PROGRESS REPORT ON EVALUATION OF A PRE-PRODUCTION HEAD-ON CRASH AVOIDANCE ASSIST SYSTEM USING AN EXTENDED "SAFETY IMPACT METHODOLOGY" (SIM)

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ABSTRACT

NHTSA reported that in 2006, 9.8% of fatal crashes and 4.1% of injury crashes were head-on crashes (Traffic Safety Facts 2006). Honda has developed a pre-production Head-on Collision Avoidance Assistance System (H-CAAS) intended to detect, warn and mitigate specific crash types, including a severe, primary crash type in which the subject vehicle drifts laterally into the path of an on-coming vehicle, typically as a result of driver inattention (due to, e.g., distraction, drowsiness or alcohol impairment). The goal of this research is to estimate H-CAAS safety benefits, at a national level, focusing on both primary and secondary technology relevant crash types (TRCT's). This paper provides a progress report on the evaluation of US-level safety benefits of H-CAAS, based on the Safety Impact Methodology (SIM) tool developed by Honda and DRI and extended under Cooperative Agreements with NHTSA, as well as a description of recent extensions of the SIM itself. The SIM developed by Honda and DRI applies computer simulations of the driver-vehicle-environment, involving time-space relationships between the subject vehicle and a collision partner, and predicts crash, injury and fatality outcomes, with and without the Advanced Collision Avoidance Technology (ACAT) countermeasure, for a sample of NASS/CDS cases; and a systems model to extend the sample results to the national level, in order to estimate effectiveness and safety benefits of the countermeasure in terms of crash, injury, and fatality reductions. Data sources include NHTSA FARS, NASS/CDS, GES, and PCDS accident data; vehicle parameter and exposure data (e.g., from Polk vehicle registration data); and countermeasure-specific data from objective tests. For the H-CAAS evaluation, results from previous driving simulator objective tests involving n=9 distracted drivers and n=10 drowsy drivers were used to parameterize, calibrate and validate the SIM tool. The SIM was then used to estimate US-level safety benefits of H-CAAS. Results of extending the SIM include the addition of a simplified head-on accident reconstruction module which takes into account the generally large closing speeds, approximately 180 degree relative heading angles and the relatively small lateral offsets and drift rates of sampled head-on crashes; and substantial upgrades of the Guided Soft Target collision partner test system, in terms of a more realistic 2nd generation soft body and greater operating speed and range. The extensions to the SIM have resulted in a more robust, accurate and widely applicable suite of tools for estimating safety benefits of advanced safety technologies at a national level. A limitation of the SIM tool is that the uncertainty bounds associated with the estimates include some but not all sources of uncertainty.

INTRODUCTION

NHTSA has reported that 9.8% of fatal crashes and 4.1% of injury crashes in 2006 were head-on crashes [1]. Therefore Honda has developed a pre-production Head-on Collision Avoidance Assistance System (H-CAAS) to address this crash problem. The H-CAAS is intended to detect, warn and mitigate specific crash types, including a severe, primary crash type in which the subject vehicle drifts laterally into the path of an on-coming vehicle, typically as a result of driver inattention (due to, e.g., distraction, drowsiness or alcohol impairment).

In parallel, Honda and Dynamic Research Inc. (DRI) have been developing and applying Safety Impact Methodology (SIM) tools to evaluate the effectiveness and benefits of various advanced technologies in avoiding and mitigating specific types of crashes [2][3]. These methods were recently extended and refined under two Cooperative

Agreements with NHTSA, entitled Advanced Crash Avoidance Technologies (ACAT) series I and II. The objectives of the ACAT-I program were: 1) to develop a standardized Safety Impact Methodology (SIM) tool to evaluate the effectiveness of advanced technologies in mitigating specific types of vehicle crashes; and 2) to develop and demonstrate objective tests that are used in the SIM to verify the safety impact of a real system. The objectives of the ACAT-II program were: 1) to extend the previously developed Safety Impact Methodology (SIM) tool used to evaluate the effectiveness of advanced technologies in avoiding or mitigating specific types of vehicle crashes; and 2) to further define, develop and demonstrate objective tests that are used in the SIM to verify the safety impact of a real system.

