SAFETY IMPACT METHODOLOGY (SIM): APPLICATION AND RESULTS OF THE ADVANCED CRASH AVOIDANCE TECHNOLOGIES (ACAT) PROGRAM

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ABSTRACT

This paper provides a summary of four cooperative research projects conducted under the National Highway Traffic Safety Administration's (NHTSA) Advanced Crash Avoidance Technologies (ACAT) program. The ACAT program sought to determine the safety impact of new and emerging crash avoidance technologies that are intended to help drivers avoid crashes, reduce crash severity, and prevent injuries and fatalities. This research developed and applied a Safety Impact Methodology (SIM) framework to estimate safety benefits for the proposed pre-production crash avoidance systems.

This paper presents the application and results of the Safety Impact Methodology for four different crash avoidance technologies including: Advanced Collision Mitigation Braking System by Honda, Lane Departure Warning by Volvo-Ford, Pre-collision Safety System by Toyota, and Backing Crash Countermeasures by General Motors.

INTRODUCTION

Advanced crash avoidance technologies help drivers to avoid crashes or, if the crash is unavoidable, to reduce the harm of the crash. Crash avoidance systems are able to warn the driver of dangerous situations and pro-actively deploy countermeasures *before* a crash occurs. These countermeasures may include warnings (by means of haptic, auditory, or visual alarms) and/or actively controlling the vehicle (by braking or steering) for a limited time.

Oftentimes, in cases of driver inattention (e.g. driver distraction), the countermeasure would occur prior to the driver sensing a critical situation, giving the driver additional time to react. It is this additional time margin which enables the driver, in coordination with the crash avoidance system, to avoid or mitigate the crash. This is important as it was observed in the 100-Car Naturalistic Driving Study that nearly 80% of crashes and 65% of near-crashes involved some form of driver inattention within three seconds before the event [1].

"Developing approaches for crash avoidance safety technologies is challenging in that, prior to significant market penetration, it is difficult to determine real world effectiveness and safety benefits of new technologies. … While there are numerous challenges, the agency believes that it has a role in encouraging the development and deployment of all beneficial safety technologies especially, crash avoidance technologies" [2].

Crash avoidance technologies are moving from the development phase to the deployment phase at an accelerated pace. Although the potential of these advanced technologies to reduce crashes, fatalities, and injuries is great, their effectiveness is largely unknown. In order to better understand the potential safety impact of crash avoidance systems, NHTSA started the Advanced Crash Avoidance Technologies (ACAT) program in September 2006.

The ACAT program was established to identify new or emerging advanced technologies and to estimate the safety impact of these technologies. In support of this goal, this research program had two main objectives. The first objective was to develop and utilize a "Safety Impact Methodology" (SIM) to evaluate the ability of advanced technology applications to solve specific motor vehicle safety problems. The second objective was to demonstrate how the results of objective tests can be used by the SIM to assess the safety impact of a real system.

NHTSA entered into a cooperative research agreement with four partners in the automotive industry. The cooperative agreement partners joined with other subcontractors in industry and academia to form the following four teams:

- Team 1: Honda R&D Co., Ltd.-Dynamic Research, Inc. (Honda-DRI) Team for the Advanced Collision Mitigation Braking System (A-CMBS)

- Team 2: Volvo Car Corporation-Ford Motor Company-University of Michigan Transportation Research Institute (Volvo-Ford-UMTRI) Team for Lane Departure Warning (LDW)

- Team 3: Toyota Motor Corporation (Toyota) Team for the Pre-Collision Safety System (PCS)

- Team 4: General Motors Corporation-Virginia Tech Transportation Institute (GM-VTTI) Team for Backing Crash Countermeasures

"[The] Advanced Crash Avoidance Technologies (ACAT) program, in which NHTSA partners with automobile manufacturers to improve information on safety impacts of crash avoidance technologies, is intended to encourage manufacturer efforts to develop such technologies" [3]. This research was completed in the fall of 2009 and final reports from each team have been submitted. This paper summarizes the findings of the four ACAT teams.

Each team carried out the following tasks:

- Identification of the safety problem area
- Description of the advanced technology
- Development of SIM tool
- Development of objective tests
- Conduct and analysis of objective tests
- Estimation of safety benefits using SIM tool

Each team was able to evaluate the estimated effectiveness of their specific pre-production crash avoidance system using their SIM, using the framework described below. Each of the approaches taken by the by the various teams represents a novel method to predict the estimated safety impact of pre-production crash avoidance technologies.

NHTSA SIM FRAMEWORK

Using the SIM framework shown in Figure 1, each team developed their own computational "SIM tool" based on this methodology. The framework identifies the principle components of SIM and interactions between these components including: Data Usage, Case Scenarios, Objective Testing, Model Creation, Data Generation, Countermeasure Performance Analysis, and Safety Benefits. A short description of each component and its function is given:

Data Usage identifies the sources and frequencies of the data used to define the traffic conflict(s) of interest.

Case Scenarios describe the specific problem area and corresponding conditions selected for countermeasure application.

Objective Testing collects empirical data from test tracks, simulators and other sources to provide distributions of values for model parameters (driver, vehicle, and countermeasure).

Model Creation develops a set of computational equations and executable tools to describe driver-vehicle operation in normal and conflict related driving and their respective response both with and without the countermeasure.

Data Generation applies the model to the selected scenarios to document the performance of countermeasure operation versus performance with no countermeasure.

Countermeasure Performance Analysis compares the number of events (e.g., crashes) associated with presence and absence of the countermeasure to assess system effectiveness.

Safety Benefits reports the estimated benefits in terms of quantity of events avoided or mitigated.

The framework does not dictate a specific approach or method. The framework communicates NHTSA's operational vision of a SIM and the activities NHTSA identified as critical to developing a sound methodology. This framework can be adjusted to accommodate and communicate various approaches to estimate safety benefits. A more detailed description of the SIM framework is given in [4].

BASIC SAFETY BENEFIT EQUATIONS

The methodologies used to estimate safety benefits are based on the benefits equation [5]:

$$B = N_{WO} - N_W \tag{1}$$

where,

B = benefits, (which can be the number of crashes, number of fatalities, "harm", or other such measures)

N_{wo} = value of this measure, (for example, number of crashes) that occurs without the system

N_w = value of the measure with the system fully deployed

The benefits equation can be rewritten as:

$$B = N_{WO} \times SE \qquad (2)$$

where,

N_{wo} = size of the problem addressed, and
SE = effectiveness of the system.

An extension of this idea is that the overall benefits consist of the sum of benefits across a number of specific scenarios:

$$B = \sum_i N_{WO_i} \times E_i \qquad (3)$$

where,

"i" is an index referring to individual scenarios;
N_{woi} = the number of crashes that occur in scenario "*i*" when the ACAT countermeasure is not available
E_i = the effectiveness of the ACAT countermeasure in preventing crashes in scenario "*i*."

