCW** | 13,541 | 1,921 | 209 |
| **BSW/LCW** | 5,353-9,490 | 225-399 | 25-44 |
| **Total** | 41,638-45,775 | 7,674-7,848 | 838-857 |

*Note: Two estimates are provided for the BSW/LCW application because two different data sources were used.*

# 1 Introduction

Volpe, The National Transportation Systems Center (Volpe), is supporting the National Highway Traffic Safety Administration (NHTSA) by developing a general methodology for projecting the potential safety benefits of crash warning applications based on vehicle-to-vehicle (V2V) communications for heavy vehicles (e.g., medium and heavy trucks, as well as buses with gross vehicle weight rating over 10,000 pounds). This V2V technology uses a dedicated short-range communication link to broadcast basic safety messages at 5.9 GHz among vehicles and between vehicles and the infrastructure. By combining inputs from V2V technology with relative positioning based on the Global Positioning System, a number of crash warning applications have been developed to reduce the occurrence and mitigate the severity of motor vehicle crashes. Volpe also separately estimated potential safety benefits of crash warning applications for light vehicles [2].

## 1.1 Safety Applications

This report addresses the following three crash warning applications:

1. Intersection Movement Assist (IMA), which warns drivers of vehicles approaching from a lateral direction at an intersection (or any road junction).
2. Forward Crash Warning (FCW), which warns drivers of stopped, slowing, or slower vehicles ahead in the same lane.
3. Blind Spot Warning/Lane Change Warning (BSW/LCW), which alerts drivers to the presence of vehicles approaching or in their blind spot in the adjacent lane.

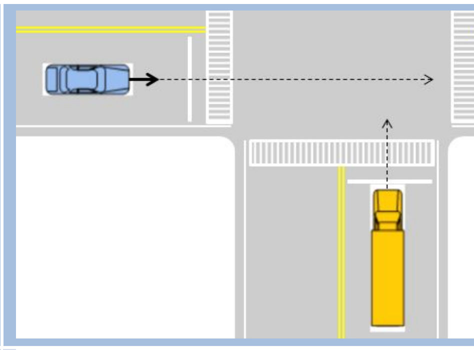
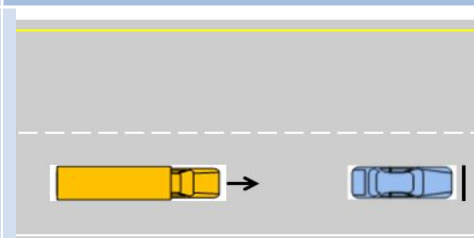
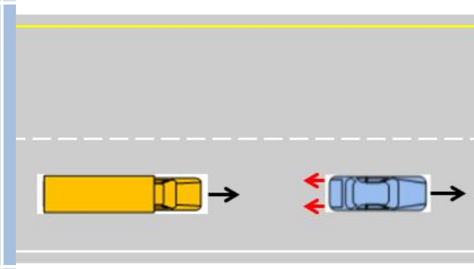
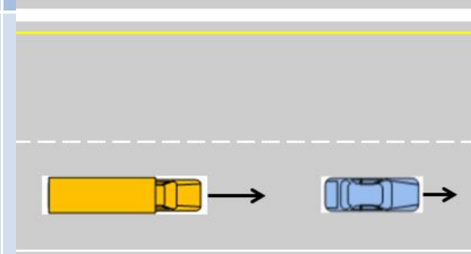
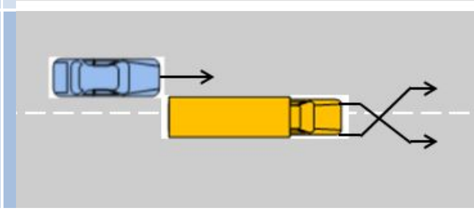
These applications are designed to assist the driver in preventing motor vehicle crashes. They warn the driver using cautionary and/or crash-imminent alerts to reduce driver exposure by obtaining a timely driver response to safety-critical driving conflicts. Cautionary alerts provide information that may be helpful to the driver's situational awareness (e.g., letting drivers know there is a vehicle in their blind spot, even though they are not showing intent to change lanes). Crash-imminent alerts are designed to make drivers aware of an imminent threat (e.g., letting drivers know there is a vehicle in their blind spot when they have shown intent to change lanes). Both cautionary and crash-imminent alerts are presented to the driver using both a visual indicator and an auditory tone. However, the auditory tone associated with the cautionary alert is of shorter duration compared to the tone associated with the crash-imminent alert.

Each of the three crash warning applications is designed to alert drivers to specific driving conflicts that correspond to target pre-crash scenarios. Generally, pre-crash scenarios depict vehicle movements and dynamics as well as the critical event occurring immediately prior to crashes [3]. Thus, while these V2V crash warning applications have the potential to yield safety benefits by reducing the number of annual crashes that involve at least two motor vehicles (i.e., crash avoidance benefit), they also have incremental benefits (not estimated in this study) from mitigating the injury severity of unavoidable crashes by reducing the crash impact speed (i.e., injury mitigation benefit).

## 1.2 Target Crashes

Recent analysis of the target crash population for V2V safety applications has identified five priority pre-crash scenarios, as illustrated in Table 1 [4].

**Table 1. Depiction of V2V Priority Pre-Crash Scenarios**

| Pre-Crash Scenario | Description | Schematic |
|---|---|---|
| **Straight Crossing Paths (SCP)** | Heavy vehicle stops at a stop sign-controlled or uncontrolled road junction/ intersection, and then proceeds by going straight or turning left against lateral-crossing traffic (SCP-S). This also includes a heavy vehicle running a red light, stop sign, or no control at a road junction/ intersection across the path of another straight-crossing vehicle from a lateral direction (SCP-M). |  |
| **Lead Vehicle Stopped (LVS)** | Heavy vehicle is going straight at a constant speed, decelerating, or starting in a traffic lane, and then closes in on a stopped lead vehicle in the same lane. |  |
| **Lead Vehicle Decelerating (LVD)** | Heavy vehicle is going straight at a constant speed or decelerating while following another lead vehicle in the same lane, and then the lead vehicle suddenly decelerates. |  |
| **Lead Vehicle Moving at Constant Speed (LVM)** | Heavy vehicle is going straight at a constant speed or decelerating, and then closes in on a lead vehicle moving at a slower constant speed in the same lane. |  |
| **Changing Lanes/Same Direction** | Heavy vehicle is changing lanes, passing, or merging and then encroaches into another vehicle traveling in the same direction. |  |

This report separates the IMA application into the following two distinct operating scenarios:

- IMA - Moving (IMA-M), which addresses all SCP-M pre-crash scenarios described above. In this operating scenario, the heavy vehicle as the host vehicle (HV) is traveling at a constant speed (i.e., greater than or equal to 10 miles per hour (mph)) as it approaches, and intends to continue through the road junction/intersection (e.g., a vehicle running a red light or stop sign).

- IMA - Stop/Proceed (IMA-S), which addresses all SCP-S pre-crash scenarios as explained above. In this operating scenario, the HV is initially at a stop or moving at a very low speed (i.e., less than 10 mph), then accelerates at a constant level intending to go through the road junction/intersection.

This analysis assumes that the IMA application issues a warning at any travel speed by the HV as long as the speed of the approaching remote vehicle (RV) is greater than or equal to 10 mph. For the IMA-M operating scenario, either or both vehicles can be the HV.

The three V2V crash warning applications address the five pre-crash scenarios illustrated in Table 2.

**Table 2. Mapping of V2V Applications to Target Pre-Crash Scenarios**

| Application | Scenario |
|---|---|
| **Intersection Movement Assist** | Straight Crossing Paths |
| **Forward Crash Warning** | Lead Vehicle Stopped |
| **Forward Crash Warning** | Lead Vehicle Decelerating |
| **Forward Crash Warning** | Lead Vehicle Moving at Constant Speed |
| **Blind Spot Warning/Lane Change Warning** | Changing Lanes/Same Direction |

## 1.3 General Assumptions

This analysis focuses on heavy vehicles as the host vehicles of the safety applications, and assumes the following in order to estimate their crash avoidance effectiveness and project their potential safety benefits:

- Deployment rate:
    - All heavy vehicles are fully integrated with V2V technology and corresponding safety applications.
    - All vehicles (i.e., light vehicles, motorcycles, etc.) are fully equipped with V2V technology and can communicate with fully integrated heavy vehicles.
    - Full deployment is achieved with a complete turnover of the fleet or a mix with retrofitted vehicles.
- Computer modeling and simulation:
    - Simple driving conflicts are modeled using basic kinematic equations, where only the HV responds to the conflict while the other vehicle stays the course.
    - No external conflicts or unintended consequences are modeled.
    - Only the driver of the HV responds to a driving conflict (or warning) with a single appropriate response (brake or steer) that depends on the nature of the conflict.
    - All motion and reaction occur without intermittent delays or interference, and are constant until otherwise acted upon.

These general assumptions are carried throughout the application of the safety benefits estimation methodology, independent of the V2V safety application or pre-crash scenario. Further assumptions about specific safety applications or pre-crash scenarios are discussed in the following sections.

# 2 Safety Benefit Estimation Methodology

This report projects the potential safety benefits of V2V-based crash warning systems using data collected from the National Advanced Driving Simulator (NADS) experiments and the Integrated Vehicle-Based Safety System (IVBSS) field operational test of prototype systems.

Safety is ideally measured using actual crash data from naturalistic baseline and treatment driving conditions (i.e., drivers unassisted versus drivers assisted with crash warning applications). However, when a crash-avoidance technology is new and not yet widespread (or even present) in the on-road fleet, actual crash data from real-world driving are not available because crashes have not yet occurred and cannot occur without equipped vehicles on the roads. Moreover, crash data are rare or non-existent during the conduct of naturalistic driving field operational tests since widespread exposure is required to ensure adequate crash data. With field operational tests the scope is typically limited to a few instrumented vehicles driven by volunteer subjects for a relatively short period of time. Nevertheless, finding a way to assess the safety benefits of such emerging technologies is vital to government efforts to promote their development and deployment. In conjunction with NHTSA, Volpe has formulated a methodology to incorporate driver/vehicle/system performance data from a non-crash driving environment, such as field operational tests, into kinematic simulations to predict the potential safety benefits of V2V-based crash warning applications. Performance data are observed from driver encounters and responses to driving conflicts that are targeted by the V2V-based safety applications. “Driving conflicts” refer to driving events that could result in a crash without proper driver intervention to avoid the crash. This section describes this methodology, along with the input data and sources.

## 2.1 Basic Equations

Safety benefits are expressed in terms of annual reductions in the number of police-reported crashes (i.e., crash avoidance). The following equation computes the potential number of target crashes that might be avoided by the assistance of a crash warning application that addresses a target pre-crash scenario [5]:

$$\mathbf{B_A = N_C \times E_A} \qquad \mathbf{(1)}$$

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

Statistics of baseline target crashes ($\mathbf{N_C}$) are directly obtained from national crash databases such as NHTSA’s National Automotive Sampling System (NASS) General Estimates System[1] (GES) crash database and Fatality Analysis Reporting System (FARS) crash databases[ [6]][ [7]]. On the other hand, the parameter $\mathbf{E_A}$ must be estimated from driver/vehicle/system performance data. The following equation is used to estimate the crash avoidance effectiveness:

$$\mathbf{E_A = 1 - \text{Exposure Ratio} \times \text{Prevention Ratio}} \qquad \mathbf{(2)}$$

The driving conflict Exposure Ratio (ER) is the ability of a crash warning system to reduce the occurrence of conflicts in normal driving behavior [8]. Driving conflicts correspond to the kinematics of target pre-crash scenarios that represent vehicle movements and orientation, as well as the safety-critical event immediately prior to the crash. An exposure to a driving conflict is counted when:

[1] NHTSA has replaced the NASS GES with the new Crash Report Sampling System (CRSS).

1. Movements of the HV and target RV match the configuration of the driving conflict, and
2. The HV and RV will crash if either vehicle does not attempt an avoidance action.

To illustrate an exposure to a driving conflict, consider an HV intending to make a lane change onto an adjacent lane that 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 lane-change conflict. Thus, the ER variable represents the ability of the application to reduce the likelihood of the HV entering such lane-change conflicts. Typically, ER can be determined from data collected in the baseline condition (i.e., *without* application assistance) and the treatment condition (i.e., *with* application assistance) during naturalistic driving field operational tests or controlled experiments using driving simulators or test tracks[2].

The Crash Prevention Ratio (PR) is the ability of a crash warning system to reduce the likelihood of a crash when a vehicle enters a driving conflict [8]. This ratio represents the ability of the warning application to help the driver avoid a crash once the HV has entered a driving conflict, such as a lane change while another vehicle is in the blind spot. It accounts for whether or not the HV will crash with the RV in a driving conflict as a result of its crash avoidance action, such as braking to stop, in baseline and treatment conditions. The values of the PR parameter are estimated using computer simulations such as NADS and the Safety Impact Methodology (SIM) simulation tool as described in Section 2.2 [9].