Final results from the ACAT-I program were reported in [4], with mid-term progress and final results summarized in [5] and [6].

This paper provides a mid-term progress report on the ACAT-II research program to refine the Honda-DRI ACAT-I SIM tool and to use this tool to estimate the H-CAAS safety benefits, at a US level. The final results from the ACAT-II program are planned to be reported in [7].

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 (e.g., [8]);
2. Using these databases, reconstruct the pre-crash, crash, and post-crash vehicle trajectories and driver control time histories of real crash and non-crash cases 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 reconstructed time histories to specify each of the selected tests;
7. Use a Guided Soft Target (GST) as the collision partner (CP) in the Track tests to follow precisely the reconstructed CP trajectory [9];
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 programs, 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

NHTSA's Safety Impact Methodology framework [10] 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 four main areas indicated by the box color coding (i.e., red, yellow, blue, and purple). Of the 22 different Functions, 11 Functions were implemented by the Honda-DRI SIM tool (Figure 2), the other 11 Functions would be accomplished "off-line".

Overview of the Honda-DRI SIM

The Honda-DRI SIM comprises four main modules as illustrated in Figure 2. The color coding of each module in Figure 2 corresponds to the color shading of the 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.

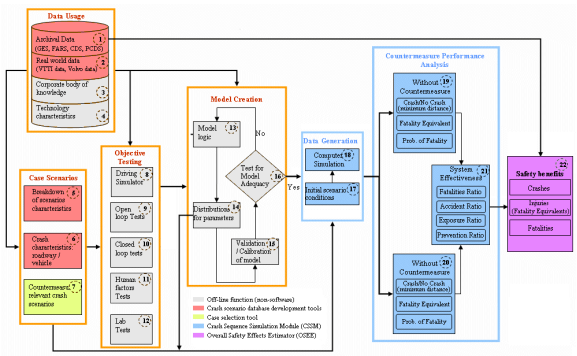

Figure 1. NHTSA ACAT SIM Framework [10]

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

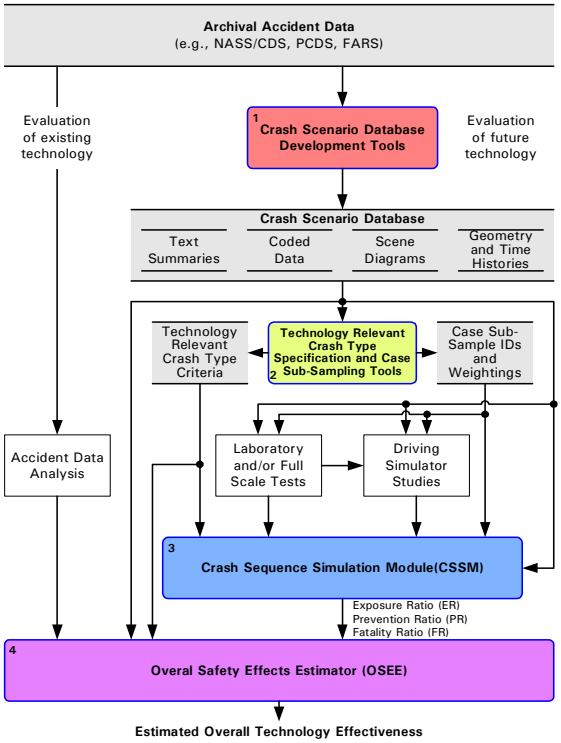

Figure 2. Honda-DRI SIM Tool Modules

Crash Scenario Database Development Tools (Module 1)

There are three main steps that are used to construct the crash scenario database from the archival US DOT accident data (Module 1) as illustrated in Figure 3. 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 [11][12][13][14]. The resulting coded dataset 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 website for each of the CDS and PCDS crash cases. Finally, the geometry and trajectory 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.