ACAT PROGRAM

The ACAT program was a proof-of-concept effort that sought to determine the feasibility of developing estimates of effectiveness for specific safety technologies in the absence of data from real world crashes or field operational tests. Although these estimates are provided, the focus of this project was on the development of the SIM and linking it to the results of the objective tests. The SIM used the data available at the time of the study to estimate safety benefits, the calculation of which involved various assumptions and limitations.

Note that each team estimated safety benefits using their own set of equations derived from the basic benefits equations shown. The target populations and addressable crashes for each ACAT were distinctly different as each ACAT team was trying to solve a different safety problem. Team 1 estimated the ***overall effectiveness*** and safety benefits using the entire US motor vehicle fleet as the baseline population. Team 2, Team 3, and Team 4 estimated the ***system effectiveness*** and safety benefits using specific target populations as the baseline population, which were different for each technology. Therefore, each ACAT project should be viewed as an independent, stand-alone effort.

All four teams implemented a SIM which can be expressed within the framework stipulated by NHTSA. A summary table comparing the approaches of the four teams and the details of their approaches within the respective components of the SIM framework are shown in Table 1. This is followed by a summary of the implementation of the SIM for each of the four teams, respectively. For more information please refer to the Final Reports of each project.

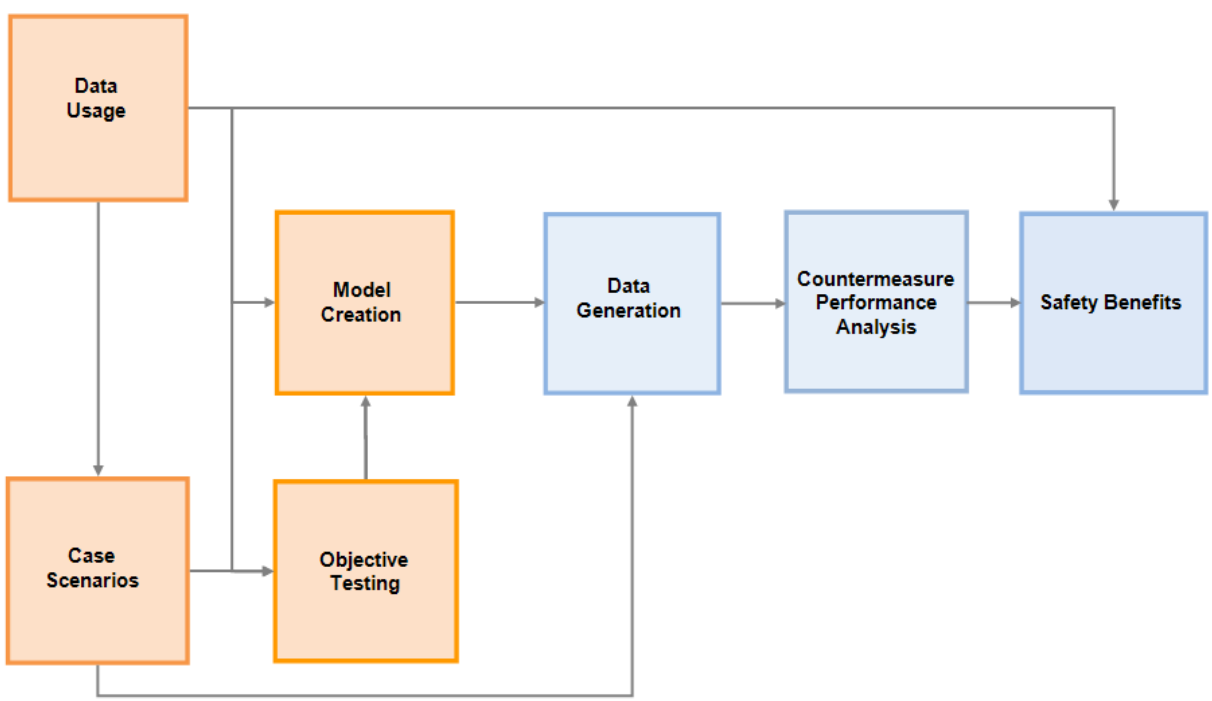

Figure 1. NHTSA SIM Framework

Table 1.
Comparison of SIM for the four ACAT teams

SIM Blocks	Components of SIM Framework	Team 1: Advanced Collision Mitigation Braking System (A-CMBS)	Team 2: Lane Departure Warning (LDW)	Team 3: Pre-Collision Safety System (PCS)	Team 4: Backing Crash Countermeasures
Data Usage	Archival Data, Real world data, Corporate body of knowledge and Technology characteristics	NASS/CDS, PCDS, FARS, and GES data	GES, CDS, Highway Performance Monitoring System (HPMS), and RDCW-FOT data	GES, CDS, FARS and Event data recorder (EDR)	FARS, GES, SCI, Public domain research, GM research archives, and VTTI data
Case Scenarios	Breakdown of scenarios, Crash Characteristics and Technology relevant scenarios	- Vehicle-vehicle, intersecting paths - Vehicle-vehicle, rear-end/forward impact - Vehicle-vehicle, head-on - Single vehicle, pedestrian	Inadvertent lane or road departure	SAP-98 Rear-end collision - Lead vehicle stopped - Lead vehicle decelerating Head-on collision Collision to object	10 scenarios (6 pedestrian crashes, 3 vehicle-to-vehicle crashes, and 1 vehicle-to-fixed-object crashes).
Objective Testing	Driving simulator, test track and Lab/HMI test	Driving simulator and lab tests involved. Tests include Guided Soft Target - vehicle conflict tests using naïve and trained driver.	Driving simulator tests with naïve subjects to develop the driver model. Trained driver tests for system validation.	Driving simulator involved. (LVS, LVD). Vehicle tests with -fixed obstacles for system performance	Track and public road tests involved. All 10 scenarios tested. Pedestrian tests conducted using mannequins.
Model Creation	Model definition, validation and calibration	Indigenous simulation model. Cases validated against automated reconstruction and simulation	Using distribution of parameters. Model generated with Matlab/ Simulink/CarSIM	Model validated from test track and EDR data.	Matlab/Simulink model. Validated based on previous corporate sponsored research
Data Generation	Digital computer simulation and simulator testing	Reconstructed crashes simulated with and without the ACAT with a sample of typical drivers.	Monte Carlo simulation run with and without ACAT	Simulator Testing results	Monte Carlo simulation run with and without ACAT
Countermeasure Performance Analysis	Without countermeasure, With countermeasure, System effectiveness.	DeltaV, Crash/No crash, Exposure ratio, Prevention ratio	Crash/No, Crash, Exposure ratio, Prevention ratio	Crash/ No crash, Speed reduction Crashes avoided, Fatalities/Injuries reduced	Crash/No crash, Prevention ratio
Safety Benefits	Safety benefits	Crashes, fatalities, injuries (Fatality Equivalents)	Crashes reduced/ mitigated	Crash reduction, fatalities and injury reduction.	Crashes reduced/ mitigated

TEAM 1: ADVANCED COLLISION MITIGATION BRAKING SYSTEM (A-CMBS)

For the ACAT program, DRI, with support from Honda, developed a tool to evaluate Honda's prototype Advanced Collision Mitigation Brake System (A-CMBS). The A-CMBS addresses four primary collision types including: intersecting paths, rear-end/forward impact, head-on, and pedestrian crashes. The SIM tool provides an estimate of safety benefits in terms of reduction in crashes, vehicles involved, and fatalities [6].

