

Extension of the Honda-DRI “Safety Impact Methodology” (SIM) for the NHTSA Advanced Crash Avoidance Technology (ACAT) Program and Application to a Prototype Advanced Collision Mitigation Braking System

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ABSTRACT

The Advanced Crash Avoidance Technologies (ACAT) program initiated by the National Highway Safety Administration had two major 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) have been developing and applying such SIMs for several years and have a Cooperative Agreement with NHTSA to further develop a SIM that provides an estimate of full systems safety benefits at a national level. Objective tests that produce quantifiable, repeatable and reproducible results have been developed to ensure that the proposed safety problem countermeasure will meet full system performance specifications and that the results are directly linked to the safety needs and 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 real accidents, include 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 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 is used to evaluate a Honda prototype Advanced Collision Mitigation Braking System (A-CMBS).

INTRODUCTION

This paper presents a mid-term progress report on the Safety Impact Methodology (SIM) extended by Honda and Dynamic Research Inc. (DRI) under NHTSA Cooperative Agreement DTNH22-06-H-00070, entitled Advanced Crash Avoidance Technologies (ACAT) which is currently planned to be completed in March 2009. The purposes of the SIM are to evaluate the effectiveness of advanced technologies in mitigating specific types of vehicle crash avoidance accidents; and to develop and demonstrate objective tests that are used by the SIM to verify the safety impact of a real system. The Honda-DRI

SIM, developed in response to these objectives comprises the following key steps and assumptions:

1. Access US crash databases such as NASS/Crash Data System (CDS), Pedestrian Crash Data System (PCDS) and naturalistic driving databases (such as the Virginia Tech Transportation Institute (VTTI) 100 car naturalistic driving database);
2. Using these databases, reconstruct real crash and non-crash cases and their motion and control time histories using an Automated Accident Reconstruction Tool (AART);
3. Based on the specific ACAT being evaluated, and using the typologies in these databases and a Technology-Relevant Case Specification tool, the ACAT designer identifies Technology-Relevant Crash Types (TRCTs);
4. Sample real reconstructed cases from within each TRCT for simulation and testing purposes, using a Case Sampling Tool;
5. From this sample, select “representative” cases for testing, using a Test Selection Tool;
6. Use the previously reconstructed time histories to specify each of the selected tests;
7. Use a Guided Soft Target (GST) to enable the collision partner (CP) in the full-scale test to follow precisely the reconstructed CP trajectory;
8. Measure (the change in) impact conditions due to actions of the ACAT (both in tests and in computer simulations with the test sample, including the effects of drivers’ interactions (which are modeled in the simulations based on the drivers’ reactions in the tests);
9. Calibrate and validate the simulation results by correlating them with the test results, using quantitative criteria;
10. Refine the simulation to the extent necessary to meet the criteria as appropriate (i.e., refining parameters based on the collected test data);
11. Run the calibrated/validated simulations for all TRCT cases sampled in Step 4, above;
12. Based on the calibrated/validated simulation results, estimate the effectiveness (i.e., safety benefit) of the ACAT at the US level, in terms of indices such as Accident Ratio, Fatality Ratio, and Effectiveness, among others.

Within the ACAT project, these steps are organized under several tasks including: definition of the SIM, definition of the advanced technology and the related safety area to be addressed, and development of objective tests for predicting safety benefits. Each of these tasks and highlights of the novel and comprehensive Honda-DRI SIM are described subsequently.

THE SAFETY IMPACT METHODOLOGY

Figure 1 illustrates the overall SIM tool concept used to estimate the effectiveness of safety technologies based on information about the driver, vehicle, technology, and environment, and archival accident and exposure data (Refs 1 to 5); as implemented using previously developed Honda-DRI tools as described in Refs 6 and 7. The SIM tool comprises:

1. Crash scenario database development tools (Block 1);
2. Technology relevant case specification and case sub-sampling tools (Block 2);
3. A Crash Avoidance Simulation Tool (CAST) (Block 3);
4. A Fatality Analysis System (FAS) tool (Block 4).

