

Extension of the Honda-DRI Safety Impact Methodology for the NHTSA Advanced Crash Avoidance Technology (ACAT) Program and Application to the Evaluation of an Advanced Collision Mitigation Braking System - Final Results of the ACAT-I Program

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ABSTRACT

The Advanced Crash Avoidance Technologies (ACAT) program initiated by the National Highway Traffic Safety Administration had two major overall objectives. These were to develop a standardized Safety Impact Methodology (SIM) tool to evaluate the effectiveness of advanced technologies in avoiding and mitigating specific types of vehicle crashes; and to develop and demonstrate objective tests that are used in the SIM to verify the safety impact of a real system. Honda and Dynamic Research Inc. (DRI) had been developing and applying such SIMs for several years and had a Cooperative Agreement with NHTSA to further develop a SIM in order to determine the feasibility of developing estimates of effectiveness for specific not-yet-deployed safety technologies in the absence of data from real world or field operational tests, and linking it to the results from objective tests. Objective tests that produce quantifiable, repeatable and reproducible results were developed to calibrate the level of correlation between the actual prototype of the proposed safety problem countermeasure and the math model of the prototype in a sample of technology-relevant accidents being addressed. The objective tests, which are based on dynamic reconstructions of a sub-sample of the technology-relevant

NASS/CDS and PCDS real world accidents, included full-scale track tests with an expert driver using automatically guided soft targets (GSTs) of an automobile and a pedestrian, and driving simulator tests with a jury of typical drivers in order to include the effects of a sample of driver reactions to collision partners and to system warnings and interventions. Results from the objective tests were used to parameterize, calibrate and validate the SIM tool, which was then used to estimate US-level safety benefits. The SIM tool itself includes modules for automated reconstruction of conflict and crash scenarios; definition and sampling of technology-relevant crash types; dynamic simulation involving a human-vehicle-device-environmental model; and an overall safety effects estimator. An example application of the developed SIM tool and related objective tests were used to evaluate a Honda prototype Advanced Collision Mitigation Braking System (A-CMBS). Results indicated that the total collision and fatality effectiveness values for all police-reported crashes of the Honda A-CMBS were 8.3% and 3.7% respectively, and this corresponds to estimated safety benefits of 511,336 fewer collisions and 1,623 fewer fatalities at the US 2005 calendar year level. Overall, the ACAT-I project was successful in developing and demonstrating a

methodology that can be used to estimate the safety benefits of a wide range of advanced crash avoidance technologies.

INTRODUCTION

This paper summarizes cooperative research under the Advanced Crash Avoidance Technologies (ACAT) program of the National Highway Traffic Safety Administration (NHTSA). This particular study extended earlier work by Honda and Dynamic Research Inc (DRI) [1,2] to develop evaluation tools similar to those of interest in the ACAT project. Honda and DRI had been developing and applying such a SIM during the previous several years. DRI, with the support of Honda, entered into a Cooperative Agreement with NHTSA to extend the existing SIM, which provides an estimate of full systems safety benefits at the US level. A mid-term progress report for this study was presented in [3]. More detailed results from this study are presented in [4].

PROJECT AIMS

The goals of NHTSA's ACAT program were twofold. These were:

- to develop a standardized Safety Impact Methodology (SIM) tool to evaluate the effectiveness of advanced crash avoidance technologies in mitigating specific types of vehicle crashes; and
- to develop and demonstrate objective tests that are used in the SIM to verify the safety impact of a real system.

SCOPE OF THE STUDY

The scope of this study involved:

- Theoretical and software extensions to the existing Honda-DRI SIM tool;
- Development of objective test procedures and apparatus that produce quantifiable, repeatable and reproducible results intended to verify the response characteristics and performance of a given ACAT safety technology;
- Objective test procedures that included track tests with an expert driver using automatically Guided Soft Targets (GSTs) of a passenger car and of a pedestrian;
- Driving Simulator tests with a jury of 12 typical drivers, in order to measure the drivers' response characteristics to system warnings and interventions as well as to Collision Partner motions and a standardized in-car distraction;
- Using the data from the objective tests to parameterize, calibrate and validate the SIM tool;

- Delivering an extended SIM tool which includes modules for automated reconstruction of conflict and crash scenarios¹ from available databases; automated definition and sampling of Technology Relevant Crash Types; dynamic simulations involving a human-vehicle-device-environmental model; and an overall safety effects estimator;

- An example application of the extended SIM tool and the developed objective tests which involved safety effectiveness and benefits estimation for Honda's prototype Advanced Collision Mitigation Brake System (A-CMBS).