Data Usage

The Honda-DRI approach begins with the construction of a crash scenario database from archival national accident databases in the United States such as the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) and Pedestrian Crashworthiness Data System (NASS/PCDS). The CDS database provides detailed descriptions of tow-away crashes involving one or more light passenger vehicles based on in-depth at-scene crash investigations. The PCDS database provides detailed descriptions of vehicle-pedestrian crashes also based on in-depth at-scene crash investigations. These data are also supplemented by information from the Fatality Analysis Reporting System (FARS) for fatal crashes. This crash scenario database contains in-depth information and time-space reconstructions of real-world accidents based on their time-domain relationship. This data was used to classify the crash scenarios in terms of technology relevance and to create sub-samples of cases in each Technology Relevant Crash Type (TRCT).

Case Scenarios

The characterization of the crash scenarios begins with identifying the combination of driver, vehicle, and environment dynamics presented during the crash. Unlike traditional segmentation processes, Team 1 reconstructs actual scenarios from the NASS/CDS and PCDS databases using the Automated Accident Reconstruction Tool (AART) and segments them into their respective TRCTs. The AART estimates the time-space relationships of the Subject Vehicle and Collision Partner trajectories based on digitized scene diagrams, coded data, and Newtonian physics combined with a number of assumptions. The process adopts a stratified sampling process to select a subset of TRCTs to facilitate simulation. The primary TRCTs from the AART reconstructions used for the safety benefit estimation were:

- Vehicle-vehicle, intersecting paths
- Vehicle-vehicle, rear-end/forward impact
- Vehicle-vehicle, head-on
- Single vehicle, pedestrian

Objective Testing

The purpose of objective testing in the Honda-DRI ACAT project was to observe and measure the response of an expert driver to the countermeasure intervention; and to observe and measure the response of the vehicle to automatic interventions. A small sample of reconstructed cases was used for this purpose. These response measurements were used for parameterizing and calibrating the driving simulator test conditions and the models in the CSSM. The objective tests included Laboratory Tests, Track Tests, and Driving Simulator Tests.

Laboratory Tests were conducted to measure the characteristics of the countermeasure warnings as experienced by a driver during a potential conflict event. The results from these tests were used to create and calibrate the Driving Simulator (DS) as well as to provide parameter values for the CSSM model. Lab tests involved testing the vehicle fitted with ACAT for human factor attributes like warning location, magnitude and spectra as well as vehicle components like vehicle weight, dimensions, etc. that serve as input to the simulations.

Track Tests involved *driver-in-the-loop tests* for expert driver response, delays and magnitudes to warnings and *driver-out-of-the-loop tests* for vehicle response to the ACAT system. The results were used to calibrate the DS and CSSM models of the ACAT system. In order to run the track tests two targets were developed: the Car Guided Soft Target (GST) and the Pedestrian Guided Soft Target (PGST). The GST consists of a self-propelled, self-steering and braking, GPS-guided, low-profile, hardened Dynamic Motion Element chassis, to which soft, 3D targets of a light passenger vehicle (constructed of separable foam panels) are attached as shown in Figure 2.

Figure 2. GST on Dynamic Motion Element base.

The Pedestrian GST consists of a cable-driven, low-profile, hardened "turtle" trolley, the longitudinal position of which is GPS-guided, and to which an inflatable pedestrian form is attached. Both prototypes were instrumental in obtaining driver performance measures for the objective track tests.

Driving Simulator Tests involved driver-in-the-loop tests and were used to measure the response of subject drivers to the intervention by the countermeasure system. Both an expert driver and 12 typical drivers were tested. The measurements included the type of driver response (braking, steering or a combination) and the delay and magnitude of each response. 12 cases were selected for the simulator testing, which included three cases for each of the four TRCTs described earlier. An example case used in the driving simulator for each of the four TRCTs is shown in Figure 3.

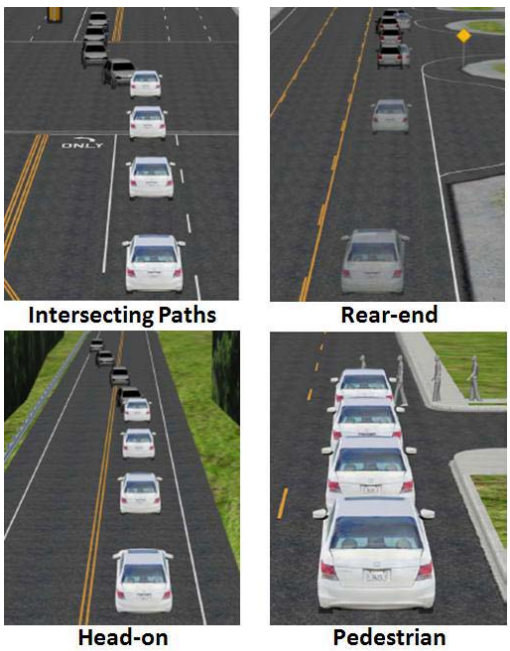

Figure 3. Illustration of the four primary Technology Relevant Crash Types

To ensure test reproducibility and repeatability, timing, and consistency of Subject Vehicle (SV) speed, cruise control was used for the SV. A visual distraction task was used in which a light was turned on at 2.0 sec prior to the start of the first expected A-CMBS warning and was turned off at 0.82 sec prior to either the pre-calculated start of A-CMBS braking, or the reconstructed time of impact to the Collision Partner (CP) if there was no A-CMBS braking.

A suite of models form the core of the simulation tool and lie within the framework of development of the Crash Sequence Simulation Module (CSSM). The core function of the CSSM is a time domain simulation of the *Driver model,* which is based on the NASA Architecture for Procedure Execution (Apex) human operator programming language, the *Vehicle model* (with and without ACAT) and *Environment model* in Matlab /Simulink. The Apex and Simulink models are linked together providing visual object information to the driver model; and driver control to the vehicle model. The virtual reality display used to view the runs is also driven by the Simulink model.