Equation (2) is rewritten as follows to account for the baseline and treatment conditions:

$$\mathbf{E_A = 1 - \frac{EM_{with}}{EM_{without}} \times \frac{CP_{with}}{CP_{without}}} \qquad \mathbf{(3)}$$

**$\mathbf{EM_{with}}$** ≡ Exposure Measure to a driving conflict corresponding to a target scenario in treatment condition

**$\mathbf{EM_{without}}$** ≡ Exposure Measure to a driving conflict corresponding to a target scenario in baseline condition

**$\mathbf{CP_{with}}$** ≡ Crash Probability when exposed to a driving conflict corresponding to a target scenario in treatment condition

**$\mathbf{CP_{without}}$** ≡ Crash Probability when exposed to a driving conflict corresponding to a target scenario in baseline condition

The numerator and denominator in Equation (3) refer respectively to the treatment and baseline conditions. The **$\mathbf{EM_{without}}$** and **$\mathbf{EM_{with}}$** parameters are estimated from exposure measures that are obtained from data collected in field operational tests or controlled experiments during the baseline and treatment conditions, respectively. Exposure measures are expressed in terms of the number of encounters with a driving conflict over the total miles driven, or the number of maneuvers made leading to a driving conflict over the total number of driver intents to make such a maneuver (e.g., changing lanes in the presence of another vehicle in the blind spot). The **$\mathbf{CP_{without}}$** and **$\mathbf{CP_{with}}$** parameters are derived by using performance data from such tests and/or experiments during the baseline and treatment conditions, respectively, as input to the SIM tool that runs Monte Carlo simulations, using a large number of iterations to estimate the

[2] Controlled experiments are most suitable for "Go - No Go" decisions that trigger the driving conflicts. For example, a "Go" decision and initiation of a lane-change or left-turn maneuver in the presence of a threat vehicle creates a driving conflict. On the other hand, a "No Go" decision keeps the vehicle in its current state, such as remaining in the same lane or stopped by respectively aborting the lane change or left turn. Moreover, controlled experiments are conducted by incorporating the various driver-environment factors that contribute to the crash/pre-crash scenario being simulated by these experiments.

crash probability measure. The crash probability is calculated from the total number of crashes over the total number of encounters with a driving conflict.

## 2.2 Input Data and Sources

Figure 1 illustrates the framework used to estimate the crash avoidance effectiveness and benefits of the crash warning applications. The main components encompass multiple sources of real-world input data and the SIM tool that interacts with these input data to generate parameter values for estimating the crash avoidance effectiveness of the safety applications. Field operational tests, driving simulator experiments, and human factors-based test track studies produce driver/vehicle performance data with and without the assistance of the safety applications. Crash databases contain historical crash statistics for target pre-crash scenarios, which provide the baseline values of all needed parameters and conditions. Characterization engineering tests yield information about the performance and capability of the safety applications.

This study used data from the IVBSS field operational test and the NADS experiment. IVBSS provided crash avoidance effectiveness estimates for FCW and BSW/LCW applications. NADS provided IMA-M crash avoidance effectiveness estimates. In addition, the SIM tool provided crash avoidance effectiveness for IMA-S and BSW/LCW, using the NADS data as input. Volpe used a range of system effectiveness values for BSW/LCW in this study due to the difference in estimates between the IVBSS data and the SIM tool.

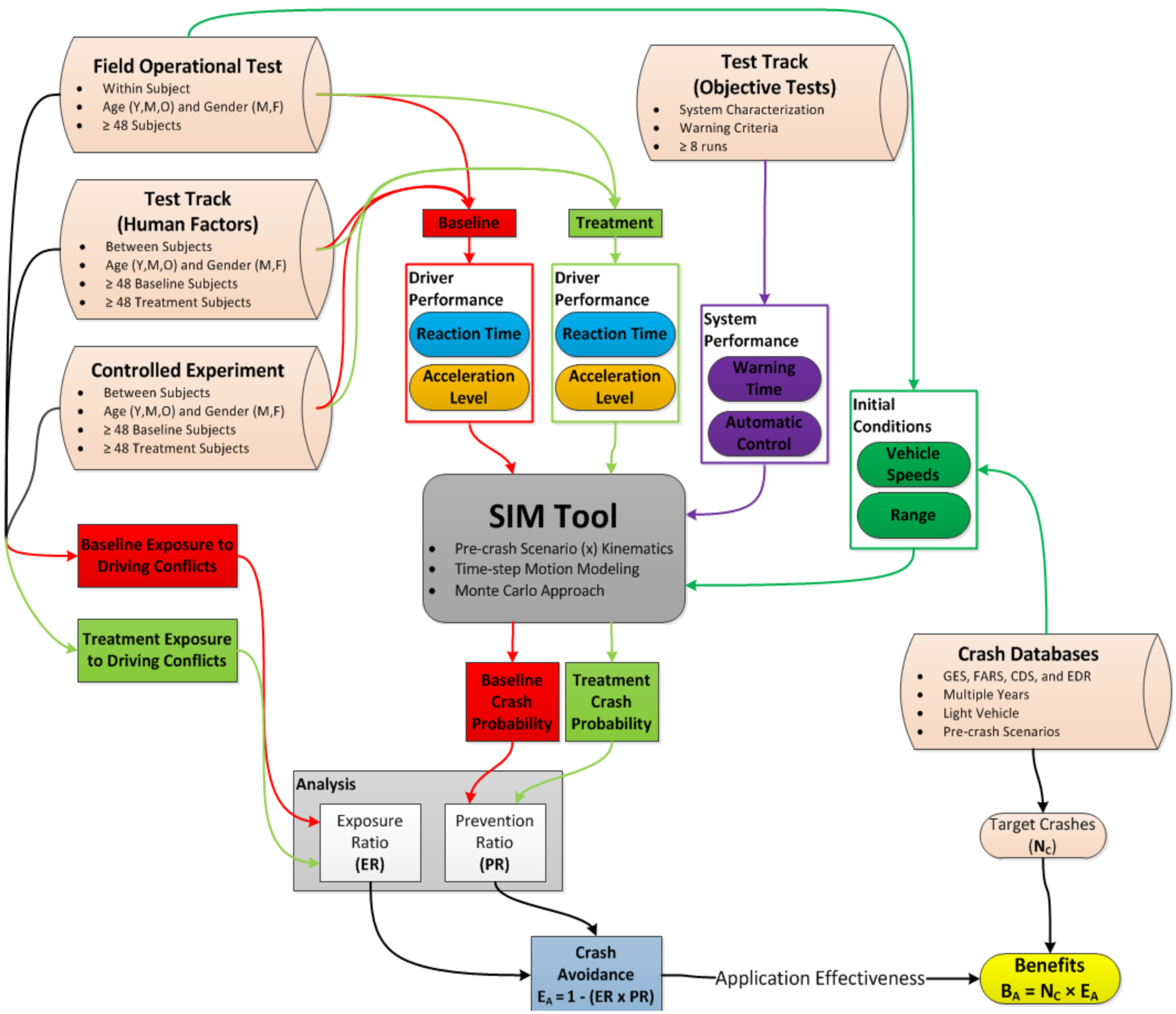



**Figure 1. Estimation Framework for Crash Avoidance Benefits**

### 2.2.1 Safety Impact Methodology (SIM) Tool

The SIM computer-based simulation tool estimates the **CP** parameters in Equation (3) for the baseline and treatment conditions. The basic function of the SIM tool is to simulate the kinematics of driving conflicts corresponding to target pre-crash scenarios. This tool uses input data from national crash databases; driver, vehicle, and safety application performance data from naturalistic field operational tests such as the IVBSS; track tests; and related driver, vehicle, or safety application evaluation studies. Outputs of the tool consist of the number of crashes avoided and resulting impact speed reduction from unavoided crashes. These can be translated into harm reduction, including savings in crash comprehensive costs and decreases in the number of persons injured at different Maximum Abbreviated Injury Scale (MAIS) levels. Note that Volpe's analysis of V2V safety applications focused on crash avoidance only.

To generate driving conflicts, simulate vehicle motions and driver response, and determine outcomes, the kinematic modules within the SIM tool need data on crashes, with and without the assistance of the safety applications. Figure 2 illustrates the structure of the SIM tool [9]. The SIM process for estimating crash warning effectiveness starts by generating pre-crash scenarios using crash statistics. From each scenario, specific driving conflicts (combination of driver, vehicle, and scenario characteristics) are generated using probability distributions.

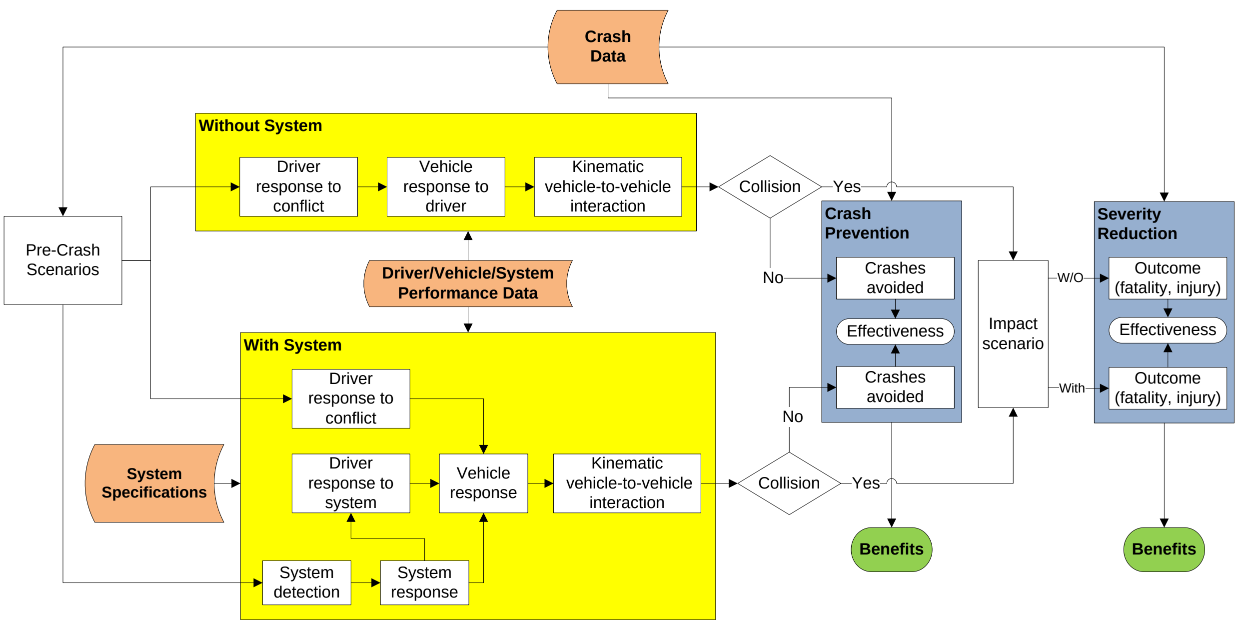



**Figure 2. SIM Tool Logic and Structure**

The SIM tool follows the same general assumptions listed in Section 1.3.

Each specific conflict is a single event, with only the vehicles involved in the conflict included in the simulation. Unintended consequences (e.g., a crash caused by avoiding the initial crash event via steering onto the path of another vehicle) that involve other non-conflict vehicles are not captured by the simulation due to their complexity and involvement of multiple factors. Note that baseline crashes involving a prior evasive maneuver are very rare, according to GES statistics. Other unintended consequences, such as an increase in driver distraction or speeding, are modeled in the SIM tool using statistical distributions of data collected from the test conditions. The distributions used to generate the specific conflicts include safety application performance (i.e., application activation), driver reaction time, acceleration level (i.e., braking or steering level), and the vehicle speed/distance to collision distributions. Figure 1 illustrates the input source(s) for each of these distributions. These distributions support the use of a Monte Carlo approach to run thousands of driving conflicts in baseline and treatment conditions. Volpe summarized the results from these conflict simulations, then externally analyzed the results, using the equations in Section 2.1, to estimate the crash avoidance effectiveness values for the pre-crash scenario/safety application combinations. Effectiveness estimates were then applied to the target crash population for each pre-crash scenario to estimate the potential safety benefits that might result from the full deployment of the safety applications.

### 2.2.2 National Crash Databases

NHTSA's NASS GES and FARS crash databases contain historical crash data at the national level and are useful in quantifying and characterizing the crash problems addressed by the V2V safety applications.

The GES is a sample of more than five million annual police-reported crashes that involve injury or major property damage. The database includes weighting factors to provide a nationally-representative estimate of the crash population. FARS data is a complete nationwide census of all police-reported crashes that involve a fatality. Specifically, these databases provide estimates for the parameter, $\mathbf{N_C}$, in Equation (1) for the crash avoidance analysis. Based on 2011-2013 GES statistics, the annual target crash population related to the three safety applications is approximately 92,875 police-reported crashes involving at least one heavy vehicle (includes medium and heavy trucks as well as buses with a gross vehicle weight rating over 10,000 pounds). These crashes exclude those involving control loss, vehicle defects, or impaired heavy-vehicle drivers, which V2V-based safety applications could not necessarily mitigate. Furthermore, target crashes consist only of heavy vehicles that were either making the maneuver (i.e., changing lanes or merging) or, in the case of rear-end crashes, striking the lead vehicle; which correspond to the vehicle scenarios that V2V-based safety applications are designed to warn. The annual target injury population amounts to approximately 36,122 injured persons at the MAIS $1^+$ levels, based on crash statistics from the 2011-2013 GES and FARS databases. Appendix A lists the values used to convert the injury levels from the police-reported KABCO scale in the GES database to the MAIS scale. The FARS is queried to obtain the actual count of persons killed in target crashes.

The crash databases also contain details to characterize each pre-crash scenario. This can include travel speeds, environmental conditions, vehicle motion, driver factors, and attempted avoidance maneuvers. These details result in an accurate depiction of the driving conflict and support the estimation of $\mathbf{E_A}$ and **EM** from Equation (3).

### 2.2.3 Driver/Vehicle Performance Data Sources

Field operational tests, driving simulator experiments, and test track studies generate human factors data that characterize the driver/vehicle/application performance in baseline and treatment test conditions. Field operational tests offer real-world naturalistic driving experience. The IVBSS field operational test collected naturalistic driving data from 18 test subjects who drove 10 IVBSS-equipped heavy trucks, accumulating 600,000 miles over a 10-month period. The test period consisted of 2 months of baseline driving, when the IVBSS was disabled, and an 8-month treatment period, when the IVBSS was enabled and alerts were presented to the drivers. The heavy trucks were equipped with integrated vehicle-based FCW, LCW, and lane departure warning applications [10]. The FCW and LCW applications in the IVBSS field test performed the same functions as the equivalent V2V-based applications in the Safety Pilot Model Deployment.