SAFETY IMPACT METHODOLOGY

NHTSA's Safety Impact Methodology framework [5] is illustrated in [Figure 1](#). This framework comprises 22 different Functions (e.g., "Archival Data"). These functions are grouped into nine different activities illustrated by the large open boxes (e.g., "Data Usage"), which are also grouped into three main areas indicated by the box color coding (i.e., orange, blue, and purple). Of the 22 different Functions, 11 Functions were implemented by the Honda-DRI SIM tool ([Figure 2](#)), the other 11 Functions were accomplished "off-line".

OVERVIEW OF THE SIM

The Honda-DRI SIM comprises four main modules as illustrated in [Figure 2](#). The color coding of each module in [Figure 2](#) corresponds the color shading functions in [Figure 1](#). The main SIM modules comprise:

1. Crash scenario database development tools to accomplish NHTSA Framework Functions 1, 2, 5, and 6;
2. Technology relevant case specification and case sub-sampling tools to accomplish Function 7;
3. A Crash Sequence Simulation Module (CSSM) to accomplish Functions 17 to 21; and
4. An Overall Safety Effects Estimator (OSEE) to accomplish Function 22.

¹Conflict and crash scenarios described herein are based on individual conflicts or crashes, not hypothetical situations or based on aggregated information. These scenarios typically have case weightings corresponding to the probability that they were sampled. These weighted scenarios are assumed be representative of the traffic conflicts and crashes in the US.

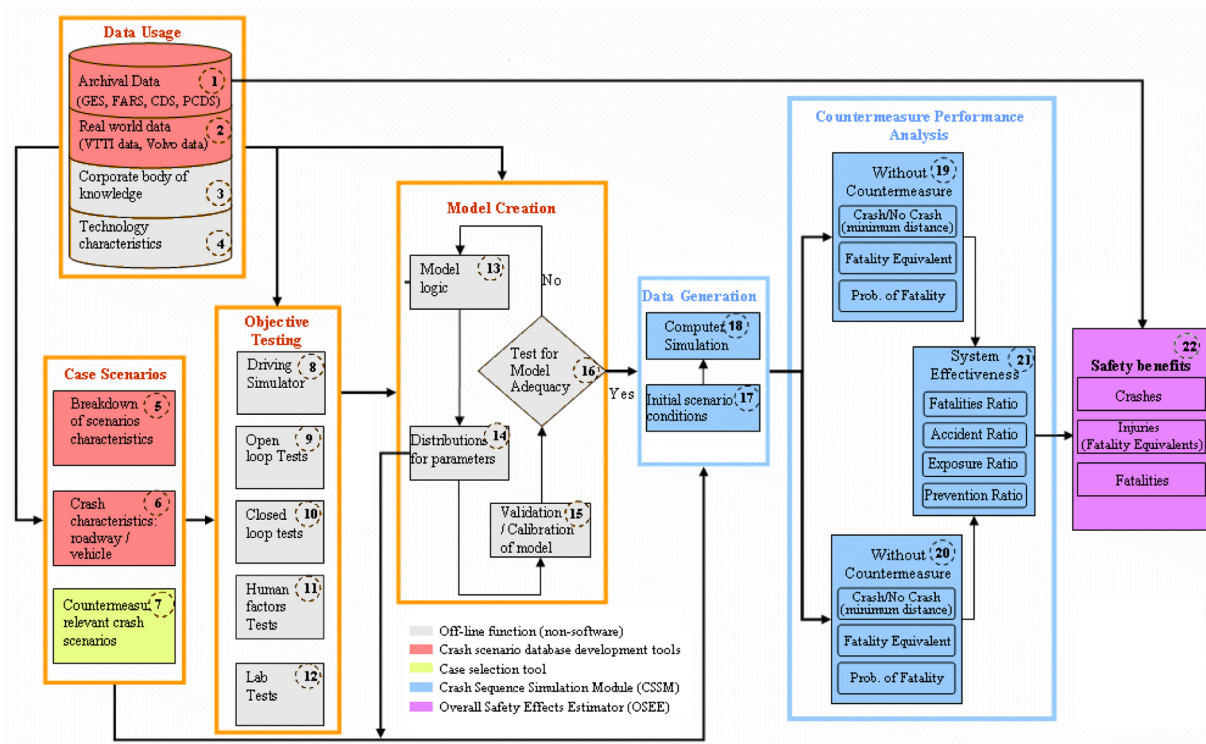


Figure 1. NHTSA ACAT SIM Framework [5]