The CSSM has a graphical user interface that enables the user to select the desired crash scenarios and driver behaviors for simulation. The CSSM then initializes and runs the time domain simulations for all desired combinations of crash scenarios and driver behaviors specified by the user. Simulation post processing was accomplished by creating a graphical summary of the driver behavior and other time domain outputs. The CSSM driver model comprises Long term memory, Sensing/Perception, Working memory, and Motor response as illustrated in Figure 4. *Long term memory* comprises declarative knowledge and procedural knowledge, such as vehicle steering and speed control procedures. The *sensing and perception* passes visual, tactile, and auditory information to the long term memory. *Working memory* is implemented in the NASA Apex Action Selection Architecture. The *Motor response* function outputs the commanded steering wheel angle, forward acceleration in g's, and brake deceleration in g's to the Simulink vehicle-ACAT-environment model.

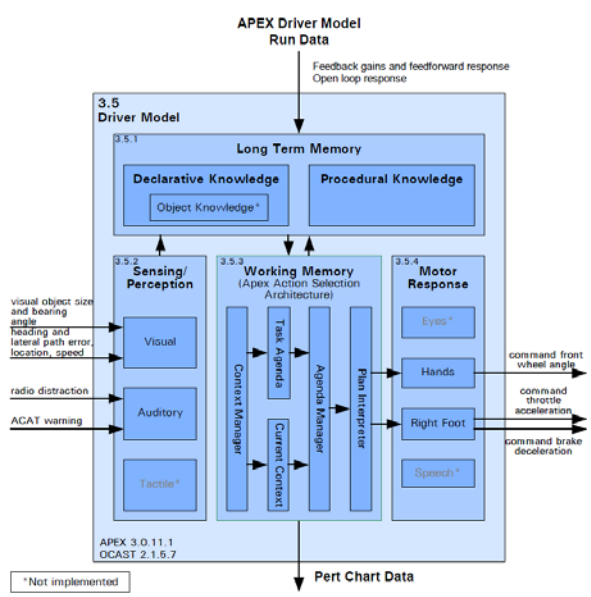

Figure 4. Apex driver model.

The vehicle dynamics model in the CSSM was constructed as a Matlab/Simulink model. The model uses three inputs: primary control inputs, vehicle states, and a number of vehicle-specific parameters to calculate the vehicle state for each time step. This information is used to calculate values for parameters including: yaw rate, heading angle, and lateral velocity, which is fed back to the model. The vehicle model also includes a distance and azimuth sensor model, control logic, and a brake actuator model, apart from the conventional vehicle dynamics model. The pre-crash vehicle motions are described using quasi-steady state equations-of-motion in terms of state variables.

The countermeasure model was also constructed as a Matlab/Simulink model that allows an interface with the vehicle model and the Apex driver model. The model uses information from the subject vehicle and data from the sensors to determine the state of its outputs. There are many intermediate outputs of the A-CMBS model that are processed further in order to get the final output signals. The resultant final outputs of the A-CMBS model include: braking level, warning, and seat belt tensioner mode.

Data Generation

A time domain simulation of the driver, vehicle, and environment is conducted by the CSSM. The output from each CSSM simulation includes a yes/no data element that indicates whether or not a crash occurred during the simulation. If a crash occurred then the change in vehicle velocities (i.e. ΔVs) for the crash were computed based on the impact geometry and speeds. The ΔV values were in turn used to estimate the probability of driver fatality (POF) and injury Fatality Equivalents (FE). If a crash did not occur then the POF and FE are zero. Results for simulations with and without the countermeasure were combined to determine the reduction in the probability of crash, POF and injury FE's.

The advantages of using a sample of "reconstructed crash cases" are that: they include co-variations that have been observed to occur in all the case variables (i.e., not just those judged to be key variables); they are more likely to be "realistic"; currently, they are more recent (e.g., in the case of NASS/CDS) from most regularly updated databases; they have established weighting factors that relate them to national level crash data; and in general, they appear to be nearly the "best available," most representative and most complete detailed level data for crashes in the United States.

Countermeasure Performance Analysis and Safety Benefits

The core of the performance analysis lies in the application of the Overall Safety Effects Estimator (OSEE) which estimates the overall safety benefits in terms of the reduction in the numbers of collisions and fatalities at the US level using the fleet systems model. This is based on data for technology effectiveness functions, crash scenarios, retrospective as well as forecasted data. The technology effectiveness functions describe the Exposure, Prevention and Fatality Ratios (ER, PR, FR) for each technology relevant crash type and are based on results from the CSSM simulations.

The estimated safety benefits were computed based on extensions to the baseline benefits equations described in [5] starting with Eq. (3). Depending on the type of benefits (the number of conflicts, crashes, or fatalities) the effectiveness term (E_i) is:

$$E_i = \begin{cases} 1 - ER_i & \text{for conflicts} \\ 1 - ER_i \times PR_i & \text{for crashes} \\ 1 - ER_i \times PR_i \times FR_{p,i} & \text{for fatalities} \end{cases}$$

where,

ER_i and PR_i, are the estimated Exposure Ratio and Prevention Ratio, respectively for scenario "*i*" and $FR_{p,i}$ is the Fatality Ratio for person "*p*" in scenario "*i*".

The overall estimated safety benefits are the sum of the benefits for each crash type. The benefits for each crash type are equal to the estimated effectiveness (E_i) times the size of the problem for each crash type (N_{woi}). The overall benefits estimates of the Honda A-CMBS, if it had been installed in the entire US Light Passenger Vehicle Fleet in the 2005 calendar year are shown in Table 2. The baseline population in this table comes from Traffic Safety Facts 2005.

Table 2.
Safety benefit estimates for the Advanced Collision Mitigation Braking System (A-CMBS)

	Crash Problem Size for the Entire US Fleet	Estimated Overall Effectiveness for the Entire US Fleet	Estimated Safety Benefits
Crashes	6,146,907	8%	511,000
Vehicles	10,838,878	9%	1,013,000
Fatalities	43,510	4%	1,623

TEAM 2: LANE DEPARTURE WARNING (LDW)

As part of the ACAT program, Volvo, Ford and the University of Michigan Transportation Research Institute (UMTRI) developed a SIM that addresses lane departure crashes. The Volvo-Ford-UMTRI (VFU) team used interactions between driver, vehicle, environment and technology elements in a Monte Carlo simulation model to estimate safety benefits in terms of crashes avoided [7].

Data Usage

The VFU SIM was tailored to lane departure crash types. These include road departure and lane departure crashes. The VFU SIM utilizes GES, CDS, Road Departure Crash Warning (RDCW) Field Operational Test data, Michigan State data and a Swedish in-depth crash database (Factors Influencing the Causation of incidences and Accidents, FICA) to establish the typical characteristics of the LDW relevant crash population.