To estimate the PR parameter in Equation (2), the SIM tool simulates driver/vehicle performance parameters in response to encounters with safety-critical driving conflicts (i.e., near-crash events). Typically, limited-duration or short-term-use field operational tests provide few opportunities to observe driver response in safety-critical driving conflicts where intense crash avoidance action is required. Like crashes, near-crash events are relatively rare over shorter periods of driving. Controlled experiments in driving simulators or on closed-course test tracks provide a safe source to obtain data on driver/vehicle performance in safety-critical driving conflicts, which could supplement data collected from field operational tests, such as the Safety Pilot Model Deployment. Volpe used driver performance data from the NADS Simulator study to estimate the PR parameter for the IMA (IMA-M and IMA-S) and LCW applications. Section 2.2.4 provides a detailed description of the NADS Simulator study.

### *2.2.4 Overview of NADS Heavy Truck Simulator Study*

The primary objective of the NADS study [11] was to provide additional data for IMA, FCW, and LCW safety applications to supplement the data collected during the Safety Pilot Model Deployment, and to calculate system effectiveness and benefits for these V2V applications. Professional commercial truck drivers were recruited and their response to the above V2V applications was evaluated in a variety of controlled simulated conditions. The study used the NADS-1 simulator, consisting of a 24-foot dome within which a Freightliner tractor cab was mounted (Figure 3). To portray the external roadway environment, the simulator included three front projectors and five rear projectors. In addition, two displays were mounted inside the cab (Figure 4) to interface with the subjects, showing the setup of experimental scenarios, and the V2V warning alerts.

The study was conducted in two parts. During the first part 96 drivers participated in simulated drives of primarily IMA and LCW events. During the second part 40 drivers participated in simulated drives of FCW and LCW events only. The recruitment criteria included:

- Drivers were between the ages of 22 and 60,
- held a valid, unrestricted class A commercial driver's license (corrected vision and hearing loss acceptable),
- had at least six months of driving experience with this license and had driven an average of at least 2000 miles per month for the past six months,
- were in good general health, and
- did not participate in prior new vehicle technology studies.

Note that since the population of commercial drivers consisted primarily of males, there was no attempt to balance the test participants by gender.

#### 2.2.4.1 NADS Scenario Description

A total of four drive scenarios were simulated in the NADS study (Figure 5). Each scenario contained two pre-crash scenarios addressed by the V2V safety applications. For FCW, the two events simulated were LVS and LVD; for IMA the events were straight crossing path at signal (SCP-M) and straight crossing path at non-signal (SCP-S); and for LCW, the events were lane change left (LCL) and lane change right (LCR). Table 3 provides details for each scenario, including the initial conditions (HV and RV initial speeds), roadway type, and posted speed limit. Note that for the SCP-M and SCP-S test scenarios, the alert was issued when the HV time to intersection (TTI) was 6 seconds and the RV was visible to the HV driver when the TTI was 3.5 seconds.


**Figure 3. Freightliner Tractor Cab Mounted in NADS-1 Simulator**

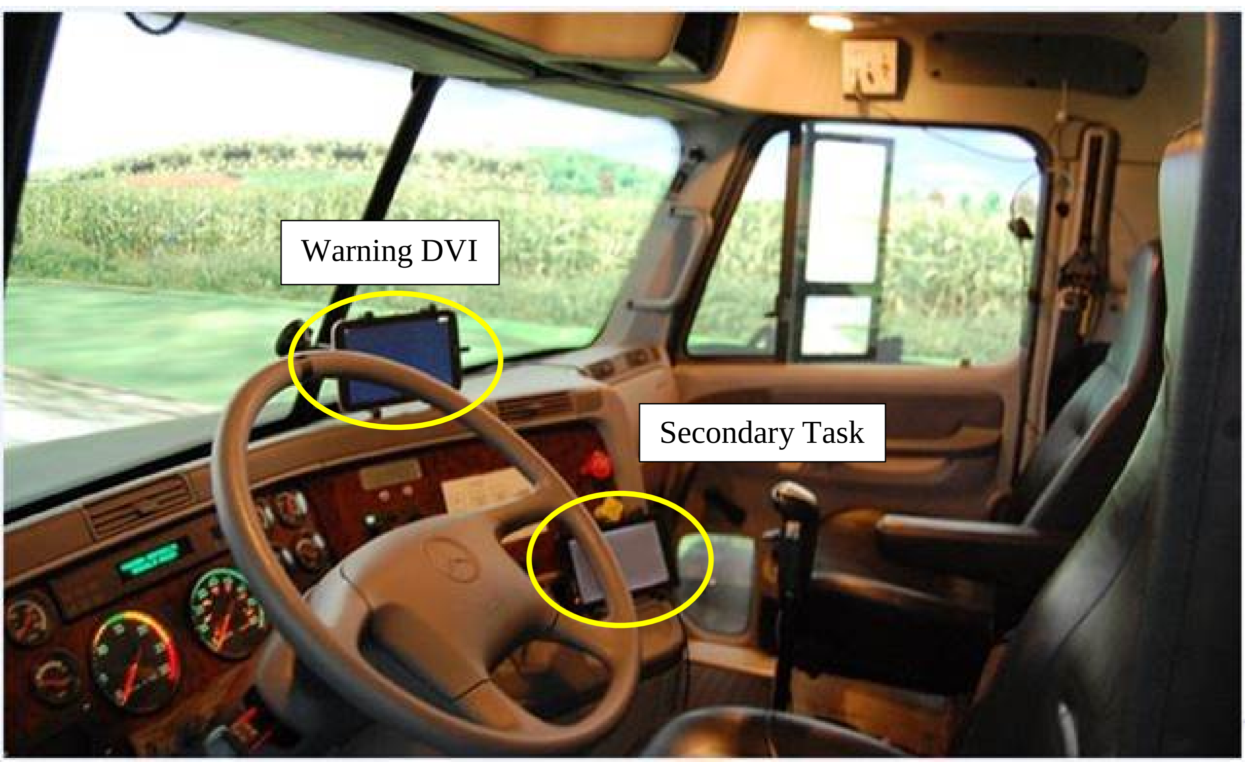



**Figure 4. Freightliner Tractor Cab Interior - NADS-1 Simulator**

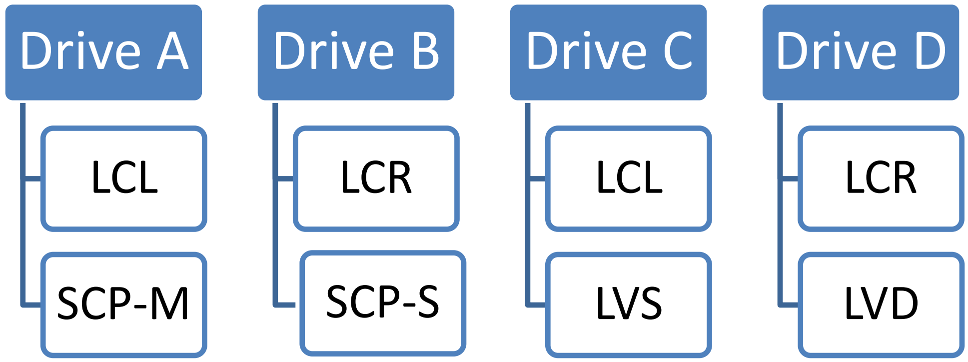



**Figure 5. NADS Simulated Drive Scenarios**

**Table 3. Description of NADS Simulated Scenarios**

| Scenario | Roadway | Posted Speed Limit | Initial Conditions | | Scenario Description |
|---|---|---|---|---|---|
| | | | HV Speed | RV Speed | |
| **LVS** | 2 Lane Rural Highway (HW) | 45 mph | 30-45 mph | 0 mph | This event occurs on a 2-lane roadway with a posted speed limit of 45 mph. A lead vehicle is traveling at the posted speed limit in front of the truck operator. A stopped vehicle is in the truck's travel lane in front of the lead vehicle. The truck operator engages with the secondary task on the connected vehicles display and the lead vehicle changes lanes to the left to reveal the stopped vehicle. As the lead vehicle changes lanes, a vehicle appears in the oncoming lane to inhibit the driver from changing lanes. This vehicle is in the oncoming lane, between the driver and the stopped vehicle. |
| **LVD** | 2 Lane Rural HW | 55 mph | 45-55 mph | 45-55 mph | This event occurs on a 2-lane rural roadway with a posted speed limit of 55 mph. A lead vehicle pulls out ahead of the driver at the first intersection. The vehicle maintains a 4.0 s gap with the driver, with the constraints of traveling between 50-65 mph to maintain this gap. After passing the third intersection, and before the fourth intersection, the driver is presented with a message task to engage. After a period of 2.0 s from the display of the message the lead vehicle decelerates at 8.33 m/s2 for a period of 5.0 s. As the lead vehicle brakes, a vehicle appears in the oncoming lane to inhibit the driver from changing lanes. This vehicle is near the lead vehicle as it begins braking. |
| **SCP-M** | 4 Way Intersection (signalized) | 40 mph | 40–45 mph | 40-45 mph | This event occurs at a signalized intersection with a green light in the direction of the truck operator and a red light in the direction of the incurring vehicle. Both directions have a posted speed limit of 40 mph. Both vehicles are traveling at constant speeds nominally at the speed limit. As the truck operator approaches the green light intersection, the incurring vehicle approaches from the left. The initial approach of the incurring vehicle is obscured to the driver, and the RV becomes visible at 3.5 s away from the intersection. |

| Scenario | Roadway | Posted Speed Limit | Initial Conditions | | Scenario Description |
|---|---|---|---|---|---|
| | | | HV Speed | RV Speed | |
| **SCP-S** | 4 Way Intersection (w/Stop Sign) | 40 mph | 0-4 mph | 44 mph | This event occurs at a 4-way intersection with a stop sign in the direction of travel and no traffic control for cross traffic. Both directions have a posted speed limit of 40 mph. The incurring vehicle is traveling at constant speed nominally at the speed limit. The approach of the incurring vehicle from the left is obscured to the driver, and the RV becomes visible at 3.5 s away from the intersection. |
| **LCL** | 4 Lane/2 Way | 55 mph | 50-60 mph | 65-75 mph | This event occurs on a 4-lane roadway with the truck in the right lane with a speed limit of 55 mph. Traffic periodically passes the truck. The truck is approaching a slower moving vehicle traveling at 40 mph. After the driver turns on the left turn signal, a vehicle traveling 10 mph faster than the driver appears next to the trailer, in the adjacent lane (left). |
| **LCR** | 4 Lane/2 Way | 55 mph | 50-60 mph | 65-75 mph | This event occurs on a 4-lane roadway with the truck in the left lane with a speed limit of 55 mph. The truck is moving with the flow of traffic in the left lane past slow moving traffic in the right lane with a car following close behind the truck. After the driver turns on the right turn signal, a vehicle traveling 10 mph faster than the driver appears next to the trailer, in the adjacent lane (right). |

#### 2.2.4.2 Breakdown of NADS Scenarios by Test Subject

Table 4 shows the NADS simulation matrix for the 136 participants, broken down by drive scenario, safety application, and alert condition. With one exception, each driver was exposed to two scenario events. In addition, half of the drivers were exposed to an alert (treatment) and half were not (baseline). Table 5 breaks down the NADS simulated cases by scenario type.

**Table 4. Breakdown of NADS Participants by Drive Scenario**

| Drive Scenario | V2V Safety Application | | | V2V Condition | |
|---|---|---|---|---|---|
| | FCW | IMA | BSW/LCW | Treatment | Baseline |
| LCL-SCP-M | | X | X | 20 | 21 |
| LCR-SCP-S | | X | X | 21 | 20 |
| LCL-LVS | X | | X | 13 | 13 |
| LCR-LVD | X | | X | 14 | 14 |
| Total | | | | 68 | 68 |

**Table 5. Total NADS Simulated Cases by Scenario Type**

| Scenario | Treatment | Baseline | Sum |
|---|---|---|---|
| LVS | 13 | 13 | 26 |
| LVD | 14 | 14 | 28 |
| SCP-M | 20 | 20 | 40 |
| SCP-S | 21 | 20 | 41 |
| LCL | 33 | 34 | 67 |
| LCR | 35 | 34 | 69 |
| Total | | | **271** |

#### 2.2.4.3 NADS Output Data

Sample output variables in each NADS data set include:

- Steering wheel position
- Throttle position
- Brake pedal force
- Vehicle speed
- Turn signal use
- Vehicle acceleration
- Lane deviation
- Distance from HV to RV
- Distance to collision point
- Collision with tractor/trailer

# 3 IMA Effectiveness and Potential Safety Benefits

Figure 6 specifies the framework illustrated in Figure 1 for estimating potential crash avoidance benefits for the IMA application in the IMA-S operating scenario. Volpe did not use the SIM tool to estimate crash avoidance effectiveness of the IMA application in the IMA-M operating scenario due to the large number of crashes generated from the NADS simulation study, and instead used crash counts directly from the NADS study. The SIM tool was used to estimate crash avoidance effectiveness of the IMA application in the IMA-S scenario. Refer to Section 3.3.