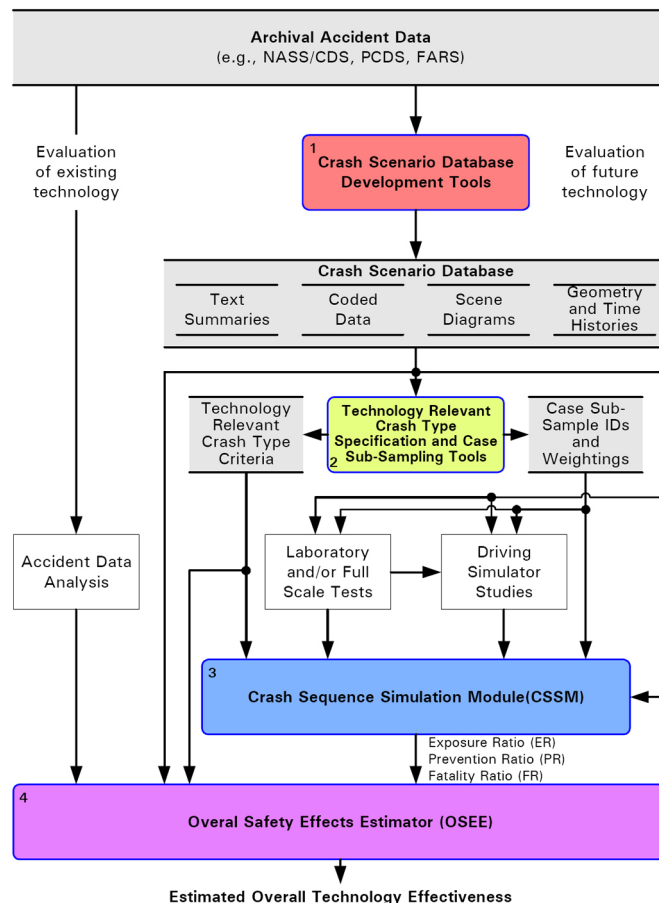


Figure 2. Honda-DRI SIM Tool Schematic

Module 1 - Crash Scenario Database Development Tools

The Crash Scenario Database Development tools comprise three main sub-modules as illustrated in Figure 3. Sub-module 1.1 extracts a set of coded vehicle level crash scenarios from the NASS/CDS, PCDS, and GES databases [6, 7, 8], which are used throughout the SIM tool. Sub-module 1.2 downloads crash scene diagrams from a NHTSA website for each NASS/CDS case in the crash scenarios from Sub-module 1.1. This sub-module also downloads reports from a NHTSA website for each NASS/PCDS case and then extracts the scene diagrams in GIF format. Sub-module 1.3 is an Automated Accident Reconstruction Tool (AART).

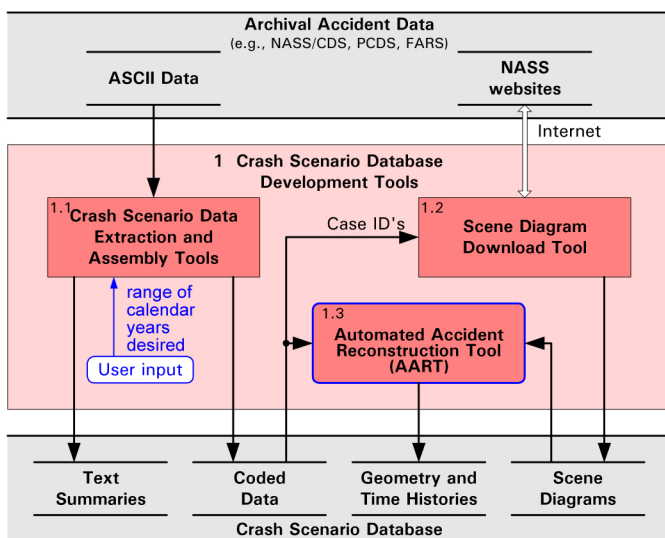


Figure 3. Crash Scenario Database Development Tools

The AART is used to reconstruct the time-space relationships of the collision partners using physics based models of the pre-crash, crash, and post-crash phases as illustrated in Figure 4 and the available coded information and digitized information from the crash scene diagrams.