Each of these blocks in turn comprises a dozen or more sub-blocks, within which the related functionalities and methods are implemented. The following describes some highlights and features of the main blocks and some of the sub-blocks.

CRASH SCENARIO DATABASE DEVELOPMENT TOOLS (BLOCK 1) - There are three main steps that are used to construct the crash scenario database from the archival US DOT accident data (Block 1). The “Crash Scenario Data Extraction and Assembly Tools” extract a set of crash scenarios weighted to US annual levels, comprising text summaries and coded data, from hierarchical US DOT accident data. The resulting coded data comprises one record for each vehicle involved in a crash. A “Scene Diagram Download Tool” is then used to extract scene diagrams from the NASS/CDS website for each of the CDS crash cases. Finally, the geometry and time histories of the vehicles, collision partners, and occluding objects are digitized and reconstructed using the scene diagrams and an “Automated Accident Reconstruction Tool” (AART) and ancillary digitizing tools. The latter are further described subsequently.

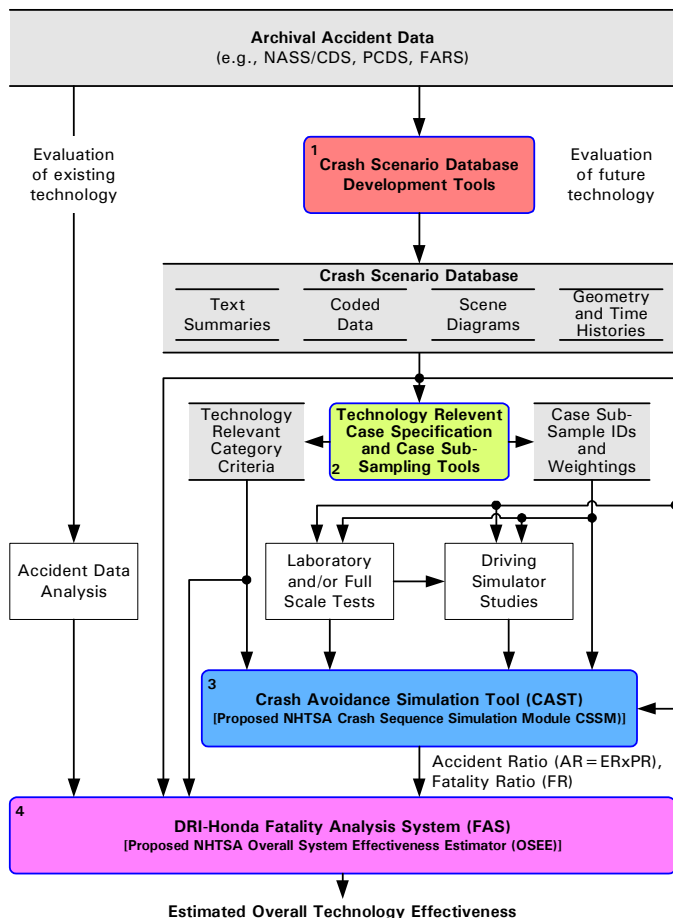


Figure 1 - Existing DRI-Honda SIM Tools

AUTOMATED ACCIDENT RECONSTRUCTION TOOL AND ANCILLARY DIGITIZING TOOLS - The unique AART originally developed by Honda and DRI estimates plausible pre-crash, crash and post-crash time-space relationships of the crash involved vehicles and fixed objects based on the coded data and scene diagram for each accident. It comprises a separate 1-vehicle crash scene digitizer and solver, and 2-vehicle crash scene digitizer and solver. The digitizers have an interactive Graphical User Interface (GUI) which saves digitized data to intermediate files for subsequent batch processing by solvers. The ancillary digitizing tools are interactive GUI's that create additional supporting files for the intended vehicle path and any occluding objects. In addition, top view animations of the reconstructed geometry and time history files are automatically created for viewing, diagnosis, and presentation purposes.