## 3.1 IMA Target Crash Statistics

Target crash statistics for the IMA application are provided in terms of the annual number of crashes, the distribution of injury levels and property damage resulting from these target crashes, and the annual comprehensive cost of these crashes, including economic cost components[3] and quality-of-life valuations.[4]

### *3.1.1 Annual Target Crash Population*

The annual IMA target crash population amounts to approximately 35,517 police-reported crashes, based on crash statistics from the 2011-2013 GES databases. Table 6 breaks down IMA target crashes (including target injury and property damage only (PDO) crashes) by the IMA operating scenario. IMA crashes represent 38 percent of all the target crashes addressed by the IMA, FCW, and BSW/LCW applications. The IMA application could eliminate this target crash population if the application worked perfectly under all driving conditions and all drivers responded in a timely and appropriate manner to IMA alerts (i.e., if the effectiveness were 100 percent, the IMA application could prevent all target crashes and related injuries it is designed to address). As shown in Table 6, about 11,922 target crashes (34 percent) resulted in at least one injured person (i.e., injury crash) and the remaining 66 percent were PDO crashes.

**Table 6. Breakdown of IMA Target Crashes by Injury and PDO Type**

| Operating Scenario | Number of Injury Crashes | Number of PDO Crashes | Total Number of Crashes |
|---|---|---|---|
| **IMA – Stop/Proceed** | 7,905 | 18,229 | 26,134 |
| **IMA – Moving** | 4,017 | 5,366 | 9,383 |
| **Total** | 11,922 | 23,595 | 35,517 |

[3] Economic cost components include productivity losses, property damage, medical costs, rehabilitation costs, congestion costs, legal and court costs, emergency services, such as medical, police, and fire services; insurance administration costs, and the costs to employers.

[4] Quality-of-life valuations refer to intangible crash consequences, such as physical pain or lost quality-of-life.

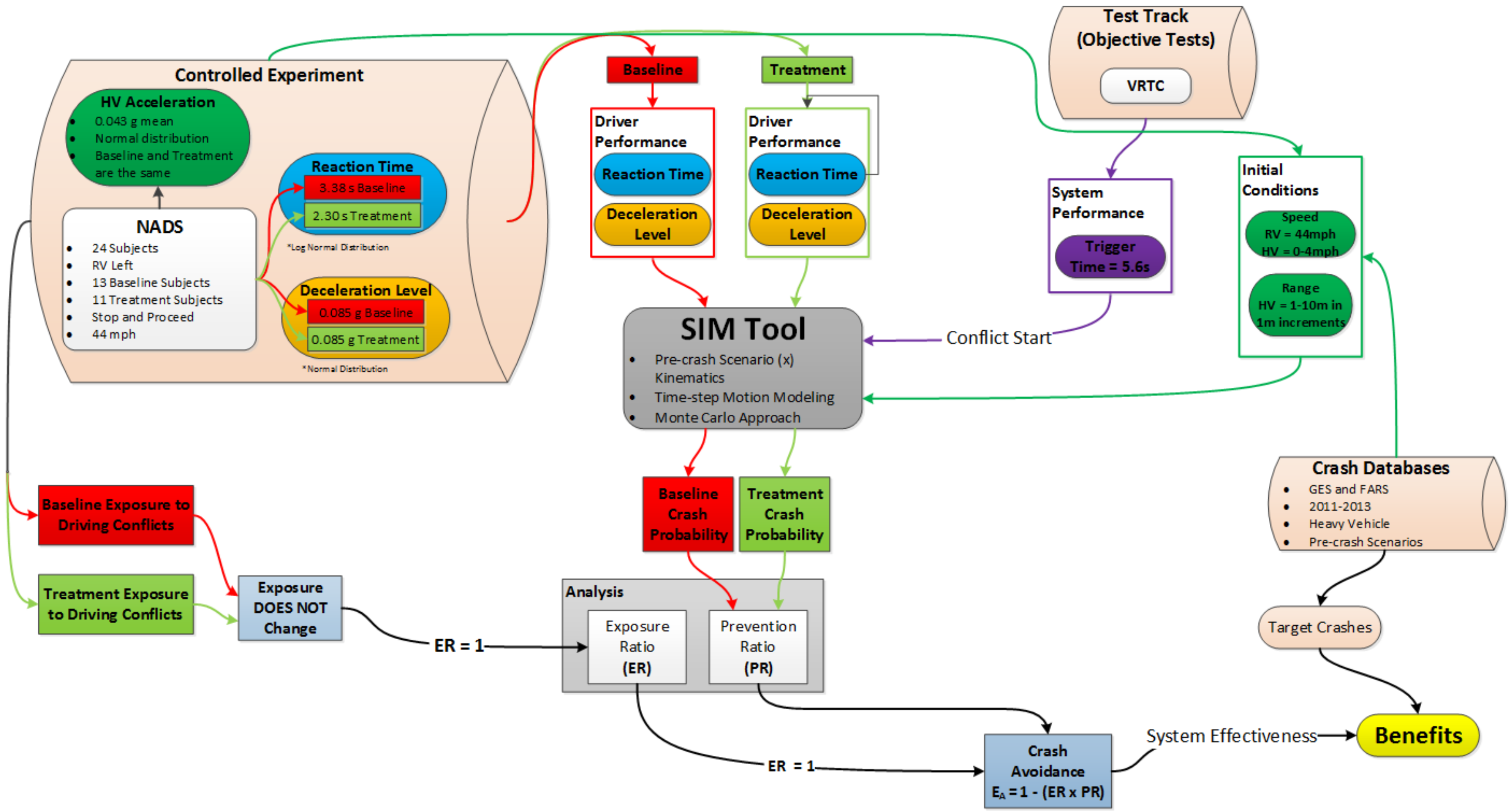



**Figure 6. Estimation Framework for IMA-S Crash Avoidance Benefits**

### 3.1.2 Annual Target Injury Population

The annual target injury population is approximately 16,420 injured persons, based on crash statistics from the 2011-2013 GES and FARS databases. Table 7 shows the distribution of target injured persons by their MAIS injury level for the IMA V2V safety applications. This table also shows the number of PDO vehicles in target crashes. A total of 645 persons (4 percent of all injured persons) died in target crashes.

**Table 7. Distribution of Injured Persons by MAIS Level and IMA Operating Scenario**

| MAIS Injury | IMA-Moving | IMA-Stop/Proceed | Total |
|---|---|---|---|
| 0 - No Injury | 6,768 | 12,763 | 19,531 |
| 1 - Minor | 4,649 | 8,789 | 13,438 |
| 2 - Moderate | 570 | 1,076 | 1,646 |
| 3 - Serious | 185 | 350 | 535 |
| 4 - Severe | 39 | 75 | 114 |
| 5 - Critical | 15 | 27 | 42 |
| 6 - Fatal | 120 | 525 | 645 |
| Total MAIS 1-6 | 5,578 | 10,842 | 16,420 |
| PDO Vehicles | 10,808 | 36,733 | 47,541 |

### 3.1.3 Annual Target Comprehensive Cost

The annual comprehensive cost of IMA target crashes amounts to approximately $8,568M (IMA-S ($6,581M) and IMA-M ($1,987M)). This cost corresponds to 937 equivalent lives[5] lost annually. The comprehensive cost is calculated by multiplying the annual frequency of PDO vehicles and target injured persons at various MAIS levels in Table 7 with the respective comprehensive unit costs for police-reported crashes, expressed in year 2010 economics, as listed in Table 8. [12]

**Table 8. Comprehensive Unit Costs for Police-Reported Crashes Based on 2010 Dollars**

| MAIS 0 | MAIS 1 | MAIS 2 | MAIS 3 | MAIS 4 | MAIS 5 | Fatal | PDO Vehicle |
|---|---|---|---|---|---|---|---|
| $4,380 | $43,942 | $399,626 | $992,825 | $2,432,091 | $5,579,614 | $9,145,998 | $6,076 |

## 3.2 Input Data for IMA Effectiveness Estimation

Volpe analyzed NADS data to extract key metrics to estimate the crash avoidance effectiveness for IMA, FCW (Section 4), and LCW (Section 5) V2V safety applications on board heavy vehicles. As a precursor, Volpe performed a quality control check for time shift, bias, and sign convention anomalies and to ensure the data appeared reasonable and was practical. Data was also formatted so that key metrics required for input to the SIM tool program could be analyzed efficiently.

5 An equivalent life is worth $9,145,998.

Table 9 lists the key metrics required for estimating the crash avoidance effectiveness using the SIM Tool by V2V safety application.

**Table 9. Key Parameters in SIM Tool**

| V2V Safety Application | Target Scenario | Key Parameter in Sim Tool |
|---|---|---|
| **IMA** | SCP-M<br>SCP-S | HV brake reaction time<br>HV average brake response |
| **FCW** | LVS<br>LVD | HV brake reaction time<br>HV average brake response |
| **BSW/LCW** | LCL<br>LCR | HV steering reaction time<br>HV countersteer jerk |

### *3.2.1 IMA Results*

Figure 7 shows the overall results obtained from the NADS SCP simulations. The majority of the crashes occurred in the SCP-M simulations where almost all of the participants (19 of 20) in the baseline condition ended up in a crash. In contrast, about half of the participants (9 of 20) in the treatment condition impacted the RV. Based on the number of crashes, crash avoidance effectiveness for the IMA application in the moving scenario can be calculated using these figures. The minimum number of crashes occurred in the SCP-S simulations where there was only one crash. Due to the low crash count in the SCP-S simulations, the SIM tool was used to estimate the crash avoidance for the IMA application in the stop/proceed scenario. Volpe analyzed the key SIM tool input metrics listed in Table 9. The results of the analysis are discussed in Sections 3.2.2 and 3.3.

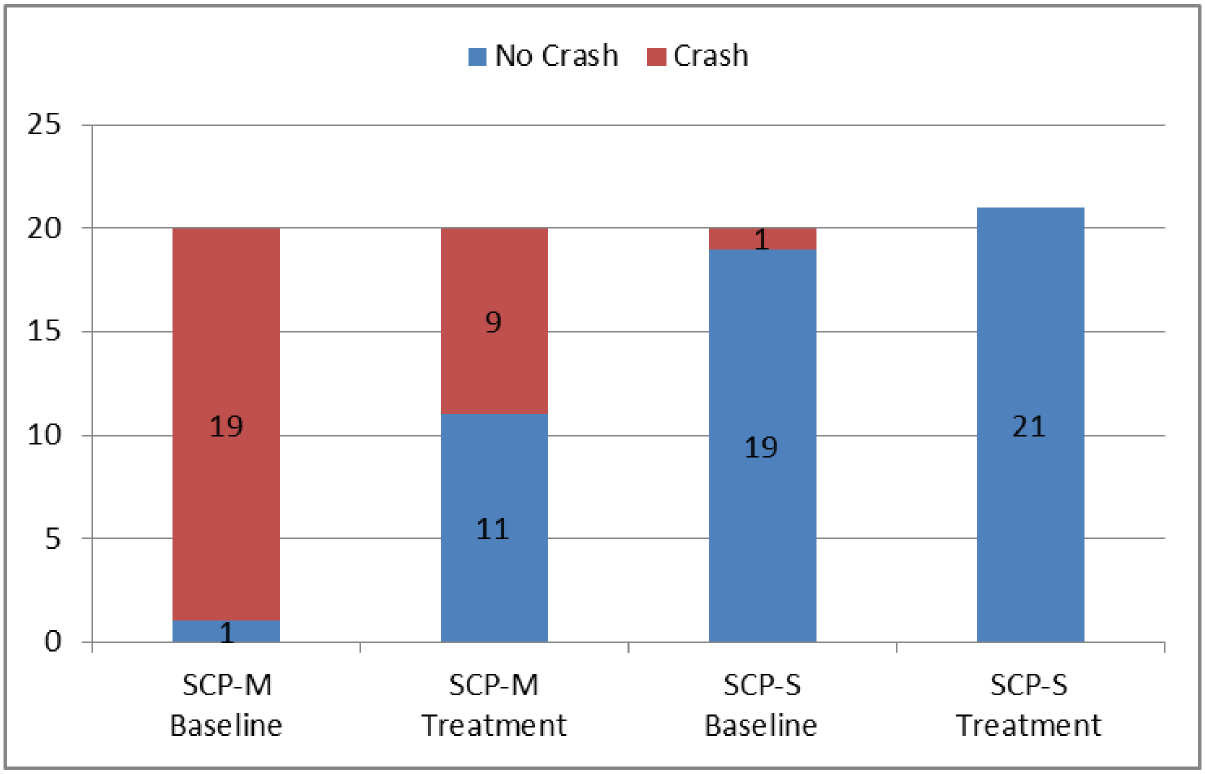



**Figure 7. NADS SCP Overall Results**

### *3.2.2 Analysis of SIM Input Parameters – SCP-S*

Table 10 shows results from the analysis of driver brake response times, obtained from the SCP-S simulations. The table lists the number of participants, mean response times, and standard deviation of the mean values for both baseline and treatment conditions, in addition to the T-test p-value. These are cases where the driver attempted to cross the intersection and braked. Several cases were excluded from the analyses; seven cases where the driver was stopped and did not attempt to cross, and nine cases where the HV moved at speed through the intersection without braking. One crash (baseline) was excluded because the driver accelerated through the intersection without braking.

A statistical analysis resulted in a statistically-significant relationship (at the 90 percent confidence level) in driver brake response times between baseline and treatment conditions. Therefore, the brake response times were used as input to the SIM tool to estimate effectiveness values.

Table 11shows the results obtained from the analysis of the HV average deceleration levels during the braking response. A statistical analysis did not reveal any statistically-significant difference in deceleration levels (T-test p-value=0.26) between baseline and treatment conditions.