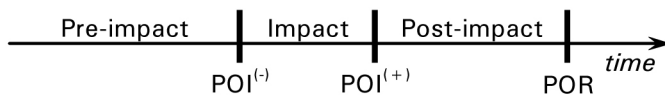


Figure 4. AART Assumed Crash Phases for Vehicle Dynamics

Module 2 - Technology Relevant Case Specification and Case Sub-Sampling Tools

The technology relevant case specification and case sub-sampling tools comprise three main sub-modules. Sub-module 2.1 is an interactive tool which the ACAT designer can use to formalize the descriptions of the technology relevant crash types in terms of coded accident database (e.g., NASS/CDS variables). These ACAT technology specific descriptions are saved in a specially formatted file for use in subsequent SIM modules. Sub-module 2.2 is an interactive tool which the ACAT evaluator can use to select a representative sample of crash scenarios (e.g., NASS/CDS cases) to be used in the ACAT evaluation. The resulting list of sampled cases is used in Sub-module 2.3 and in Module 3 (the Crash Sequence Simulation Module). Sub-module 2.3 is used to further sub-sample test cases to be used in the driver-in-the-loop and driver-not-in-the-loop tests.

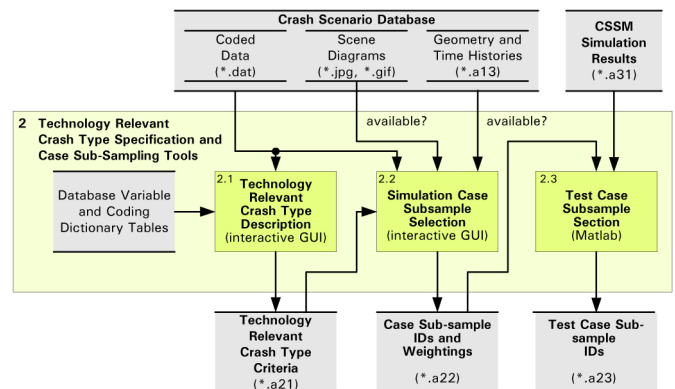


Figure 5. Technology Relevant Crash Type Specification and Case Sub-Sampling Tools

Module 3 - Crash Sequence Simulation Module

The Crash Sequence Simulation Module illustrated in Figure 6 is an innovative time-domain simulation of the driver, the vehicle (with and without the ACAT) and the environment, in order to predict the relative effects of the ACAT and assumed driver behaviors on crash occurrence and injury consequences in real-world crash scenarios. The driver model is based on NASA's APEX and MIDAS human modeling tools [9, 10, 11]. The APEX model of the driver controls a Simulink model of the vehicle, environment and ACAT. The APEX and Simulink models are linked together with a TCP/IP communications interface; providing visual object information to the driver model and driver control outputs to the vehicle model. The simulation also has a virtual reality display output.