The AART previously developed by Honda and DRI assumes that the ground plane is horizontal and the vehicles do not pitch or roll and remain in contact with the ground with force equal to their respective weights. Therefore the vehicles move in a horizontal plane with 3 degrees-of-freedom (2 horizontal transitional degrees of freedom and 1 rotational (i.e., yaw) degree-of-freedom) each. It is further assumed that the dynamic motions of

each vehicle during the crash sequence comprise three phases. These phases are as follows:

- Pre-crash phase where the vehicle dynamics are dominated by lateral and longitudinal forces produced by rolling tires under quasi-steady state neutral steer conditions and where the steering rate is assumed to be a stochastic random variable¹; which can be approximated by a quasi-steady 4th order vehicle directional control model;
- Impact phase where the vehicle dynamics are dominated by forces resulting from contact with a single vehicle or fixed object; which can be modeled using the US DOT Crash Victim Simulator/US Air Force Articulated Total Body (ATB) program (Refs 8 and 9);
- Post-impact phase where the vehicle dynamics are assumed to comprise constant translational and angular deceleration until the vehicle comes to rest (i.e., the translational and angular velocities immediately after impact decrease to zero at a constant rate).

These three phases are separated in time by the initial point of impact ($POI^{(-)}$), point of separation ($POI^{(+)}$), and point of rest (POR), as also illustrated in Figure 2. It is further assumed that the time between $POI^{(-)}$ and $POI^{(+)}$ is very short, and the distance the vehicles travel in this period can be neglected.

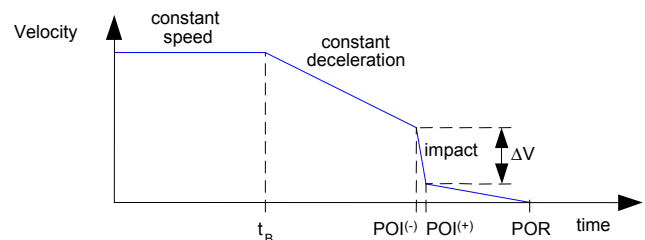


Figure 2 - Assumed speed profile (of original AART)

The ATB crash simulation assumes that each vehicle has a single mass segment with an 8th order hyper-ellipsoid shape (i.e., rectangular solids with slightly rounded corners). Rectangular fixed objects are also modeled by 8th order hyper-ellipsoids. Cylindrical objects are modeled by 2nd order ellipsoids. All vehicles and objects are constrained to move without vertical, pitch, or roll degrees-of-freedom.

The 1-vehicle crash solver estimates the vehicle trajectory from the point-of-impact ($POI^{(-)}$) to the point-of-rest (POR). Two different methods, a non-linear least

¹ This assumption means that the steering angle frequency spectrum has an integral (i.e., 1/s) shape, i.e., there are relatively large low frequency steering angle components and progressively smaller high frequency steering angle components, which is typical of human operator control activity.

squares and a Nelder-Mead simplex method, are used in order to improve the robustness of the fitting process. The results from each method are saved in intermediate files and the better fitting result is then selected. The pre-impact vehicle trajectory is then estimated and the resulting geometry and time histories are assembled and saved.

The 2-vehicle crash solver is similar to the 1-vehicle crash solver, but includes an intermediate step to refine the POI⁽⁻⁾ to the POR solution based on the best fit from the first pass. Again, the better result between the two fit methods is selected, the pre-impact vehicle trajectories are estimated, and the reconstructed geometry and time histories are assembled and saved.

The 1-vehicle and 2-vehicle crash POI⁽⁻⁾ to the POR solvers seek to minimize the following “figure-of-merit” for each reconstructed crash:

$$J = (y - \hat{y}(\hat{p}))^T W (y - \hat{y}(\hat{p})) \quad (1)$$

where

y is a vector of POI⁽⁻⁾ to the POR motion data (such as positions and delta Vs), depending on the number of vehicles involved,

p is a vector of reconstruction model parameters, which also depends on the number of vehicles involved, and

W is an appropriately sized symmetric matrix representing the relative weightings for errors in each of the elements in y , which are inversely related to the square of the assumed uncertainties.