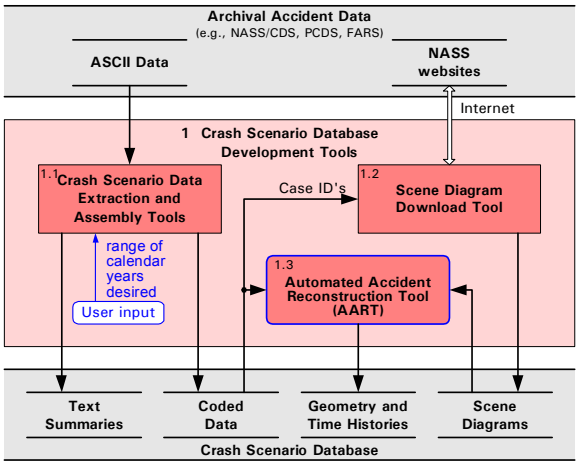

Figure 3. Crash Scenario Database Development Tools

Automated Accident Reconstruction Tool (Module 1.3)

The unique AART 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 an interactive Graphical User Interface (GUI) which enables the user to digitize the pre-impact, point-of-impact, and point-of-rest locations for the crash involved vehicles. Specialized versions of the AART were developed for 1) NASS CDS and PCDS crashes involving one or two vehicles, or one vehicle with a pedestrian, with 3-dof (planar) motions and a single impact event; 2) a simplified AART for

head-on crash cases that are assumed or known to involve a low lateral acceleration drift; and 3) a version to reconstruct the subject vehicle trajectories in VTTI near-crash cases based on the available GPS, speed, and acceleration data.

The AART 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-impact 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 variable; 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 reconstructed using the WinSMASH Damage Algorithm based on vehicle damage information [15] (provided sufficient information is available) and/or fit to the US DOT Crash Victim Simulator/US Air Force Articulated Total Body (ATB) program [16][17]. The ATB program can then be used to simulate and predict changes in the crash Delta-V based on changes in the crash geometry and vehicle speeds;
- 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 illustrated in Figure 4.

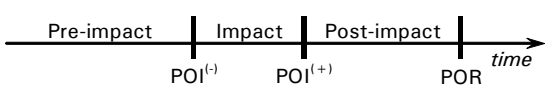

Figure 4. Assumed Crash Phases for Vehicle Dynamics

It is also assumed that the longitudinal vehicle acceleration and corresponding speed vs time can be separated into phases as illustrated in Figure 5. It was assumed that the longitudinal pre-crash acceleration during pre-impact phases can be approximated by up to three different constant acceleration levels which are functions of the coded CDS data for "attempted avoidance maneuver." "pre-event movement", and "road-surface condition." It is also assumed that the initial speed is either the "police reported travel speed" if it is known, or the "speed limit" plus 7 km/h if the police reported travel speed is unknown (based on data in [18]).

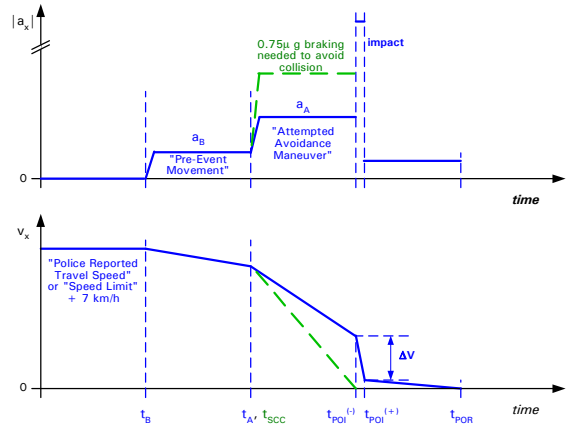

Figure 5. Assumed speed profile (NASS AART)

The change in acceleration is assumed to occur at times t_B and t_A as illustrated in Figure 5. The t_A time nominally corresponds to the Safety Critical Conflict time (t_{scc}). The t_{scc} was defined for the purpose of this tool as the time at which if the driver began braking and/or steering at 0.75 g times the coefficient of friction (mu) then the crash could be avoided.