Case Scenarios

A key component for effective development of a computational model is defining the driving and crash characteristics of the typical scenarios where LDW might be of assistance. These characteristics were captured through a set of *Driving Scenarios (DS*). Each driving scenario represents a typical combination of driver, vehicle, and environment states that precedes lane/road departures. However, it should be noted that the DS are not pre-crash scenarios as such, since driving under the DS conditions does not automatically result in a crash. Rather they represent combinations of conditions that have the potential to produce lane departures and resultant crashes.

For the purpose of scenario development, baseline population and pre-crash scenario factors were obtained from NASS/GES and NASS/CDS and the Swedish in-depth database. Roadway geometry data were obtained from Michigan State data and Federal Highway Administration (FHWA) Highway Performance Monitoring System (HPMS) data. Vehicle kinematics data were obtained from naturalistic RDCW data. All these sources were used in developing a combination of fixed as well as variant parameters of the DS, that feed into to the SIM model. An example of such a driving scenario would be a vehicle traveling on a dry but curved roadway with two or more divided lanes in daylight with no adverse conditions, with a driver who is not distracted or fatigued. Overall, 25 such high priority technology relevant scenarios, capturing the typical conditions of slightly more than 90% of the relevant crashes were developed, which form the basis for input to the computational model.

Objective Testing

Objective tests were performed in the ACAT project in the form of track tests for system performance verification and parameter estimation in the computational model, road tests to establish system availability under different DS's, and two driving simulator studies were conducted to analyze distracted and drowsy driver reactions to various HMI warnings. It should be noted that the outputs of objective tests were not used directly in the computational model, but rather were used to generate parameter values for running simulations as well as to validate and calibrate the computational model.

Model Creation

VFU's approach focuses on developing a computational model that ties driver, vehicle, environment, and technology elements together to generate realistic interactions between them in a dynamic environment, in order to produce reliable performance outputs. This was accomplished by developing models for the vehicle, technology, and driver, respectively. The Vehicle Model was implemented using CarSIM and was embedded as a subsystem in Matlab's Simulink tool. Output from the driving simulator studies was used to calibrate and validate the Vehicle Model. An illustration of the CarSIM model is shown in Figure 5.

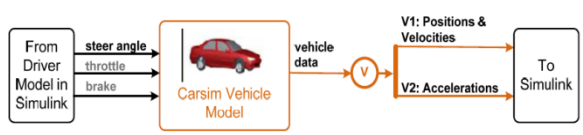

Figure 5. Architecture of the Vehicle Model.

For the countermeasure model, a generic model of the Volvo Lane Departure Warning (LDW) system was developed for implementation in the SIM. The warning algorithm is a function of the lane position and the vehicle's lateral velocity with respect to the lane markings. When the distance between inside of the lane marker and the outside of the nearest front tire is less than the set threshold distance, a lane excursion is flagged, as depicted in Figure 6. While the system was fitted with two levels of sensitivity, the LDW model was implemented with high sensitivity.

Figure 6. Vehicle location when the lane departure is detected.

A unique feature of the VFU model is the approach to modeling driver performance. The underlying principle is that drivers leave the lane due to inattention. This principle is coupled with the idea that when drivers become inattentive they switch from a lane-keeping mode, that keeps the vehicle within the lane, to a mode of no action. A return to alertness is modeled by the driver returning to the lane-keeping mode. A warning is one event that will cause a driver to return to alertness from an inattentive state of mind. The modeling utilizes a partitioning of parameters into those that are derived from crash data and those that are derived from quantitative analysis of naturalistic driving data.

Data Generation

The basic process used for data generation is a Monte Carlo simulation program, which is implemented without and with support from the Lane Departure Warning system. A novel feature of this process is the use of randomly selected cases from the Michigan State crash data files as the means of obtaining variations in key variables such as lane width and detailed road geometry at sampled crash sites. This approach reduces the need for simplified distributions of these key variables which would be used in a more traditional Monte Carlo process.

The core of the Monte Carlo process lies in defining and simulating the *virtual driving event*, which is a driving scenario (a combination of the Driver, Vehicle, Environment and Technology (DVET) components) presented as a combination of initial conditions, model parameters, road conditions, and environmental conditions. Each of these parameters is selected randomly for a single run in the simulation. Each simulation is designed to represent a single potential lane or road departure "event" without the technology. Thousands of such runs are executed to form the baseline Virtual Crash Population. Repeat simulations with the technology enabled generates the data required to assess safety benefits estimates.

Some elements that are unique to the VFU ACAT project in the data generation process are as follows:

Inverse Time to Lane Change (ITTLC) ITTLC is the reciprocal of the estimated time to lane crossing given the instantaneous position and lateral velocity of the subject vehicle. The ITTLC serves as the primary control variable while sampling initial parameters, which include vehicle kinematic variables obtained from naturalistic driving and parameters obtained by sampling from random distributions.

Transition Probabilities In the context of a driving scenario, transition probability is defined as the expected probability of a vehicle transitioning from a normal driving scenario to a crash scenario. This process applies a sampling approach from the ITTLC bins and obtains expectations based on the relative frequencies in those bins. Transition probabilities are an essential component of the VFU SIM methodology, providing an efficient method to amplify crash risk in simulations without introducing systematic bias.

Crash Metric As an alternative to generating actual crashes and representing the detailed locations of potential collision objects, a distance-based measure of crash probability was developed. This basic crash risk model associates a crash metric with the lateral or longitudinal distance traversed at various locations outside the desired lane, as shown in Figure 7.

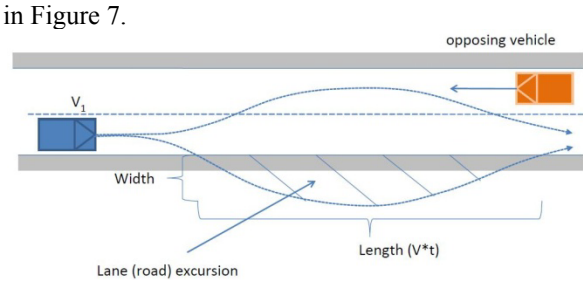

Figure 7. Crash risk related to trajectory output from simulation.

The logic behind it is that the lane deviations are unplanned and hold a uniform risk of colliding with a fixed or moving object that is proportional to "exposure", i.e. the size and duration of the lane excursion. For fixed objects and neighboring lane excursions, this is a distance-based metric based on an arbitrary boundary layer, while for road excursions, the Maximum Road Excursion (MRE) metric is used, which increases linearly within the clear zone (for road departure) to a maximum value at the edge of the clear zone.