**Table 10. Statistics of HV Driver Brake Response Time (s) – SCP-S**

| Measure | Baseline | Treatment |
|---|---|---|
| **Number of Participants** | 13 | 11 |
| **Mean** | 3.4 | 2.3 |
| **Standard Deviation** | 1.47 | 1.37 |
| **T-test p-value** | 0.1 | |

**Table 11. Statistics of HV Average Brake Response ($ft/s^2$) – SCP-S**

| Measure | Baseline | Treatment |
|---|---|---|
| **Number of Participants** | 13 | 11 |
| **Mean** | 2.39 | 3.15 |
| **Standard Deviation** | 1.77 | 1.42 |
| **T-test p-value** | 0.26 | |

Volpe used the SIM tool to estimate the probability of a crash in a driving conflict for the IMA-S operating scenario, using input data from the NADS study. The SIM tool requires input from driver, vehicle, and system performance data, along with initial conflict conditions to set up the conflict, simulate the conflict, and determine conflict results. Note that the HV reacts in the simulation but the RV does not. The RV can impact the HV while it is passing through the intersection.[6]

Table 12 lists the SIM tool parameters for the IMA-S scenario. Numerical values include minimum, maximum, mean, and standard deviation values. As noted in the table, the HV initial distance to the intersection was varied during the simulations. A total of 10,000 runs were conducted. Section 3.3 presents detailed results.

[6] RV dimensions = 4.8m x 2.4m; HV dimensions = 9.6m x 4m.

**Table 12. SIM Tool Input – IMA-S**

| | Inputs: | Min | Max | Mean | Std. Dev. | Distribution | Notes |
|---|---|---|---|---|---|---|---|
| Initial Conditions | Host Vehicle Acceleration (g) | 0.006 | 0.073 | 0.043 | 0.018 | Normal | Combined Control and Treatment (p = 0.38) |
| | Host Initial Distance (m) | x | x | x | x | Rectangular | Sensitivity Analysis (1 to 10 m in 1 m increments) |
| | Remote Vehicle Initial Velocity (km/h) | 71.455 | 71.455 | 71.455 | 1 | Rectangular | Based on NADS (44.4 mph) |
| | Time to Intersecting Path (s) | 5.6 | 5.6 | 5.6 | 5.6 | Rectangular | |
| Driver Response | Host Driver Reaction Time (Control) (s) | 0.800 | 4.900 | 3.380 | 1.470 | Log Normal | NADS Data (p = 0.10) |
| | Host Driver Deceleration (Control) (g) | 0.003 | 0.181 | 0.085 | 0.051 | Normal | Combined Control and Treatment (p = 0.26) |
| | Host Driver Reaction Time (Treatment) (s) | 0.100 | 4.300 | 2.300 | 1.370 | Log Normal | NADS Data (p = 0.10) |
| | Host Driver Deceleration (Treatment) (g) | 0.003 | 0.181 | 0.085 | 0.051 | Normal | Combined Control and Treatment (p = 0.26) |

*$g = 9.81\ m/s^2$ ($32.2\ ft/s^2$); 1 km/h = 0.62 mph*

## 3.3 IMA Effectiveness Estimation Results

### *3.3.1 IMA-S Scenario*

This analysis conservatively assumes that the ER value is 1 for the IMA application in the IMA-S operating scenario and that there is no change in driver exposure to intersection driving conflicts between baseline and treatment test conditions.

The following two figures are an overlay of CP values versus HV initial distance from the intersection for both treatment and baseline conditions where the RV approaches from the left (Figure 8) and from the right (Figure 9). The HV was placed at a uniform distance, back from the point of intersection with the RV. As shown in Table 12, the distance ranged from one to 10 meters. Both figures show there is a greater probability of a crash occurring in the baseline condition compared to treatment. Assuming an exposure ratio of 1, the crash avoidance effectiveness values were solely based on the ability to reduce the probability of crash from the SIM tool (see Reference [9] for the SIM tool's detailed implementation of this scenario). Figure 10 shows crash avoidance effectiveness versus distance. The results are approximately the same for cases where the RV approaches from the left compared to the right. The average crash avoidance effectiveness between two to five meters from the intersection is 60 percent. The average effectiveness between five and eight meters is 75 percent. The high effectiveness estimates can be attributed to the low CP values. Therefore, the estimated overall average crash avoidance effectiveness of the IMA-S application is 68 percent.

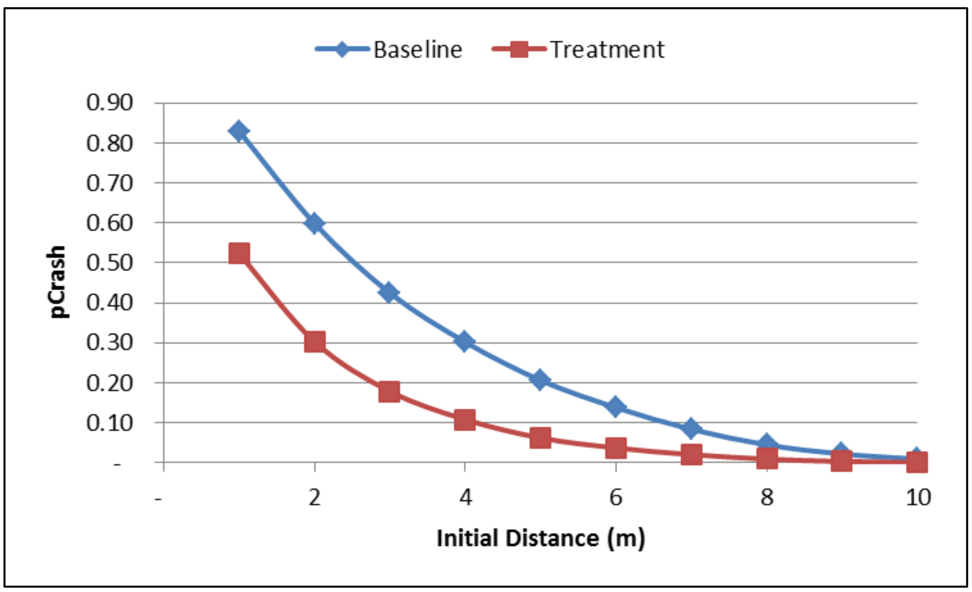



**Figure 8. IMA-S Crash Probability versus HV Distance to Intersection – RV Approach (Left)**

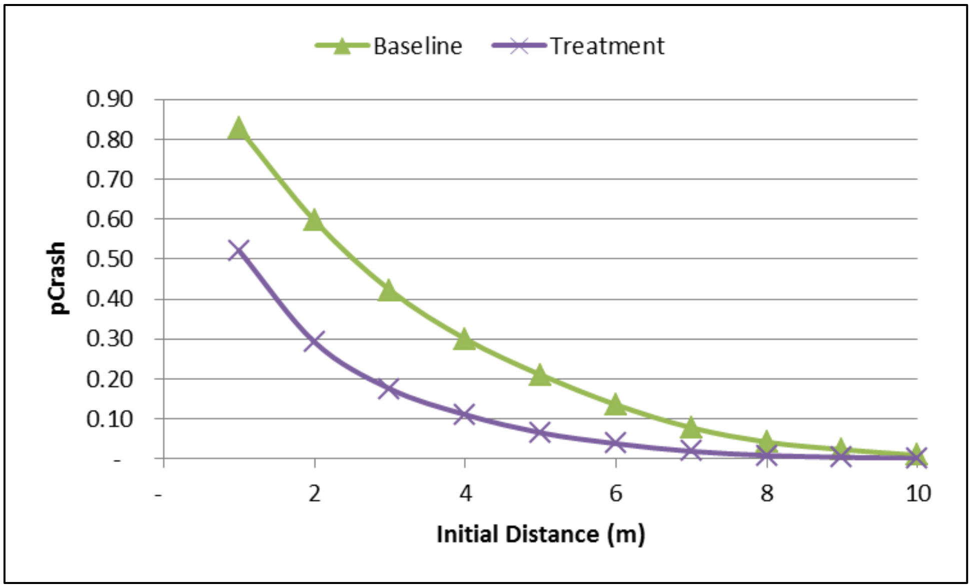



**Figure 9. IMA-S Crash Probability versus HV Distance to Intersection – RV Approach (Right)**

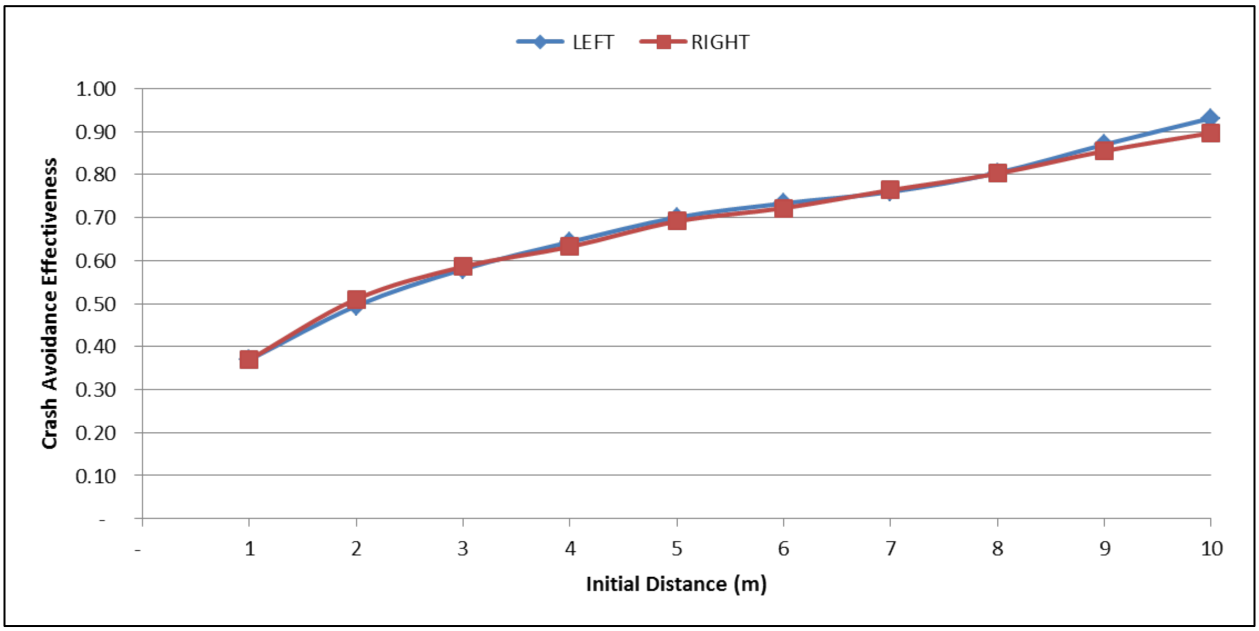



**Figure 10. IMA-S Crash Avoidance Effectiveness versus HV Distance to Intersection**

### *3.3.2 IMA-M Scenario*

As stated at the beginning of Section 3, crash avoidance effectiveness of the IMA application in the IMA-M operating scenario is estimated from the crash counts yielded from the NADS study. Table 13 presents the results of the NADS SCP-M experiment. Almost all participants in the baseline condition ended up in a crash. In contrast, about half of the participants in the treatment condition collided with the RV. As a result, the crash avoidance effectiveness of the IMA application in this driving simulator experiment is calculated at 53 percent. Volpe assumes that this estimate of the IMA crash avoidance effectiveness applies to all travel speeds by the HV and RV in the SCP scenario.

**Table 13. Results of SCP-M Experiment for Heavy Vehicles**

| Scenario Outcome | Baseline | Treatment |
|---|---|---|
| Crash | 19 | 9 |
| No Crash | 1 | 11 |
| Total | 20 | 20 |
| Crash Ratio | 0.95 | 0.45 |
| Crash Avoidance Effectiveness | 53% | |

## 3.4 IMA Safety Benefits

Table 14 presents the safety benefits of the IMA safety application in terms of crashes avoided, cost saved, and equivalent lives saved (using 2011-2013 GES and FARS data and 2010 economic values). Based on this analysis, the IMA application has the potential to reduce annual IMA-S crashes by about 68 percent and IMA-M crashes by about 53 percent, avoiding 17,770 and 4,974 crashes, respectively. In addition, the IMA application could save about $5,528M (≅ 39 percent of the total $14,275M comprehensive cost) in annual target crash comprehensive cost. This cost benefit translates into 604 equivalent lives saved.

**Table 14. Overall Benefits for the IMA Safety Application**

| Application | Safety Benefits by Measure | | |
|---|---|---|---|
| | Crashes Avoided | Cost Saved ($M) | Equivalent Lives Saved |
| IMA-Stop/Proceed | 17,770 | 4,475 | 489 |
| IMA-Moving | 4,974 | 1,053 | 115 |
| Total | 22,744 | 5,528 | 604 |

# 4 FCW Effectiveness and Potential Safety Benefits

This section discusses the crash avoidance effectiveness for the FCW application, obtained from estimates derived from the IVBSS field operational test.

## 4.1 FCW Target Crash Statistics

Crash statistics are broken down by the annual number of FCW target crashes, distribution of injury levels and property damage that resulted from these crashes, and the comprehensive cost associated with these crashes.

### *4.1.1 Annual Target Crash Population*

The annual FCW target crash population is approximately 33,025 police-reported crashes, based on crash statistics from the 2011-2013 GES databases. Table 15 provides a breakdown of target crashes (including target injury and PDO crashes) by FCW operating scenario. These crashes represent 36 percent of all the target crashes addressed by the IMA, FCW, and BSW/LCW applications. The FCW application could eliminate this target crash population if the application worked perfectly under all driving conditions and all drivers responded in a timely and appropriate manner to FCW alerts (i.e., if the effectiveness were 100 percent, then the FCW application could prevent all target crashes and related injuries that it is designed to address). As shown in Table 15, about 11,028 target crashes (33 percent) resulted in at least one injured person (i.e., injury crash) and the remaining 67 percent were PDO crashes.