<u>Pre-crash Phase</u> It is assumed during the pre-crash phase that each vehicle is neutral steering (i.e., has zero cornering compliance and understeer gradient) and the quasi-steady equations of motion for each vehicle are therefore [19]:

$$\begin{aligned} \dot{X} &= u\cos\psi - v\sin\psi \\ \dot{Y} &= u\sin\psi + v\cos\psi \\ \dot{\psi} &= r = \frac{u}{a+b+u^2K_u}\delta_w \end{aligned} \qquad (1.)$$

and

$$v = u\beta \approx r\left(b - u^2 D_r\right) \qquad (2.)$$

where

$$K_u = D_f - D_r \qquad (3.)$$

and where

- X and Y are the coordinates of the vehicle cg in the inertial (ground) 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,
- a and b are the distances between the vehicle c.g. and the front and rear axles respectively,
- D_f and D_r are the front and rear cornering compliances, and
- K_u is the understeer gradient.

It is furthermore assumed for the current evaluation that the vehicles have neutral steering with no lateral slip, therefore D_f, D_r and K_u are zero.

It is also assumed that the time derivative of the front wheel angle ($\dot{\delta}_w(t)$) is a stochastic random (white noise) process such that

$$\begin{aligned} E\left(\dot{\delta}_w(t)\right) &= 0 \\ E\left(\dot{\delta}_w(t)\dot{\delta}_w(t+\tau)\right) &= \delta(\tau) \end{aligned} \qquad (4.)$$

where $E(x)$ is the expected value of x and $\delta(\tau)$ is the Dirac function. This assumption means that the front wheel angle has a $1/s^2$ power spectral density, which is typical of human operator control activity. Therefore the assumed steering angle tends to have relatively large low frequency components and small high frequency components necessary to follow the reconstructed path.

Impact Phase The impact phase is assumed to be a single impact event beginning at $POI^{(-)}$ and ending at $POI^{(+)}$, which is ultimately modeled by a time-domain ATB crash simulation. Therefore the time between $POI^{(-)}$ and $POI^{(+)}$ is typically a small finite value, and the distance the vehicles travels in this period is also a small finite value. The ATB simulation also assumes that each vehicle has a single mass segment with an 8th order hyper-ellipsoid shape (i.e., rectangular solids with slightly rounded corners). All vehicles and objects are constrained to move without vertical, pitch, or roll degrees-of-freedom.

The 3-DOF AART also closely fits the Delta-Vx and Delta-Vy results to the WinSMASH Delta-V values in the CDS database (i.e., a "Delta-V Constraint"), provided there is sufficient coded information (e.g., damage data) to calculate the WinSMASH collision force moment arm (h) as illustrated in Figure 6. The WinSMASH damage algorithm assumes that: the time between $POI^{(-)}$ and $POI^{(+)}$ is very short and can be neglected, and the distance the vehicles travel in this period is small and can be neglected, and each vehicle is rectangular in rectangular plan view. It is further assumed that the net effects of the differences in the ATB and WinSMASH assumptions are relatively small, and can be addressed by varying the vehicle-vehicle contact friction and coefficient-of-restitution in the ATB simulation to fit the WinSMASH result. This fitting process is accomplished in a "batch" preprocessor for a user selected range of calendar years. Detailed equations are in [7].

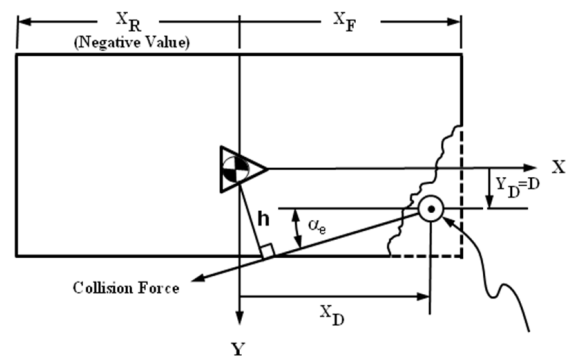

Figure 6. WinSMASH Damage and Collision Force Moment Arm

Post-Impact Phase It is assumed that the tires of each vehicle after impact separation are sliding without rolling (e.g., locked or damaged wheels or suspension) during the post-impact phase, resulting in constant horizontal forces and yaw moments acting on the vehicle. Therefore the vehicle has constant translational and angular deceleration from $POI^{(+)}$ to POR (i.e., the translational and angular velocities after impact decrease to zero at a constant rate).