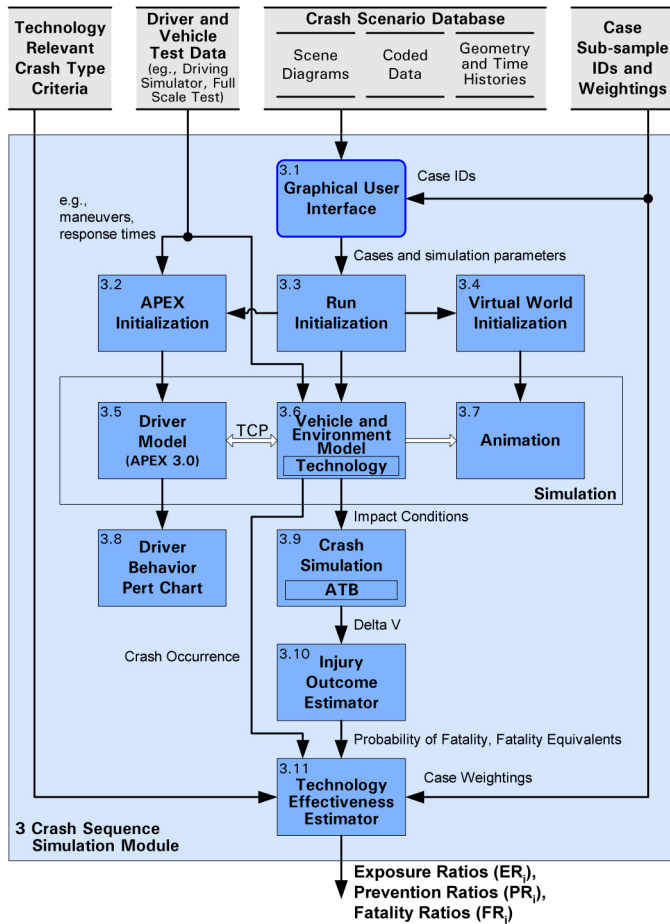


Figure 6. Crash Sequence Simulation Tool

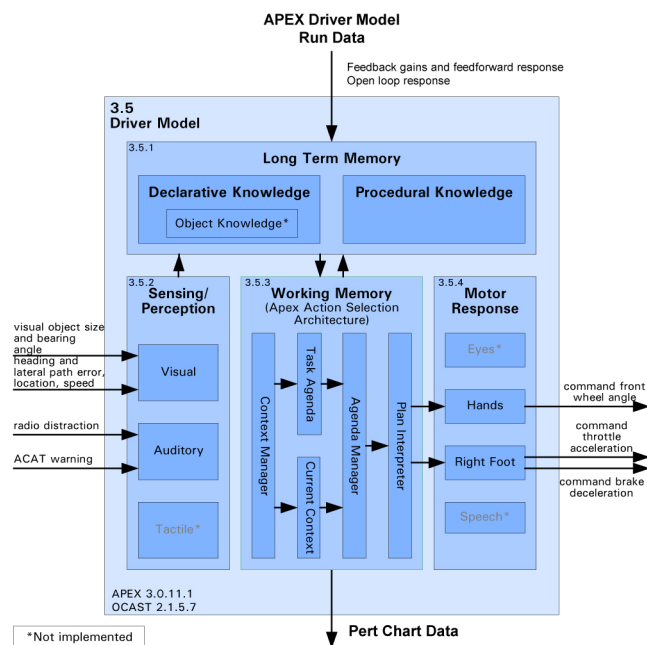


Figure 7. NASA MIDAS-based Driver Model

Module 4 - Overall Safety Effects Estimator

The Overall Safety Effects Estimator is a uniquely powerful, integrated tool for estimating the combined effects of multiple, complimentary or redundant ACATs on the number of crashes and fatalities based on technology effectiveness functions, crash scenarios, and retrospective and forecasted data [1]. The technology effectiveness functions describe the exposure, prevention, and fatality ratios (ER, PR, FR) vs technology relevant category criteria.² These functions are based on results from the CSSM and other a-priori knowledge (e.g., published literature and statistical accident data analyses for existing technologies such as side airbags [12]) expressed as mathematical functions of the relevant human, vehicle, environment and accident factors. Retrospective data sources include FARS and GES accident databases [14, 8] and R.L. Polk & Co. National Vehicle Population Profile® vehicle registration data [15].

The results from the OSEE are used to estimate the size of the problem, technology effectiveness, and benefits according to the equations [13]:

$$B = N_{WO} - N_W \quad (1)$$

$$B = \sum_i B_i = \sum_i N_{WO_i} \times E_i \quad (2)$$

where,

- B is the benefit, (which can be the number of crashes, number of fatalities, or other such measures);
- N_{WO} is the value of this measure (e.g., the number of crashes) that occurs *without* the system; and
- N_W is the value of the measure *with* the system fully deployed;
- " i " is an index referring to individual scenarios;
- E_i is the effectiveness of the system in reducing the value of the measure (e.g., fatalities) in a specific crash-related scenario;
- N_{WO_i} is baseline value of the measure in individual scenario " i "; and
- B_i is the benefit in each of the individual scenarios.