The figure-of-merit J is minimized using the aforementioned non-linear least squares and Nelder-Mead simplex methods, which are iterative. The non-linear least squares method (Ref 10) involves the numerical computation of the Jacobian matrix of $\partial \hat{y}$ with respect to $\partial \hat{p}$ at each iteration. The simplex method is implemented by the Matlab “fminsearch” function (Ref 11).

It is assumed that each vehicle is neutral steering (i.e., has zero understeer gradient) and the quasi-steady pre-crash equations of motion for each vehicle are therefore (Ref 12).

$$\begin{aligned} \dot{X} &= u \cos \psi - v \sin \psi \\ \dot{Y} &= u \sin \psi + v \cos \psi \\ \dot{\psi} &= r = \frac{u}{l} \delta_w \\ v &= rb \end{aligned} \quad (2)$$

where

X and Y are the coordinates of the vehicle cg in the inertial frame,

ψ is the heading of the vehicle in the inertial frame,

u and v are the longitudinal and lateral components of the vehicle velocity in the vehicle frame,

r is the yaw rate of the vehicle,

δ_w is the average steer angle of the front wheels.

The original AART assumed that the vehicle is initially traveling at a constant speed. If the impact speed is less than the reported travel speed or speed limit, then it is assumed that the driver brakes at a constant deceleration until the point of impact, as illustrated in Figure 2; and that the deceleration depends on the roadway surface conditions as coded in the case data.

It is also assumed that $\dot{\delta}_w(t)$ is a stochastic random (white noise) process (see footnote 1) such that

$$\begin{aligned} E(\dot{\delta}_w(t)) &= 0 \\ E(\dot{\delta}_w(t) \dot{\delta}_w(t + \tau)) &= \delta(\tau) \end{aligned} \quad (3)$$

where $E(x)$ is the expected value of x and $\delta(\tau)$ is the Dirac function. Therefore the assumed steering angle tends to have relatively large low frequency components and small high frequency components necessary to follow the reconstructed path.

For each vehicle, the solution steps comprise estimating the pre-impact velocity time history based on the reported travel speed or speed limit, and impact speed, with pre-impact braking depending on the roadway surface condition if the impact speed is less than the initial speed; constructing an initial estimate for pre-impact trajectory that satisfies equations (2), estimating a trajectory innovation using a Kalman Filter-Smoother (Ref 13), and updating the estimated pre-impact trajectory based on the trajectory innovation.

TECHNOLOGY RELEVANT CASE SPECIFICATION AND CASE SUB-SAMPLING TOOLS - The “technology relevant case specification” and “case sub-sampling” tools formalize the descriptions of the technology relevant crash categories based on the technical description and intent of the ACAT and the case sub-sample selection. The result of applying these tools is a set of criteria in terms of coded variables and values

(e.g., number of vehicles = 1 and collision partner = pedestrian) that describe each ACAT-specific technology relevant category. A list of cases and resulting weightings is then automatically randomly sampled and generated that comprise a representative sub-sample of cases for each technology relevant category, for which scene diagrams existed and geometry and time histories had been reconstructed, for simulation purposes.

The case sub-sampling is accomplished in two steps (Ref 14). First, the weighted cases are replicated n times where n is the integer value of the case weighting factor to create an equivalent intermediate database of unweighted cases. Then, a sub-sample of cases is then randomly sampled from the intermediate database. Each of the sub-sampled cases is equally weighted because each case was sampled with equal probability.

As a result of this random sampling, the resulting 1st and 2nd statistical moments of the numerical data for these cases should therefore be in good agreement with the U.S. accident data (as sampled by NASS). In essence,

- The sample mean (1st moment) tends towards the mean of the original population as $N \rightarrow \infty$ (Strong Law of Large Numbers);
- The sample standard deviation (2nd moment) also tends towards the standard deviation of the original population as $N \rightarrow \infty$.