3-DOF NASS AART – Based on the assumed equations of motion for each phase, the solution steps are as follows:

1. Fit an initial "reference trajectory" for the vehicles ($\mathbf{x}_0(t)$) comprising a pre-impact phase with constant steer angles and speeds

(i.e., the $\delta_{w,0}(t)$ for each vehicle are constant, resulting in constant turn radius for each vehicle with neutral steering), impact phase (using the pre-computed ATB results from the WinSMASH/ATB batch preprocessor if available), and post-impact phase.

2. Determine the linearized state-space equations of motion of the vehicles ($\mathbf{x}(t)$) relative to the reference trajectory $\mathbf{x}_k(t)$, i.e.,

$$\Delta\mathbf{x}_k(t) = \mathbf{A}_k(t)\Delta\mathbf{x}_k(t) + \mathbf{B}_k(t)\Delta\dot{\delta}_{w,k}(t) \qquad (5.)$$

where, $\Delta\mathbf{x}_k(t) \triangleq \mathbf{x}(t) - \mathbf{x}_k(t)$, $\Delta\delta_{w,k}(t) \triangleq \delta_w(t) - \delta_{w,k}(t)$, and k is an iteration number.

3. Estimate a trajectory innovation ($\hat{\delta}_w(t), \Delta\hat{\mathbf{x}}_k(t)$) using a Kalman Filter-Smoother with the pre-impact, POI, and POR locations as "measurements" [20].
Update the reference trajectory based on the trajectory innovation according to the equations:

$$\hat{\mathbf{x}}_{k+1}(t) = \hat{\mathbf{x}}_k(t) + \alpha_k \Delta\hat{\mathbf{x}}_k(t) \qquad (6.)$$

$$\hat{\delta}_{w_{k+1}}(t) = \hat{\delta}_{w_k}(t) + \alpha_k \Delta\hat{\delta}_{w_k}(t) \qquad (7.)$$

where α_k is a relaxation factor for the k th iteration.

4. Repeat steps 2 through 4 for 10 iterations.
5. Estimate the safety critical conflict time and pre-impact speed profile based on the reconstructed vehicle paths, impact speeds, and coded CDS data (e.g., attempted avoidance maneuver, road surface condition), as illustrated in Figure 5.

Simplified H-CAAS AART – One of the requirements of the AART is that it should reconstruct plausible crashes. It was found that the 3-DOF AART tended to reconstruct head-on crashes with large lateral accelerations that were above the perceptual thresholds for typical drivers and likely to alert an inattentive driver before the crash. This is attributed to the typical placement of the vehicle symbols on the scene diagrams, which appeared to underestimate the pre-crash drift travel distance, and therefore overestimate the lateral drift acceleration. Therefore the pre-crash lateral g levels reconstructed by the 3-DOF AART, using the digitized pre-crash vehicle positions, were not considered plausible in head-on crashes involving low lateral drift accelerations which are typically assumed to occur in inattentive driver "drifting" into other lanes (i.e., they are sub-perceptual threshold).

The Simplified H-CAAS AART was therefore developed with the key assumption that the lateral acceleration is 0.05 g. This value was chosen because it is not noticeable kinesthetically in the absence of visual cues [21]. This small lateral drift acceleration was modeled as a constant external force acting on the vehicle, which would represent a crowning or super-elevation of the roadway, inadvertent steer input, crosswind, or any number of other events
The Simplified H-CAAS AART in effect reconstructs head-on crashes with 1 degree-of-freedom because the lateral acceleration and yaw rate are assumed to be constant during such an inattentive drift. This AART uses the subject vehicle's intended path in conjunction with the point-of-impact to determine the drift trajectory, as illustrated in Figure 7.