The OSEE also estimates the uncertainty in the results due to some, but not all, sources of variation as follows:

- The number of fatalities from the FARS databases, for a given make, model, body type, model year, and calendar year.

²The Exposure Ratio and Prevention Ratio are defined in [13] as "The Exposure Ratio is the ratio between rate of exposure (i.e., the rate at which drivers encounter an imminent crash) with the system and the rate of exposure without the system. Similarly, the Prevention Ratio is the ratio between the probability of having a crash with the system and the probability of having a crash without the system." This concept is also extended to Fatality Ratio, which is the conditional probability of a fatality with the system and the probability of a fatality without the system, given that a crash does occur.

- The number of vehicles involved in accidents from the GES databases, for a given make, model, body type, model year, and calendar year.

These uncertainty calculations are described in further detail in [4].

EXTENSIONS IN THE ACAT-I PROGRAM

The Honda-DRI tools were extensively modified and refined as part of the NHTSA-DRI-Honda ACAT Phase I (ACAT-I) SIM program. The refinements that were made to the crash scenario database development tools in Module 1 (Figure 2 and Figure 3) include:

- Expanded the assembled crash scenario dataset in scope to include pre-conflict thru near-crash phases with near-crash events from the VTTI 100-Car study near-crash event database [16];
- Expanded the assembled crash scenario dataset to include non-tow-away crashes extracted from the NASS/GES database;
- ISO 13232 based “Equivalent Life Units” were replaced with NHTSA “Fatality Equivalent” injury indices;
- Expanded the Crash Scenario Data Extraction and Assembly Tools in order to support download and extraction of CDS and PCDS scene drawings.

Refinements that were made to the AART (Module 1.3) include:

- The digitizer and solver steps were integrated so the user can see the reconstructed case during the digitizing process, in order to mitigate or eliminate a “late swerve” effect observed in the existing reconstructions near the point of impact;
- The pre-crash reference trajectory used to linearize the quasi-steady Bundorf-Leffert vehicle equations of motion [17] for the Kalman Filter-Smoother (KFS) [18] was extended to constant radius turns in order to mitigate “rubber banding” and linearization error effects;
- The KFS trajectory innovation was extended to include the impact and post-impact phases, in order to mitigate or eliminate “late swerve” effects resulting from previously separate solutions to the pre-crash and impact/post-impact phases.
- Some numerically computed terms in the linearized Jacobian matrix and KFS state transition matrices were replaced with closed form equations;
- Support for PCDS crashes involving 1 vehicle and 1 pedestrian was added;

- The assumed speed profile was refined based on coded values for “pre-event movement” and “crash avoidance maneuver” in the CDS database (Figure 8);
- Numerous refinements to the AART to improve the fits to the scene drawings and coded data in general.

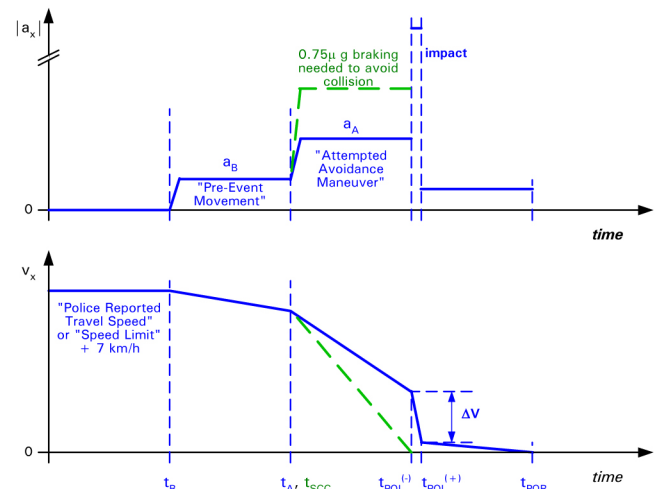


Figure 8. Assumed Vehicle Speed Profile for AART Reconstructions

Refinements that were made to Block 2 include creating a user friendly tool to:

- Assist the ACAT designer in defining the Technology Relevant Crash Types in terms of coded NASS data type variables;
- Generate a sub-sample of cases for simulation purposes; and
- Generate a sub-sub-sample of cases for driver-in-the-loop and driver-not-in-the-loop tests (i.e., Track test and Driving Simulator tests).