CRASH AVOIDANCE SIMULATION TOOL - The “Crash Avoidance Simulation Tool” (CAST) (Ref 6) is a unique time domain simulation of the driver, the vehicle (with and without 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 (Refs 15 to 17). The driver model controls a Simulink model of the vehicle, environment, and ACAT. A 3D dynamic display of the virtual world comprising the scene diagram, vehicle, and crash partner is automatically generated. 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 to the vehicle model. The virtual reality display is driven by the Simulink model.

The CAST has a graphical user interface which enables the user to select the desired crash scenarios and driver behaviors (e.g., time delays and open-loop steering and braking commands) to simulate a given case, with and without the ACAT, based on driver behaviors measured in driving simulator experiments. CAST 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 comprises creating a graphical summary of the driver behavior and other time domain outputs. If an impact occurs, an ATB crash simulation is run which estimates the crash delta-V based on the impact conditions; and the injury outcome (i.e., probability of driver fatality or equivalent life units) is estimated from the simulated delta-V's, using a pre-determined empirical model based on the injury vs delta-V data in the NASS/CDS database. Based on these results, calculated for the vehicle with and without ACAT, the effectiveness of the ACAT technology in eliminating crash occurrence and in reducing fatalities in each technology relevant category is then estimated.

Figure 3 illustrates the NASA MIDAS-based driver model, implemented in NASA APEX, comprising long term memory, sensing/perception, working memory, and motor response. Long term memory comprises declarative knowledge and procedural knowledge, such as vehicle steering and speed control procedures. Some of these procedures have vehicle, situation, and behavior specific knowledge (e.g., vehicle-dependant feedback gains and open-loop responses) that it is assumed the driver has “learned” prior to each simulation being run and which is based on experimental data.

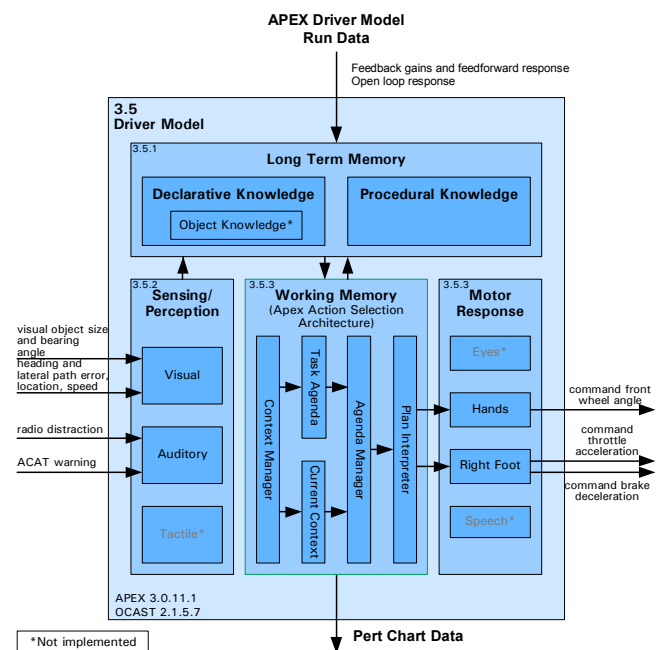


Figure 3 - Block 3.5 – Driver Model

Sensing and perception blocks currently comprise visual and auditory pass-through of visual and auditory information to long-term memory. Visual information includes the visual object size and bearing angle; and the heading and lateral path error, vehicle location (relative to some turn reference point), and speed.

Auditory information comprises a standardized radio-type distraction and ACAT warning.

The working memory block is implemented in the NASA APEX Action Selection Architecture (Refs 15 and 16).

The driver's motor response produces the commanded front wheel angle, throttle acceleration, and brake deceleration. It is assumed that the driver has compensated for and has learned the vehicle steering wheel gain.