Countermeasure Performance Analysis and Safety Benefits

The basic calculation in this activity is a comparison of crashes that occur without the system to crashes that occur with the system. The VFU team emphasized that this process is different for crash avoidance systems than it is for crashworthiness systems. The difference is that the sequence of relevant events for crash prevention starts with an aberration from "normal" driving. This starting point may lead to a variety of types of crashes or, as occurs most of the time, a corrective action that avoids a crash altogether. The VFU team implemented this process by defining a transition matrix that contained the probability of each type of crash, or no crash, for each type of starting condition, scenario, or event.

The basic benefits equation extends from the original equations such that,

$$B = N - N' = \sum_i \sum_j (T_{ji} - \varepsilon_i T'_{ji}) w_i E \qquad (4)$$

where ,

N and N' = the number of crashes with and without the system

E = the Overall system effectiveness

$\varepsilon_i = \frac{w'_i}{w_i}$ is the Exposure ratio

$T'_{ji} = P'(C_j | S_i)$, $w'_j = P'(S_j)$ Are the transition probabilities and scenario weights with the system.

$T_{ji} = P(C_j | S_i)$, $w_j = P(S_j)$ Are the transition probabilities and scenario weights without the system.

This equation is rewritten into a more general form,

$$B = \sum_j (1 - \varepsilon_j \pi_j) c_j N \qquad (5)$$

where,

$$\pi = \frac{P'(C|S)}{P(C|S)} = \frac{\sum_j T'_{ji}}{\sum_j T_{ji}} \quad \text{and} \quad c_j = \frac{N_j}{N}$$

Many simplifications and assumptions were necessary to be able to complete the overall project within the time and resources available. These included use of a limited number of driving simulator runs; use of data from one state (Michigan) instead of national data for road environment parameters; no consideration of fatigue, distraction or non-driving workload in the driver model; and use of a single model of passenger car to represent the entire passenger car fleet. Within the available resources, the team developed models that had adequate fidelity in terms of processes and mechanisms, but otherwise were as simple as possible.

For effectiveness, an initial "raw" estimte of 47% for the 181,000 crashes was calculated. This effectiveness estimate was then refined based on estimates of other influential factors like system availability, driver responsiveness, and driver compliance, which effect the outcome of the benefits estimation process. The resulting range of the final estimate is given below in Table 3.

Table 3.
Safety benefit estimates for Lane Departure Warning (LDW)

	Target Population	Estimated System Effectiveness	Estimated Safety Benefits
Crashes	181,000	13% - 32%	24,000 - 57,000

TEAM 3: PRE-COLLISION SAFETY SYSTEM (PCS)

For the ACAT program, Toyota developed a Toyota SIM (T-SIM) that estimates safety benefits for advanced driver assistance systems such as the Pre-collision Safety System (PCS) that reduces the vehicle impact speed in a crash. The PCS addresses rear-end crashes, head-on crashes, and collision-in-to-objects. The T-SIM generates estimated safety benefits including the number of crashes avoided, fatalities reduced, and casualties reduced. A graphical view of T-SIM is shown in Figure 8 [8].

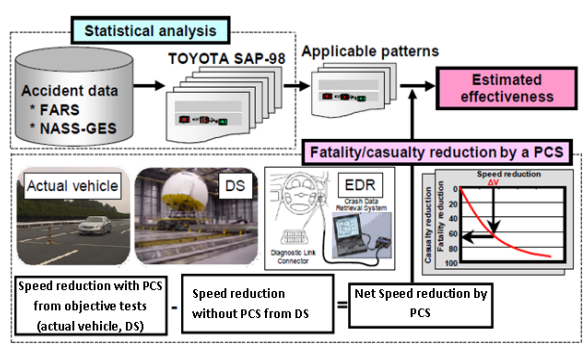

Figure 8. Structure of the T-SIM for the PCS. Data Usage.

GES, CDS, FARS, and Event Data Recorder (EDR) data were the primary databases used in the development and application of the T-SIM. The SIM process is initiated by classifying the vehicles in GES and FARS crash database as culpable and counter party. Using this classification and crash variables such as accident type, location of crash, and traffic control, the crashes in GES and FARS are grouped into 486 Standard Accident Patterns (SAPs). This set of 486 accident patterns is reduced to 98 SAP by eliminating the minor (representing less than 0.025% of all fatalities in FARS) and unclear cases. The remaining 98 SAPs represent approximately 85% of all crash cases in the accident database. EDR data is used to retrieve information concerning driver performance in baseline crashes.

Case Scenarios

The relevant crashes are separated into three major subdivisions: rear-end (Lead Vehicle Stopped (LVS) and Lead Vehicle Decelerating (LVD)), head-on, and collisions with other objects. Each subdivision is then further subdivided by travel speed ranges (5 mph bins) into the final set of scenarios. Of the 98 SAPs, 15 are considered to be relevant to the PCS. The number of crashes without the countermeasure active (N_{woi}) for each one of the relevant scenarios/SAP is calculated from FARS and GES data.

Objective Testing

The speed reduction attained by Pre-collision Brake Assist (PBA) and Pre-collision Brake (PB) is modeled using the deceleration profiles generated from test track tests, where a PCS equipped vehicle is driven, into a polyurethane-foam pole with a radar reflector, by an expert driver using several different braking levels (e.g. 0.2 g, 0.4 g), including no braking. The driver reaction and brake application profile is modeled using data from the driving simulator study, where the distracted driver reacts to a PCS warning. An example from the Driving Simulator is shown in Figure 9 where a Lead Vehicle Stopped (LVS) scenario is shown.

Model Creation

The model of driver performance consists of a delay after the occurrence of an alert, a warning or other causes that may bring the driver back to alertness, a level of braking and a gradual onset between no braking and the selected level of braking. A key assumption is that drivers react similarly to a

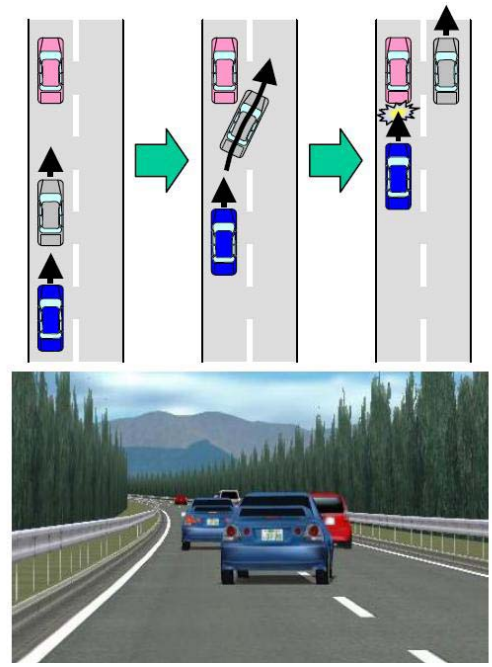

Figure 9. Driving Simulator LVS scenario showing cut-out revealing stopped vehicle.

warning, in terms of braking magnitude and application rate, as they would in normal driving when they become aware of an impending crash. The model for the combination of vehicle and countermeasure system has two parts. The Pre-collision Brake Assist (PBA) acts as an amplifier of the driver level of braking and the Pre-collision Brake (PB) produces a constant high level of deceleration, once the respective specified criteria have been reached. The effect of PBA and PB is numerically overlaid on the driver reaction data generated from the Driving Simulator (DS) as shown in Figure 10. The difference in reduction of impact speed between with and without PCS is used to estimate safety benefits.