Refinements that were made to the Crash Sequence Simulation Module (Module 3) include:

- Further refinement of the driver model to better represent the cognitive driver behavior. This includes the object recognition, threat estimation, and decision making procedures; and driver vehicle control procedures for normal/benign conflict driving and emergency driving. Further refinement of the driver steering and braking control algorithms and procedures;
- Partitioning into separate ACAT and non-ACAT modules;
- Develop Fatality Equivalent injury models for vehicle drivers and pedestrians; and develop Probability of Fatality models for pedestrians.
- Extend to support single vehicle collision with a single pedestrian;

- The Technology Effectiveness Estimator (Module 3.11) was automated, and extended to include separate exposure ratio and prevention ratio terms;
- The graphical user interface to support different ACATs, and to use a driver behavior matrix based on multiple drivers.

The Overall Safety Effects Estimator (Module 4) was also extended so as to create an output table to summarize the overall safety benefits for the modeled fleet in terms of collisions and fatalities.

ADVANCED TECHNOLOGY AND SAFETY AREA ADDRESSED

The prototype Honda A-CMBS was selected as an example of an advanced technology to be evaluated using the SIM. The prototype A-CMBS was designed to be installed on light passenger vehicles (i.e., passenger cars and light trucks) to prevent or mitigate a variety of crash types. These crash types primarily included pedestrian, rear-end, head-on and intersecting path crashes involving a distracted driver. In addition to the primary crash types, the A-CMBS is also expected to prevent or mitigate some types of forward impact, side swipe, and 3-vehicle chain crashes.

THE SIZE OF THE CRASH PROBLEM

The potential numbers of crashes, involved vehicles, and fatalities that represent the size of the problem for the entire US motor vehicle fleet are listed in [Table 1](#) in terms non-technology specific crash types that have been broadly defined in terms of NASS Accident Configurations. Some of these crashes were not expected to be addressable by the A-CMBS due to either vehicle application (e.g., passenger car vs. motorcycle), vehicle role (e.g., lead vehicle or trailing vehicle), or other technology relevant factors. For example, the results in [Table 1](#) include 245,000 crashes involving non-light passenger vehicles (e.g., motorcycle only crashes), on which the prototype A-CMBS was not designed to be installed, involving 271,000 vehicles and 4,577 fatalities.³

Table 1. Estimated Crash Problem Size for the Entire US Motor Vehicle Fleet in the 2005 Calendar Year.

Crash Category	Crash Type	Estimated Number of		
		Crashes (1000s)	Vehicles (1000s)	Fatalities
1-vehicle	Pedestrian	62	62	4,298
	Forward Impact	607	607	2,554
	Other 1-Vehicle	1,226	1,226	17,346
2-vehicle	Rear-End	1,453	2,906	1,607
	Side Swipe	428	856	352
	Opposite Direction	132	263	5,626
	Intersecting Path	1,578	3,155	6,214
	Other 2-Vehicle	292	584	2,280
3 or more Vehicles	3 or More Vehicles	371	1,181	3,233
Total		6,147	10,839	43,510

A-CMBS DESCRIPTION

The prototype Advanced Collision Mitigation System (A-CMBS) illustrated in [Figure 9](#) is the next generation of the CMBS active safety technology developed by Honda, that automatically predicts impending collisions, warns the driver, and applies braking in order to reduce the effects of an impact on occupants and vehicle damage. Whereas the original CMBS version of the system was primarily intended to respond to impending rear-end collisions, the A-CMBS has been upgraded to be effective in other types of vehicle-to-vehicle collisions (e.g., head-on, intersecting path and pedestrian) as well as rear-end collisions. Note that the A-CMBS is still under development and will be modified in the future. Many issues (e.g., reliability verification through field operational tests using product level sensors) are yet to be resolved before any mass production occurs. So, performance and effectiveness of the prototype A-CMBS for this project is not related to the possible future production A-CMBS nor to the current production CMBS.

³Throughout this evaluation the estimated values were computed to relatively high numerical precision in order to enable readers to track the data flow and to verify the tabular results and, related to this, in order to control round-off errors that could be introduced at various stages of the analysis. The computed values have been rounded off (e.g., to the nearest integer or to the nearest 1000) for reporting purposes.