**Table 15. Breakdown of FCW Target Crashes by Injury and PDO Type**

| Operating Scenario | Number of Injury Crashes | Number of PDO Crashes | Total Number of Crashes |
|---|---|---|---|
| LVS | 5,677 | 11,476 | 17,153 |
| LVM | 1,860 | 3,637 | 5,497 |
| LVD | 3,491 | 6,884 | 10,375 |
| Total | 11,028 | 21,997 | 33,025 |

### *4.1.2 Annual Target Injury Population*

The annual target injury population is approximately 16,324 injured persons, based on crash statistics from the 2011-2013 GES and FARS databases. Table 16 lists the distribution of target injured persons by their injury level for the FCW safety application, based on the MAIS and FCW operating scenario. This table also lists the number of PDO vehicles in target crashes. A total of 244 persons (1.5 percent of all injured persons) died in target crashes.

**Table 16. Distribution of Injured Persons by MAIS Level and FCW Operating Scenario**

| MAIS Injury | LVS | LVM | LVD | Total |
|---|---|---|---|---|
| 0 - No Injury | 11,322 | 3,577 | 8,790 | 23,689 |
| 1 - Minor | 7,009 | 2,473 | 4,483 | 13,965 |
| 2 - Moderate | 769 | 280 | 510 | 1,559 |
| 3 - Serious | 207 | 76 | 156 | 439 |
| 4 - Severe | 39 | 15 | 32 | 86 |
| 5 - Critical | 15 | 4 | 12 | 31 |
| 6 - Fatal | 111 | 85 | 48 | 244 |
| Total MAIS 1-6 | 8,150 | 2,933 | 5,241 | 16,324 |
| PDO Vehicles | 24,722 | 7,715 | 15,591 | 48,028 |

### *4.1.3 Annual Target Comprehensive Cost*

The annual comprehensive cost of FCW target crashes is approximately $4,685M (LVS ($2,214M), LVM ($1,193M), and LVD ($1,278M)). This cost corresponds to about 512 equivalent lives lost annually.

## 4.2 Input Data for FCW Effectiveness Estimation

This section provides an overview of the results from analyzing the FCW metrics required for input to the SIM tool.

### *4.2.1 FCW Results*

Figure 11 shows the NADS FCW overall results. Note that these results do not include 14 FCW (6 LVS and 8 LVD) simulation runs conducted in Part 1 of the study. These runs were not analyzed due to issues with the response-time histories of the HV and RV. The HV response was not restricted to brake only, which allowed the driver to steer around the RV to avoid impact in the majority of the LVS and LVD cases. NADS made the required software corrections prior to conducting the FCW simulations in Part 2 of the study. These results have been analyzed and are included in Figure 11. There were a small number of crashes during the LVS (one in the baseline condition and one in the treatment condition) and LVD (two in treatment condition) simulated runs. Since crash counts are low for the LVS and LVD scenarios, Volpe analyzed the key metrics required for input to the SIM tool. Section 4.2.2 presents the results of the analysis.

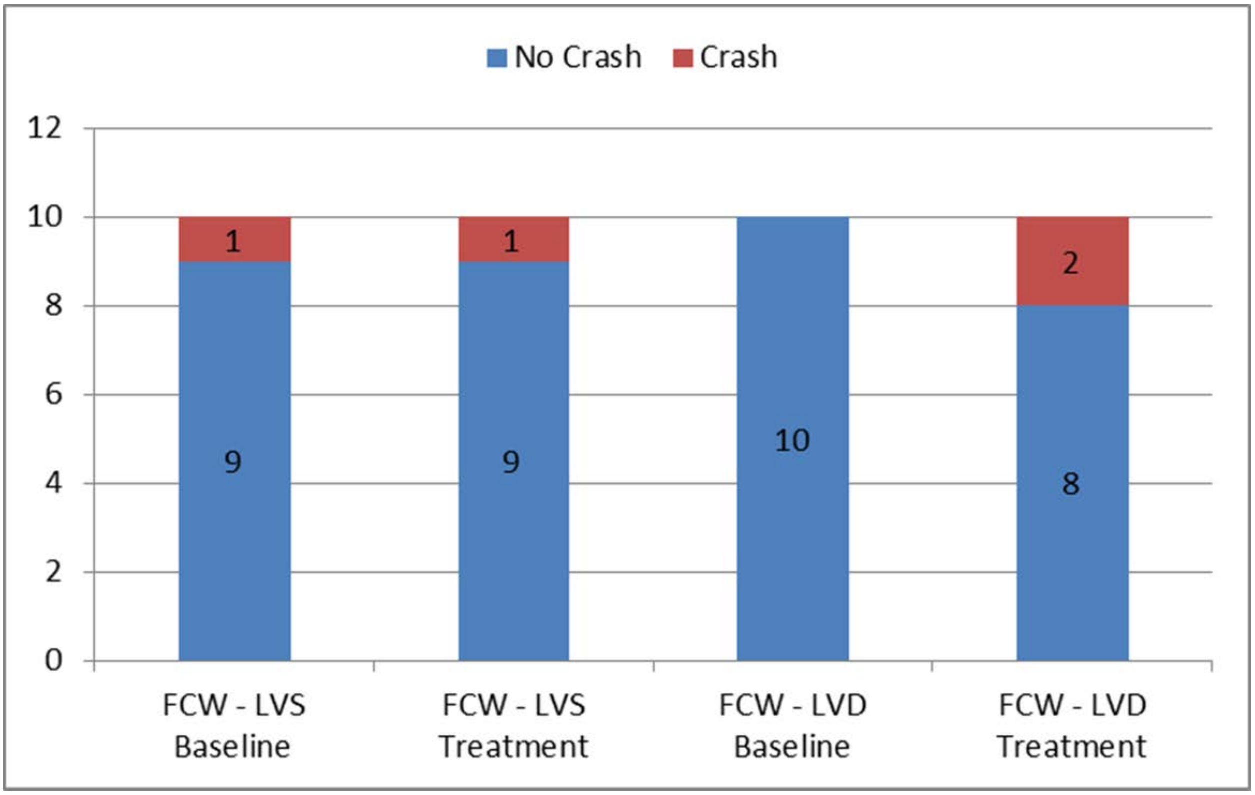



**Figure 11. NADS FCW Overall Results**

### *4.2.2 Analysis of SIM Input Parameters – FCW (LVS and LVD)*

Table 17 and Table 18 respectively show the results from analyzing the driver brake response times and average brake response levels, obtained from the FCW (LVS) simulations. One case was excluded from analysis since the initial speed of the HV was below the threshold level.

A statistical analysis of the brake response time data did not show any statistically-significant difference (p-value=0.51) between baseline and treatment conditions. Likewise, a statistical analysis did not show a statistically-significant difference in HV average deceleration levels (p-value=0.37) between baseline and treatment conditions. Therefore, for the FCW safety application, the crash avoidance effectiveness estimate of 41 percent, obtained from the IVBSS field operational test (see Section 4.3), was used to estimate benefits.

**Table 17. Statistics of HV Driver Brake Response Time (s) – FCW (LVS)**

| Measure | Baseline | Treatment |
|---|---|---|
| **Number of Participants** | 10 | 9 |
| **Mean** | 2.52 | 2.18 |
| **Standard Deviation** | 1.00 | 0.77 |
| **T-test p-value** | 0.51 | |

**Table 18. Statistics of HV Average Brake Response (ft/s2) – FCW (LVS)**

| Measure | Baseline | Treatment |
|---|---|---|
| **Number of Participants** | 10 | 9 |
| **Mean** | 11.43 | 10.37 |
| **Standard Deviation** | 2.11 | 2.90 |
| **T-test p-value** | 0.37 | |

Table 19 and Table 20 respectively show the results from analyzing the driver brake response times and average brake response levels, obtained from the FCW (LVD) simulations. Three cases were excluded from the analysis since the HV and RV separated at alert onset.

A statistical analysis of the brake response time data did not show any statistically-significant difference (p-value=0.59) between baseline and treatment conditions. Likewise, a statistical analysis did not show a statistically-significant difference in HV average deceleration levels (p-value=0.87) between baseline and treatment conditions. Therefore, for the FCW safety application, the crash avoidance effectiveness estimate obtained from the IVBSS field operational test was used to estimate benefits.

**Table 19. Statistics of HV Driver Brake Response Time (s) – FCW (LVD)**

| Measure | Baseline | Treatment |
|---|---|---|
| **Number of Participants** | 8 | 9 |
| **Mean** | 3.29 | 3.06 |
| **Standard Deviation** | 0.86 | 0.56 |
| **T-test p-value** | 0.59 | |

**Table 20. Statistics of HV Average Brake Response (ft/s2) – FCW (LVD)**

| Measure | Baseline | Treatment |
|---|---|---|
| **Number of Participants** | 8 | 9 |
| **Mean** | 11.79 | 12.09 |
| **Standard Deviation** | 3.84 | 3.77 |
| **T-test p-value** | 0.87 | |

## 4.3 FCW Effectiveness Estimation Results

Volpe estimated the crash avoidance effectiveness of the FCW V2V safety application from naturalistic driving data collected during the IVBSS field operational test. Table 21 shows the results of the IVBSS data analysis. These figures are based on an analysis of rear-end near-crash encounters per 1,000 miles traveled. By comparing the whole treatment period versus the baseline period based on rear-end near crashes where the host truck (1) did not steer and (2) braked at an average deceleration value greater than 0.2g, there was a statistically-significant difference or drop (at the 98 percent confidence level) in the number of these events from the baseline to treatment periods. This analysis assumes that this reduction (41 percent) in rear-end near crashes represents a rough estimate of the potential crash avoidance effectiveness of the V2V FCW application in all three rear-end pre-crash scenarios (i.e., LVS, LVM, and LVD scenarios).

**Table 21. IVBSS Statistics of Rear-End Near-Crashes per 1,000 Miles Driven**

| Measure | Baseline | Treatment |
|---|---|---|
| Number of Participants | 9 | 9 |
| Mean | 1.9 | 1.1 |
| Standard Deviation | 1.4 | 0.9 |
| T-Test p-value | 0.023 | |
| Exposure Reduction | 41% | |

## 4.4 FCW Safety Benefits

Table 22 lists the safety benefits of the FCW safety application in terms of crashes avoided, cost saved, and equivalent lives saved (using 2011-2013 GES and FARS data and 2010 economic values). Based on the IVBSS data analysis, the FCW application has the potential to reduce crashes by about 41 percent. This translates to a potential safety benefit of an annual reduction of 13,541 police-reported rear-end crashes. In addition, the FCW application could save about $1,921M (≅ 13 percent of the total $14,275M comprehensive cost) in annual target crash comprehensive cost. This cost benefit translates into 209 equivalent lives saved.

**Table 22. Overall Benefits for the FCW Safety Application**

| FCW Application | Safety Benefits by Measure | | |
|---|---|---|---|
| | Crashes Avoided | Cost Saved ($M) | Equivalent Lives Saved |
| LVS | 7,033 | 908 | 99 |
| LVM | 2,254 | 489 | 53 |
| LVD | 4,254 | 524 | 57 |
| Total | 13,541 | 1,921 | 209 |

# 5 BSW/LCW Effectiveness and Potential Safety Benefits

Figure 12 specifies the framework illustrated in Figure 1 for estimating potential crash avoidance benefits for the BSW/LCW safety application. The results are discussed in Sections 5.3 and 5.4.

## 5.1 BSW/LCW Target Crash Statistics

This section lists annual numbers of BSW/LCW target crashes, their injury levels, PDO vehicles, and comprehensive cost.

### *5.1.1 Annual Target Crash Population*

The annual BSW/LCW target crash population amounts to approximately 24,333 police-reported crashes, based on crash statistics from the 2011-2013 GES databases. Table 23 provides a breakdown of target crashes by injury and PDO type. These crashes represent 26 percent of all the target crashes addressed by the IMA, FCW, and BSW/LCW applications. The BSW/LCW application could eliminate this target crash population if the application worked perfectly under all driving conditions and all drivers responded in a timely and appropriate manner to the application alerts (i.e., if the effectiveness were 100 percent, then the BSW/LCW application could prevent all target crashes and related injuries that it is designed to address). As shown in Table 23, about 2,930 target crashes (12 percent) resulted in at least one injured person (i.e., injury crash), and the remaining 88 percent were PDO crashes.

**Table 23. Breakdown of BSW/LCW Target Crashes by Injury and PDO Type**

| Operating Scenario | Number of Injury Crashes | Number of PDO Crashes | Total Number of Crashes |
|---|---|---|---|
| Lane Change/Same Direction | 2,930 | 21,403 | 24,333 |

### *5.1.2 Annual Target Injury Population*

The annual target injury population amounts to approximately 3,378 injured persons, based on crash statistics from the 2011-2013 GES and FARS databases. Table 24 provides the distribution of target injured persons by their MAIS level for the BSW/LCW safety application. This table also presents statistics about the number of PDO vehicles in target crashes. A total of 32 persons (less than one percent of all injured persons) died in target crashes.