The Crash Simulation block estimates the crash delta-V based on the vehicle impact conditions. This block comprises the crash simulation setup, ATB simulation, and post processing. A sub-block automatically creates the ATB simulation input files based on the vehicle impact speeds and geometry. The CAST ATB simulation is similar to the AART ATB simulation described previously. The longitudinal and lateral components of the vehicle crash delta-V's are extracted from the ATB simulation output.

The Injury Outcome Estimator estimates driver casualty in terms of Equivalent Life Units (ELU) and probability of fatality (POF) based on the crash delta-V and the driver restraint use. The ELU is based on the injuries. The estimated ELU and POF functions have the following assumed model form:

$$\left. \begin{matrix} ELU \\ POF \end{matrix} \right\} = \frac{e^z}{1 + e^z} \quad (4)$$

where

$$z = \beta_0 + \beta_{x(-)} \Delta V_{x(-)}^2 + \beta_{x(+)} \Delta V_{x(+)}^2 + \beta_{y(-)} \Delta V_{y(-)}^2 + \beta_{y(+)} \Delta V_{y(+)}^2 \quad (5)$$

and where

$$\Delta V_{i(-)} \triangleq \begin{cases} 0 & \text{if } \Delta V_i \geq 0 \\ \Delta V_i & \text{if } \Delta V_i < 0 \end{cases}, \quad i = \{x, y\} \quad (6)$$

$$\Delta V_{i(+)} \triangleq \begin{cases} \Delta V_i & \text{if } \Delta V_i > 0 \\ 0 & \text{if } \Delta V_i \leq 0 \end{cases}$$

This assumed equation for z provides for different injury and fatality risk in frontal and rear impacts, and left and right impacts; and ellipsoidal type interaction between longitudinal and lateral delta-V. The assumed transformation in eqn (4) models the finite interval of ELU and POF between 0 and 1; and is well suited for logistic regression analysis of dichotomous fatality data as well as scalar ELU data. The estimated values for β

are based on analysis of 1997 to 2002 NASS/CDS data and published models of ELU and POF.

The Technology Effectiveness Estimator estimates the Accident Ratios and Fatality Ratios for each technology relevant crash category based on the simulation results. The Accident Ratio is the expected number of crashes with the ACAT divided by the expected number of crashes without the ACAT. The Fatality Ratio is the expected number of fatalities with the ACAT divided by the expected number of fatalities with the ACAT. Ratios less than 1 are desirable.

FATALITY ANALYSIS SYSTEM - The Fatality Analysis System (Ref 7) is a uniquely powerful, integrated tool for estimating the combined effects of multiple, complementary or redundant ACATs on effectiveness based on technology effectiveness functions, crash scenarios, and retrospective and forecasted data. The technology effectiveness functions describe the accident and fatality ratios (AR, FR) vs technology relevant category criteria. These functions are based on results from CAST or other a-priori knowledge (e.g., published literature and statistical accident data analyses for existing technologies such as side airbags, Ref 18) expressed as mathematical functions of the relevant human, vehicle, environment and accident factors. Retrospective data sources include FARS and GES accident databases (Refs 1 and 4) and R.L. Polk & Co. National Vehicle Population Profile® vehicle registration data (Ref 5). Forecasted data sources include estimated vehicle retention/scrappage rates (Ref 19).

The FAS interactive software tool uses a systems model to estimate relative changes in accident and fatality rates based on changes in vehicle, ACAT, driver, and environment factors, in order to predict future accident and fatality rates for existing and future make-model-year vehicles, based on retrospective accident and fatality rates for similar existing make-model-year vehicles. The systems model estimates the number of accidents ($\hat{a}$) and fatalities ($\hat{f}$) that occur in the crash scenarios.

Information about existing make-model-year vehicles in prior years are estimated based on retrospective data. Prior accident and fatality rates per vehicle-registration year (A/VRY and F/VRY) are computed, based on the numbers of accidents (A), fatalities (F), and vehicle-registration years (VRY). The past human and environmental factors such as driver age and gender are estimated based on GES data.

Information about existing and future make-model-year vehicles are estimated, as well as future human and environmental factors, such as age and gender, based on trends observed in past vehicles.