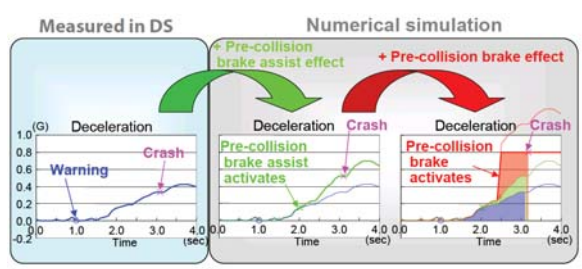

Figure 10. Effects of PBA and PB overlaid on the deceleration profile measured in the DS.

A key element of the T-SIM is the use of EDR data to estimate pre-crash speed reductions when drivers do not have the benefit of the countermeasure.

EDR data were analyzed to estimate speed reduction before crash without a PCS to know the distribution when the drivers stepped on the brake before crash. The result implies that drivers' braking behavior obtained by the DS was similar to the actual situations by EDR. It also implies how much drivers can brake during the crash imminent situation may not be different regardless of the warning. Therefore, the DS data was used for the simulation by weighting the data to have a closer distribution to the EDR data.

Data Generation

The probability of a fatality or casualty without the countermeasure for each scenario is calculated directly from FARS and GES data. The reduction of travel speed with the countermeasure is determined from the DS tests that determine driver response to a warning and from test track experiments to determine the supplementary impact of the PBA and PB subsystems. The probability of a fatality or casualty with the countermeasure for each scenario is determined by subtracting the reduction in travel speed from the original travel speed (taking into account any pre-crash braking) for each scenario and applying the probability from the original data for the reduced speed. The difference in speed reduction is used to estimate the fatality reduction for accident patterns.

Countermeasure Performance Analysis and Safety Benefits

The effectiveness of a system can be calculated by multiplying the fatality reduction and the number of fatalities in the applicable accident patterns. The effectiveness in preventing fatalities or casualties for each of 15 scenarios is equal to:

$$E_{fi} = 1 - \frac{P(fatality)_{WO\,i}}{P(fatality)_{W\,i}} \quad (6)$$

where,
$P(fatality)_{WO\,i}$ is number of fatalities for scenario "i" without the countermeasure active.
$P(fatality)_{W\,i}$ is number of fatalities for scenario "i" with the countermeasure active.

and similarly for casualties:

$$E_{ci} = 1 - \frac{P(Casuality)_{WO\,i}}{P(Casuality)_{W\,i}} \quad (7)$$

System Effectiveness is the weighted sum of the effectiveness for the individual scenarios.

While safety benefit estimates were developed by Team 3, the final report was still being reviewed at the time of this printing. Therefore these results are not published here but will be published in the final report for this ACAT project.

TEAM 4: BACKING CRASH COUNTERMEASURE SYSTEM

As part of the ACAT program, General Motors Corporation (GM) with support from Virginia Tech Transportation Institute (VTTI) developed a basic methodological framework and simulation model to estimate the effectiveness and safety benefits of a prototype backing crash countermeasure system. The SIM tool provides an estimate of safety benefits in terms of reduction in crashes and fatalities [9].

Data Usage

The data sources that were used were primarily national databases like GES, FARS, NHTSA Special Crash Investigations (SCI) Database; state databases, specifically, Nebraska, Kentucky, and North Carolina; supplemental data sources include data from National Electronic Injury Surveillance System (NEISS), Police Accident Reports (PARs), and death certificates and other non traditional sources including other naturalistic data sources from archives and literature studies. Parametric data sources including: brake reaction time, braking performance, vehicle kinematics, glance distributions, and driver trust, were also used from research archives.

Case scenarios

The scenario development and crash characterization process was undertaken to aid objective testing of specific countermeasure systems. Since the required data was not captured in the national databases directly, the activity involved a multi-step "reasoned" process that broke down the target population into the following 10 scenarios shown in Table 4. These scenarios were considered to be reasonably representative, but not exhaustive, of the types of backing crash scenarios with emphasis on pedestrian backing crash situations.

Objective Testing

The purpose of objective testing is to produce parameter estimates that can populate the SIM model to produce estimated safety benefits applicable to the overall crash problem size.

Table 4.
Objective test scenarios for Backing Crash Countermeasures

Test scene #	Roadway Type	Maneuver	Pedestrian Posture/Motion Offset/Direction of Encroachment	Distance from Bumper at Initiation of Backing
P1	Parking Lot	Backing out	Standing on center line	Near (e.g., 5')
P2	Street	Parallel Parking	Sitting on curb, Right (e.g., 2')	Farther (e.g., 30')
P3	Driveway	Backing out	Prone, Left (e.g., 2')	Moderate (e.g., 15')
P4	Driveway	Backing out	Incurring, from right	Moderate (e.g., 15')
P5	Parking Space	Backing out	Incurring from left	Near (e.g., 5')
P6	Long Driveway	Driving in Reverse	Incurring from left	Farther (e.g., 30')
V1	Inter section	Backing	Stopped behind on center line	Near (e.g., 5')
V2	Driveway / Street Junction	Backing out	Approaching from the left	Moderate (e.g.,15')
V3	Parking Lot	Backing out	Parked Behind	Farther (e.g.,30')
FO1	Driveway/ Roadside Junction	Backing out	Utility Pole, encroach to the Right	Moderate (e.g., 15')

An example of such a scenario would the incurring pedestrian scenario as shown in Figure 11. Here the pedestrian incurs from the left on a long driveway with a distance of 30 feet from bumper at the time of initiation.

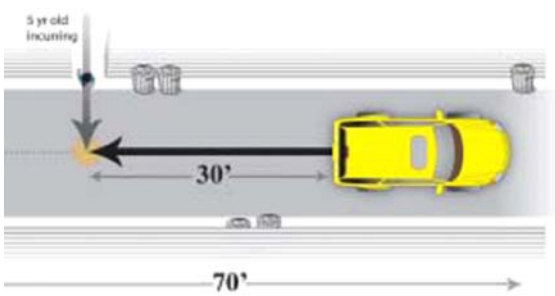

Figure 11. Illustration of the 5 year old incurring pedestrian scenario.