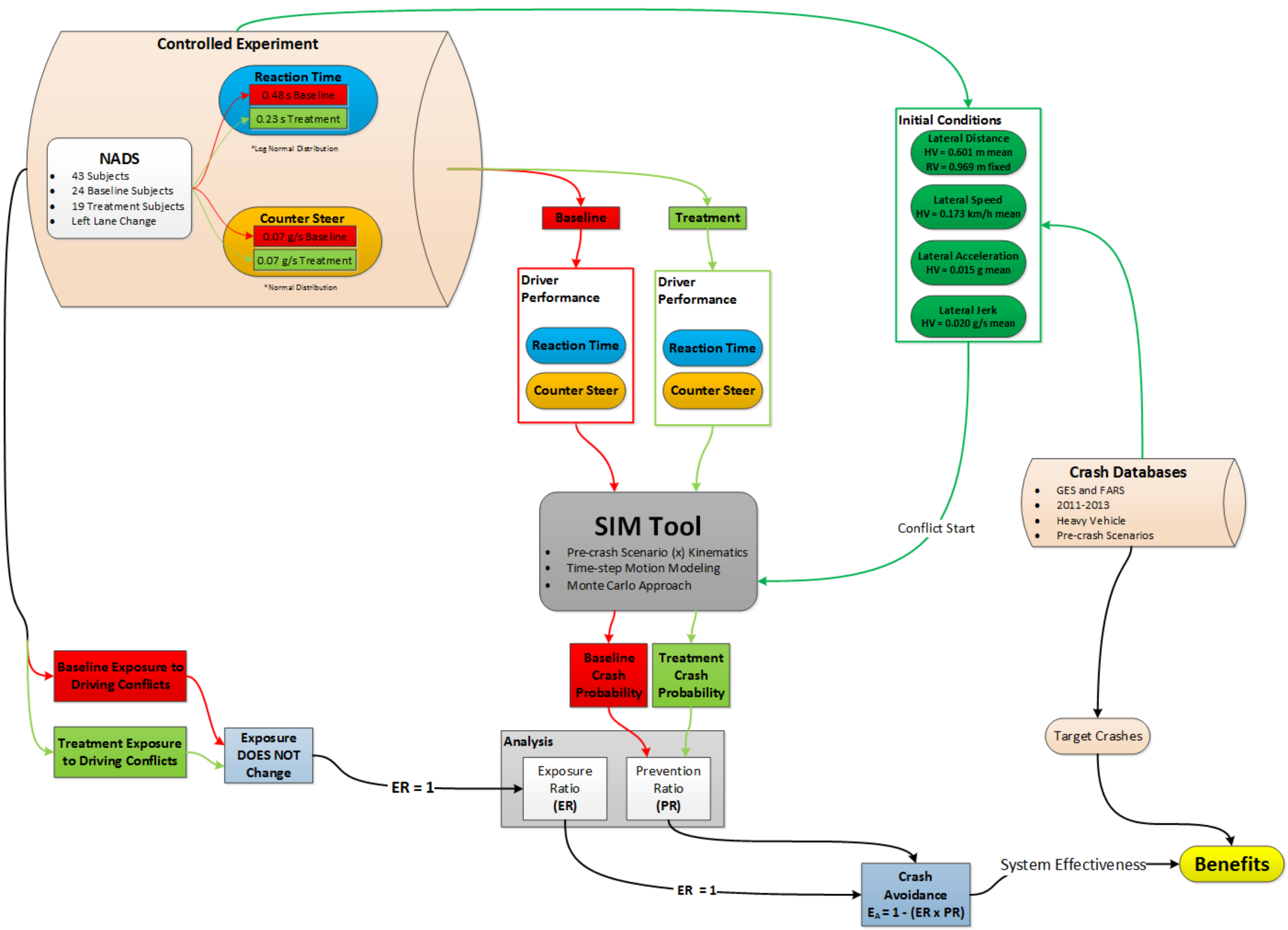



**Figure 12. Estimation Framework for BSW/LCW Crash Avoidance Benefits**

**Table 24. Distribution of Injured Persons in Target BSW/LCW Crashes by MAIS Level**

| MAIS Injury | Total |
|---|---|
| 0 - No Injury | 4,468 |
| 1 - Minor | 2,890 |
| 2 - Moderate | 330 |
| 3 - Serious | 99 |
| 4 - Severe | 20 |
| 5 - Critical | 7 |
| 6 - Fatal | 32 |
| Total MAIS 1-6 | 3,378 |
| PDO Vehicles | 43,971 |

### *5.1.3 Annual Target Comprehensive Cost*

The annual comprehensive cost of BSW/LCW target crashes amounts to approximately $1,022M. This cost corresponds to about 112 equivalent lives lost annually.

## 5.2 Input Data for BSW/LCW Effectiveness Estimation

Volpe used the SIM tool to estimate CP parameters for the BSW/LCW application, using input data from the NADS experiment. The SIM tool initializes a BSW/LCW applicable lane-change conflict by placing the HV at a specified lateral distance away from the RV and giving the HV initial motion parameters (i.e., lateral speed, lateral acceleration, and lateral jerk). These parameters define the motion of the lane change, assuming the lane change has already been initiated. The SIM tool then applies the distributions of driver abort reaction time and counter-steer level to determine the crash outcome.

### *5.2.1 BSW/LCW Results*

Figure 14 shows the NADS BSW/LCW overall results. As shown in the figure, a small number of drivers ended up in a crash during the left and right lane change simulated scenarios. There were a total of two crashes in the baseline condition during the left lane change simulated runs, and seven crashes (two in baseline condition and five in treatment condition) during the right lane change simulations. Due to the small number of crashes, Volpe analyzed the key metrics required for input to the SIM tool. The results of the analysis are discussed in Section 5.2.2.

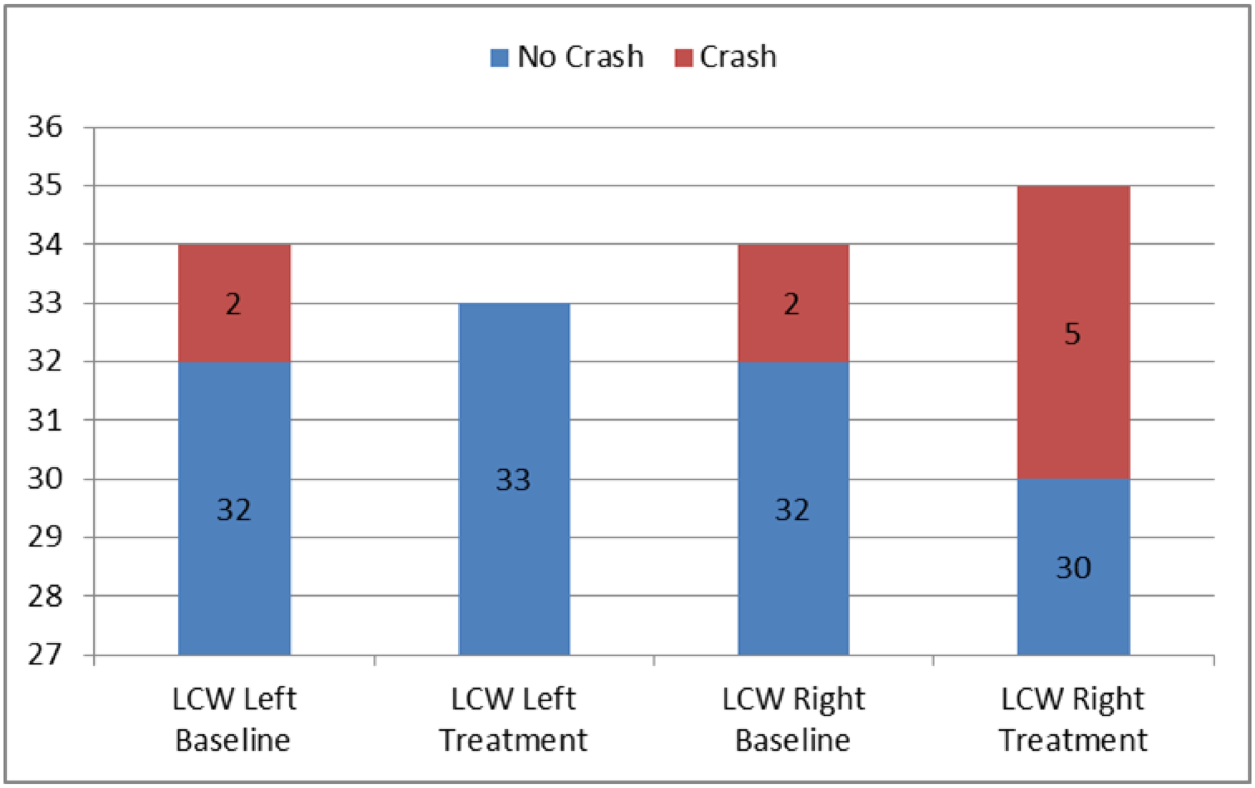



**Figure 13. NADS BSW/LCW Overall Results**

### *5.2.2 Analysis of SIM Input Parameters – BSW/LCW*

Table 25 and Table 26 respectively show results of the analysis of the driver steering response time and lateral countersteer jerk, obtained from the LCL simulations. Nine cases were excluded from the analysis where the truck driver initiated a steering response prior to alert (earlier than 9.8s). In addition, 15 cases were excluded where the HV did not change position in the lane or was moving in the other direction (determined based on lane position change from alert to steering reaction start time).

A statistical analysis showed a statistically-significant relationship (at the 93 percent confidence level) in driver steering response times between baseline and treatment conditions. Therefore, driver steering response time values were used as input to the SIM tool to estimate crash avoidance effectiveness values. Note that the crash avoidance effectiveness estimate obtained from the IVBSS field test was also used in this study to provide a range of values.

A statistical analysis did not reveal any statistically-significant difference in countersteer jerk values between baseline and treatment conditions.

**Table 25. Statistics of HV Driver Steering Response Time (s) – LCL**

| Measure | Baseline | Treatment |
|---|---|---|
| **Number of Participants** | 24 | 19 |
| **Mean** | 0.48 | 0.23 |
| **Standard Deviation** | 0.53 | 0.30 |
| **T-test p-value** | 0.07 | |

**Table 26. Statistics of HV Driver Countersteer Jerk (ft/s3) – LCL**

| Measure | Baseline | Treatment |
|---|---|---|
| **Number of Participants** | 24 | 19 |
| **Mean** | 2.38 | 2.08 |
| **Standard Deviation** | 1.38 | 2.00 |
| **T-test p-value** | 0.56 | |

Table 27 and Table 28 respectively, show results of the analysis of the driver steering response time and lateral countersteer jerk, obtained from the LCR simulations. Ten cases were excluded from the analysis because the truck driver initiated a steering response prior to alert (earlier than 9.8s) and an additional 17 cases were excluded because the HV did not change position in the lane or was moving in the other direction (determined based on lane position change from alert to steering reaction start time).

A statistical analysis showed no statistically-significant difference in driver steering response times between baseline and treatment conditions. In addition, the analysis of countersteer jerk values did not show any statistically-significant difference between the baseline and treatment conditions. Therefore, the range of crash avoidance effectiveness estimates obtained from the IVBSS field test and the SIM tool simulated results (Section 5.3) were also used for LCR operating scenario. Table 29 lists the SIM tool input parameters for LCW operating scenario.

**Table 27. Statistics of HV Driver Steering Response Time (s) – LCR**

| Measure | Baseline | Treatment |
|---|---|---|
| **Number of Participants** | 22 | 20 |
| **Mean** | 0.55 | 0.60 |
| **Standard Deviation** | 0.57 | 0.46 |
| **T-test p-value** | 0.67 | |

**Table 28. Statistics of HV Driver Countersteer Jerk ($ft/s^3$) – LCR**

| Measure | Baseline | Treatment |
|---|---|---|
| **Number of Participants** | 22 | 20 |
| **Mean** | -2.68 | -2.28 |
| **Standard Deviation** | 1.73 | 1.21 |
| **T-test p-value** | 0.40 | |

## 5.3 BSW/LCW Effectiveness Estimation Results

The SIM tool results yielded an average crash avoidance effectiveness of 39 percent from a total of 100,000 runs. This study showed that fewer runs exhibited a larger deviation in effectiveness values. Figure 14 shows the deviation in average effectiveness values as a function of number of simulated runs.

In addition, Volpe estimated the crash avoidance effectiveness of the LCW V2V safety application from the IVBSS data. The safety analysis of the IVBSS data focused on the lane-change near-crash experiences of drivers in baseline driving and the treatment period. A lane-change near-crash event was noted when:

- Another vehicle is present in the adjacent lane
- Lane boundary marking is dashed (not solid)
- HV driver performs a counter-steer response after initiating the lane change maneuver
- Maximum lateral acceleration response (in direction back into initial lane) exceeds 0.1g (0.981 $m/s^2$) on a straight road
- Maximum lane excursion distance is greater than zero and less than 0.9 meter.

All lane-change near-crashes were first video-analyzed and coded based on whether or not a valid threat was present in the adjacent lane. Afterwards, driver involvement in valid near crashes was analyzed using the measure of the number of near-crash encounters per 1,000 miles traveled. Table 30 lists the results of a two-tail, paired *t*-test that was performed to observe any statistically-significant difference in the mean values of the lane-change near-crash rates on straight roads, between baseline driving and the treatment period. In addition to the mean values, Table 30 also shows the number of distinct drivers (8), experiencing lane-change near-crashes in both baseline and treatment test periods, standard deviation values, and the ‘p’ value. Based on these IVBSS statistics, the LCW application demonstrated the potential for reducing exposure to lane-change near-crashes by 22 percent, at a confidence level slightly over 85 percent. This analysis assumes that this reduction potential represents a rough estimate of the crash avoidance effectiveness of the V2V LCW application. Since two sources of data (NADS and IVBSS) and two methods/measures (SIM tool and near crash count) were used to generate two different crash avoidance estimates, both of these values are used to provide the range of safety benefits described in Section 5.4.

**Table 29. SIM Tool Input – BSW/LCW**

| | Inputs | Min | Max | Mean | Std. Dev. | Distribution | Notes |
|---|---|---|---|---|---|---|---|
| Initial Conditions | **Host Lateral Speed @Alert (km/h)** | 0.010 | 0.673 | 0.173 | 0.156 | Normal | Combined Control and Treatment (p = 0.31) |
| | **Host Lateral Acceleration @Alert (g)** | 0.010 | 0.042 | 0.015 | 0.014 | Normal | Combined Control and Treatment (p = 0.8) |
| | **Host Lateral Jerk @Alert (g/s)** | 0.002 | 0.052 | 0.020 | 0.013 | Normal | Combined Control and Treatment |
| | **Remote Distance to Lane Marker @Alert (m)** | 0.969 | 0.969 | 0.969 | 0.000 | Rectangular | Constant from NADS |
| | **Host Distance to Lane Marker @Alert (m)** | 0.000 | 1.250 | 0.601 | 0.271 | Rectangular | Combined Control and Treatment (p=0.8) |
| Driver Response | **Host Steering Reaction Time (Control) (s)** | 0.250 | 2.000 | 0.480 | 0.530 | Log Normal | NADS Data (p = 0.07) |
| | **Host Countersteer Lateral Jerk (Control) (g/s)** | 0.007 | 0.252 | 0.070 | 0.052 | Normal | Combined Control and Treatment (p = 0.56) |
| | **Host Steering Reaction Time (Treatment) (s)** | 0.250 | 1.000 | 0.230 | 0.300 | Log Normal | NADS Data (p = 0.07) |
| | **Host Countersteer Lateral Jerk (Treatment) (g/s)** | 0.007 | 0.252 | 0.070 | 0.052 | Normal | Combined Control and Treatment (p = 0.56) |

*$g = 9.81\ m/s^2$ ($32.2\ ft/s^2$); 1 km/h = 0.62 mph*

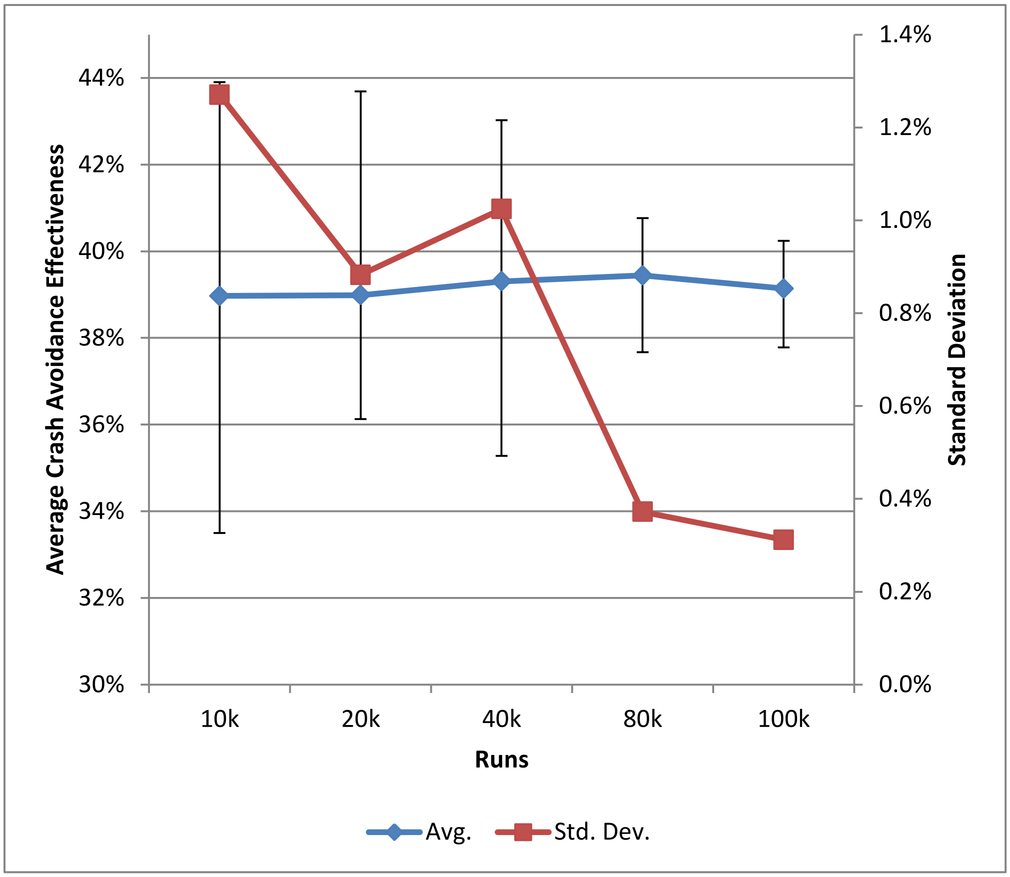



**Figure 14. Average BSW/LCW Effectiveness Estimates versus Number of Simulated Runs**

**Table 30. IVBSS Statistics of Lane-Change Near-Crashes per 1,000 Miles Driven**

| Measure | Baseline | Treatment |
|---|---|---|
| Number of Participants | 8 | 8 |
| Mean | 0.49 | 0.38 |
| Standard Deviation | 0.47 | 0.38 |
| T-Test p-value | 0.15 | 0.15 |
| Exposure Reduction | 22% | |

## 5.4 BSW/LCW Safety Benefits

Table 31 lists the safety benefits of the BSW/LCW safety application in terms of crashes avoided, cost saved, and equivalent lives saved (using 2011-2013 GES and FARS data and 2010 economic values). Based on this analysis, the BSW/LCW application has the potential to reduce between 22–39 percent of crashes, annually avoiding between 5,353–9,490 crashes as seen in Table 31. In addition, the BSW/LCW application could save between $225M–$399M (between ≅ 1.6%–2.8% of the total $14,275M comprehensive cost) in annual target crash comprehensive cost. This cost benefit translates into 25–44 equivalent lives saved.

**Table 31. Overall Safety Benefits for the BSW/LCW Safety Application**

| BSW/LCW Application | Benefits by Measure | | |
|---|---|---|---|
| | Crashes Avoided | Cost Saved ($M) | Equivalent Lives Saved |
| Safety Benefits | 5,353–9,490 | 225–399 | 25–44 |

# 6 Conclusions

This report describes and applies a methodology to estimate the crash avoidance effectiveness, and to project the potential safety benefits for V2V-based safety applications. The analysis focused on the IMA, FCW, and BSW/LCW crash warning applications for heavy vehicles. The methodology relied on national baseline crash data, driver/vehicle performance data in target driving conflicts, and the SIM tool that simulated the basic kinematics of driver/vehicle response to these driving conflicts. Safety benefits were expressed in terms of the annual number of police-reported crashes that could potentially be prevented by the full deployment[7] of the three selected V2V-based safety applications on all heavy vehicles. This analysis assumed that all other motor vehicles (e.g., passenger cars, motorcycles, etc.) were equipped with vehicle awareness devices that communicated basic safety messages with heavy vehicles.

Baseline crash data were queried from the 2011-2013 GES databases to obtain the target crash population for each safety application based on:

- Multi-vehicle pre-crash scenarios addressable by the selected V2V safety applications
- Involvement of at least one heavy vehicle in the crash
- No control loss by the heavy vehicle
- No impaired heavy-vehicle drivers
- Heavy vehicle was initiating the maneuver (where applicable)

Based on 2011-2013 GES statistics and the above criteria, the three selected V2V safety applications could potentially address between 45 percent and 49 percent of the annual 92,875 police-reported national crashes. These three applications could eliminate this target crash population if they worked perfectly under all driving conditions and all drivers responded in a timely and appropriate manner to the alerts (i.e., if the effectiveness was 100 percent, then the selected applications could prevent all crashes that they were designed to address).

Data sources, including NADS and IVBSS, were identified and used to estimate the safety effectiveness of the selected prototype applications. Data from the NADS study were analyzed to obtain driver performance data in target pre-crash scenarios under baseline and treatment test conditions. The crash avoidance effectiveness estimate for the IMA-M application was derived from the crash counts generated from the SCP-M simulations. The effectiveness estimates for the FCW and BSW/LCW applications were obtained from the IVBSS study. The SIM tool was used to estimate the effectiveness of the IMA-S and BSW/LCW applications.

Table 32 lists the estimates for the crash avoidance effectiveness of the selected safety applications in their operating scenarios, based on the following key assumptions:

- Simple modeling of driving conflicts using basic kinematic equations, where only the HV driver responds to the conflict while the RV stays the course. Future computer modeling and simulation could include the following avoidance maneuver by the RV drivers:
  - Braking in the SCP-S scenario
  - Steering and/or braking in the lane-change scenario
- HV driver responds to the driving conflict (or warning) with a single appropriate response (brake or steer) that depends on the nature of the conflict. Alternatively, the HV driver could:
  - Steer in rear-end driving conflicts instead of braking
  - Accelerate in SCP-S driving conflicts instead of braking

[7] Full deployment is achieved with a complete turnover of the fleet or a mix with retrofitted vehicles.

    - Speed up while making the lane change instead of counter-steering in response to this driving conflict

- No unintended consequences from the evasive maneuver performed by the HV driver, which may give rise to additional driving conflicts. Future modeling could account for more vehicles other than the HV and RV, such as following and surrounding traffic in all target pre-crash scenarios.

**Table 32. Crash Avoidance Effectiveness for V2V-Based Safety Applications**

| Application | Operating Scenario | Crash Avoidance Effectiveness |
|---|---|---|
| **IMA** | IMA-S | 68% |
| | IMA-M | 53% |
| **FCW** | LVS | 41% |
| | LVM | 41% |
| | LVD | 41% |
| **BSW/LCW** | Lane Change | 22%–39% |

Table 33 lists the overall projected safety benefits for the three V2V applications. Overall, the V2V applications analyzed in this report have the potential to reduce between 41,638 and 45,775 crashes annually. The reduction in crashes is approximately 45 percent–49 percent of the annual target police-reported crashes within the United States that involved at least one heavy vehicle. The three V2V safety applications could save between $7,674M and $7,848M in annual target crash comprehensive costs. This cost benefit translates to between 838 and 857 equivalent lives saved.

Finally, this methodology estimates the safety benefits of V2V prototype safety applications based on non-crash, driver/application performance data in driving conflicts. This methodology needs to be validated using actual crash data that can be obtained from the real-world experience of using production vehicle-resident crash warning and avoidance systems over a long period of time, such as forward crash warning and automated emergency braking. Validation of this methodology will improve the confidence in predicting the potential safety benefits of advanced applications (e.g., IMA) using estimates of the **EM** and **CP** parameters as surrogate crash measures. Tracking the crash experience of new similar vehicles, with and without the new technology, over a limited period of time would require collaboration among the government and original equipment manufacturers, car dealers, and volunteer car owners. This would also require new experimental designs to reach statistically-significant estimates of crash avoidance effectiveness.

**Table 33. Overall Projected Safety Benefits of Selected V2V Safety Applications**

| Application | Operating Scenario | Target Crashes | Comprehensive Cost ($M) | Source | Crashes Avoided | Cost Saved ($M) | Equivalent Lives Saved |
|---|---|---|---|---|---|---|---|
| **IMA** | IMA-S | 26,133 | 6,581 | SIM Tool using NADS Data | 17,770 | 4,475 | 489 |
| | IMA-M | 9,384 | 1,987 | NADS Crash Results | 4,974 | 1,053 | 115 |
| **FCW** | LVS | 17,153 | 2,214 | IVBSS | 7,033 | 908 | 99 |
| | LVM | 5,497 | 1,193 | | 2,254 | 489 | 53 |
| | LVD | 10,375 | 1,278 | | 4,254 | 524 | 57 |
| **BSW/LCW** | Lane Change | 24,333 | 1,022 | IVBSS & SIM tool using NADS data | 5,353–9,490 | 225–399 | 25–44 |
| **Total** | | **92,875** | **$14,275** | | **41,638–45,775** | **$7,674–$7,848** | **838–857** |

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# Appendix A: Conversion of Injury Levels from KABCO to MAIS Scale

The GES crash database does not provide detailed information about injury severity based on the Abbreviated Injury Scale (AIS) coding scheme. Instead, the GES records injury severity by crash victim on the KABCO scale from police crash reports. Police reports in almost every state use KABCO to classify crash victims as:

- K – Killed
- A – Incapacitating injury
- B – Non-incapacitating injury
- C – Possible injury
- O – No apparent injury
- ISU – Injury Severity Unknown

The KABCO coding scheme allows non-medically trained persons to make on-scene injury assessments without a hands-on examination. However, KABCO ratings are imprecise and inconsistently coded between states and over time. On the other hand, the AIS is an anatomically-based, consensus-derived global severity scoring system that classifies each injury by body region according to its relative importance on a 6-point ordinal scale (1 = minor and 6 = maximal). It is the basis for the Injury Severity Score calculation of the multiple injured patient. The AIS was developed by the Association for the Advancement of Automotive Medicine (see www.aaam1.org/ais/). To estimate injuries based on the MAIS coding structure, a translator derived from 1984–1986 NASS and 2008-2010 Crashworthiness Data System database data was applied to the GES police-reported injury profile, as shown in Table 34 [12].

**Table 34. KABCO-to-MAIS Conversion Table**

| MAIS | Police-Reported Injury Severity System | | | | | | |
|---|---|---|---|---|---|---|---|
| | O | C | B | A | K | ISU | Unknown |
| 0 | 0.9254 | 0.2343 | 0.0834 | 0.0342 | 0.0000 | 0.2153 | 0.4293 |
| 1 | 0.0726 | 0.6893 | 0.7675 | 0.5520 | 0.0000 | 0.6270 | 0.4103 |
| 2 | 0.0020 | 0.0639 | 0.1088 | 0.2081 | 0.0000 | 0.1040 | 0.0872 |
| 3 | 0.0001 | 0.0107 | 0.0319 | 0.1437 | 0.0000 | 0.0386 | 0.0474 |
| 4 | 0.0000 | 0.0014 | 0.0062 | 0.0397 | 0.0000 | 0.0044 | 0.0061 |
| 5 | 0.0000 | 0.0001 | 0.0010 | 0.0178 | 0.0000 | 0.0103 | 0.0027 |
| Killed | 0.0000 | 0.0003 | 0.0013 | 0.0046 | 1.0000 | 0.0005 | 0.0171 |
| Total | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

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