A highlight of the objective test development process was the development of pedestrian test devices. This involved development and modification of off-the-shelf dummies to develop child pedestrian test devices that have realistic radar cross-sections at the 24 GHz frequency that is used in some rear object detection systems. Test Objects used in Grid tests and Camera Field of View evaluations are depicted in Figure 12 below.

Figure 12. Test Objects used during testing (from left to right: Gen II 5 year old, Gen II 2 year old, Cardboard Cylinder, Gen II sitting child, PVC Pole, Gen 1 Prone 5 year old).

Model Creation

A unique feature of the GM-VTTI process was the development of a driver model that has three distinct submodels: the Visibility Model, the Glance Behavior Model, and the Driver Response Model.

Visibility Model In the Visibility Model, the parameters define the outside visibility by first determining which "displays" are available to the driver from look-up tables which are used to obtain a probability of visibility. That probability is compared to a pre-determined threshold to ascertain visibility, which includes left mirror, right mirror, rear - view mirror and over the shoulders. In occluding situations, the visibility matrices are zeroed out. The data for the model is obtained from objective testing performed as part of research from other projects as part of GM's corporate body of knowledge.

Glance Behavior Model The Glance Behavior Model not only provides distributions of driver glance behaviors in the presence and absence of counter measure systems but also probabilities of subsequent glance locations based on current glance locations and length of glance. The Glance Behavior Module accomplishes these goals by generating glances and keeping track of when new glances should be generated.

Driver Response Model The outputs of the Glance Behavior Model are fed to the Driver Response Model, which determines the presence, type, and level of driver response. The model first determines if the driver has detected the obstacle and countermeasure. If no detection is determined, the simulation proceeds to the next step. If there is evidence of detection, then the model generates a reaction time and braking effort appropriate for the situation and applies these parameters to determine if a crash or no crash occurred. The same process applies for automatic braking as well. A "no crash" situation is detected by the end of simulation time or if the vehicle has stopped before impacting the obstacle. A "crash" situation is identified if the obstacle is within the vehicle's width, the distance to the object is less than or equal to 0, and the vehicle speed at impact is > 0.

Data Generation

The core of the SIM model is the Monte Carlo simulation process exercised in a Matlab/Simulink environment that will extract data from a given set of distributions. The process involves picking values from a given distribution for a given iteration, which are obtained from objective tests and other sources of data. Each iteration is run several times for a new set of parameter values with and without the countermeasure active to account for the variability in outcomes. A comprehensive set of data is produced for all situations which are used in the estimation of safety benefits.

The initial modules of the SIM model define parameters that will remain fixed throughout the simulation (*Non-Variant Parameters*). Subsequent modules define parameters that change as the simulation progresses (*Variant Parameters*), which are defined inside the Simulation Control loops.

Once all the parameters are defined, the SIM starts the Monte Carlo Simulation. The simulation model should be seen as a representation of the overall backing maneuver, from the point where the vehicle is shifted to reverse all the way through to when a crash with the obstacle is recorded or an avoidance of the crash is achieved. The simulation model consists of numerous modules and sub-modules in Matlab that are initialized and called upon repeatedly and are exercised at various points of the iterations. Once all simulation control loops are completed, estimation of safety benefits is performed. A summary flowchart of the SIM flow is shown in Figure 13.

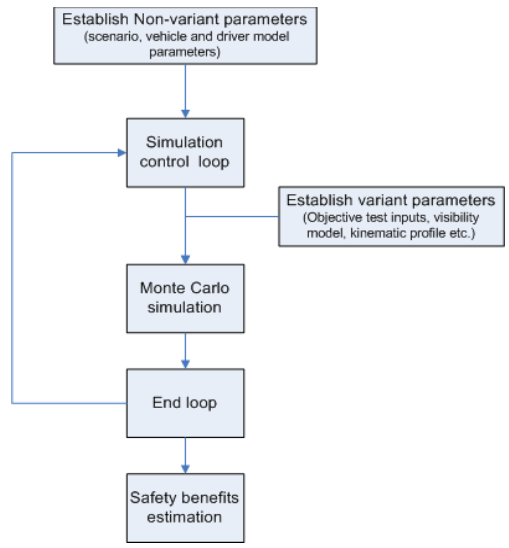

Figure 13. Flowchart of the Monte Carlo process.

Countermeasure Performance Analysis and Safety Benefits

The main outcome of the countermeasure performance analysis and safety benefits estimation process is the estimated number of crashes avoided annually following the deployment of a particular crash countermeasure. The equations that are used to determine this are given as follows:

$$C_A = C_{wo} \times D_C \times SE \tag{8}$$

where,
C_A = annual number of the type of crashes of interest
C_{wo} = annual number of the type of crashes of interest prior to a countermeasure's deployment
D_C = potential countermeasure deployment rate
SE = System Effectiveness

Another potential safety benefit is the reduction in fatalities, which is given by:

$$H_R = H_{wo} \times D_C \times SR \tag{9}$$

where:
H_R = predicted annual reduction in fatalities
H_{wo} = annual total fatalities for the type of crashes of interest prior to a countermeasure's deployment
D_C = potential countermeasure deployment rate in the vehicle fleet.
SR = System Harm-Reduction Effectiveness

Table 5 below summarizes the target crash population, estimated system effectiveness, and estimated safety benefits.

Table 5.
Safety benefit estimates for Backing Crash Countermeasures

	Target Population	Estimated System Effectiveness	Estimated Safety Benefits
Crashes	202,000	32%	65,000
Fatalities	182	62%	113

CONCLUSION AND SUMMARY

This paper describes a Safety Impact Methodology framework which was used by each of the ACAT teams to estimate safety benefits for pre-production crash avoidance systems. The SIM framework includes the following components: Data Usage, Case Scenarios, Objective Testing, Model Creation, Data Generation, Countermeasure Performance Analysis, and Safety Benefits. The specific extensions to the SIM framework developed in each of the ACAT projects were unique and can be used to estimate safety benefits for various types of crash avoidance systems.

PROGRAM INFORMATION

Detailed Final Reports [6][7][8][9] from the teams describing their ACAT projects have been submitted and are in the process of being published. These reports will be available on the NHTSA website at: http://www.nhtsa.gov/Research/Crash+Avoidance/Office+of+Crash+Avoidance+Research+Technical+Publications

The ACAT program continues with a second series of research projects known as ACAT-II. This research program involving two teams is currently underway and is set to finish in June 2011. Technical questions on the ACAT program should be referred to James Funke of NHTSA's Office of Vehicle Safety Research at (202) 366-5213 or via e-mail at james.funke@dot.gov.

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