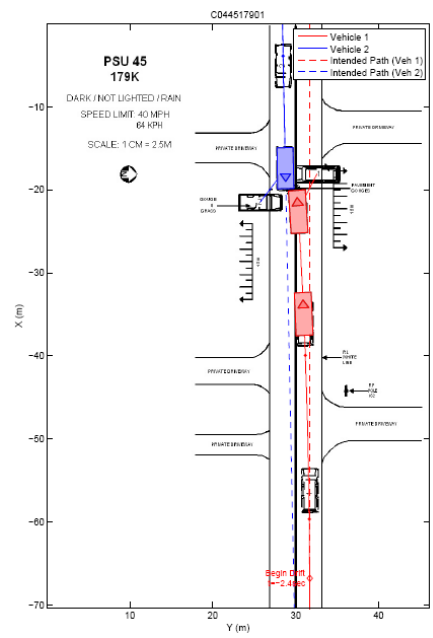

Figure 7. Scene Diagram with Intended Path and Subject Vehicle Drift using the Simplified H-CAAS AART

The Simplified H-CAAS AART determines the impact speed of the vehicles by fitting the longitudinal Delta-V, points-of-impact, and points-of-rest.

This version of the AART also estimates the pre-impact speeds of the vehicles using the data, in order of priority, listed in the second column of Table 1. The Simplified H-CAAS AART uses different data priorities in order to obtain more plausible timing of

the collision partner driver emergency braking in response to the subject vehicle drifting across the lane boundary. The main difference from the 3-DOF AART algorithm is the assumption that each vehicle was traveling at the coded travel speed (if available) or at the speed limit plus 7 km/h is more reliable than the coded avoidance maneuver or pre-event movement.

Table 1.
3-DOF and Simplified H-CAAS AART Data Priority

3-DOF AART Data Priority Order	H-CAAS AART Data Priority Order
1. A crash occurred	1. A crash occurred
2. Inattentive driver or other cause	2. Inattentive driver or other cause
3. Delta-V	3. Delta-V
4. POI and POR locations	4. POI and POR locations
	5. Initial speed is: a) coded travel speed or b) speed limit + 7 km/h
5. Coded avoidance maneuver	6. Coded avoidance maneuver
6. Coded pre-event movement	7. Coded pre-event movement
7. Initial speed is: a) coded travel speed or b) speed limit + 7 km/h	

Promoting the initial speed data above the coded avoidance and pre-event movement allows the AART to reconcile apparent inconsistencies in the coded data by changing the assumed acceleration levels for the pre-event and avoidance maneuvers.
The Simplified H-CAAS AART has the ability to reconstruct head-on crashes where the vehicles are originally traveling on either a straight or curved path. However, the 3-DOF AART is recommended for reconstruction of cases with more complicated vehicle trajectories.

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

The "technology relevant case specification" and "case sub-sampling" tools illustrated in Figure 8 enable the user to formalize the descriptions of the technology relevant crash categories based on the technical description and intent of the ACAT and select a sub-sample of cases for simulation and testing purposes. The result of applying these tools is a set of criteria in terms of NHTSA Universal Descriptors [22] and other coded variables and vehicle specific values (e.g., the Critical Precrash Event= "This vehicle traveling over the lane line on left side of travel lane" and the NASS Accident Type = "Same Trafficway Opposite Direction") 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.

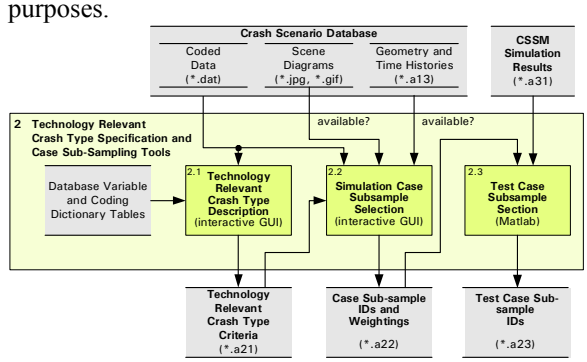

Figure 8. Technology Relevant Crash Type Specification and Case Sub-Sampling Tools

Crash Sequence Simulation Module (Module 3)

The "Crash Sequence Simulation Module" (CSSM) illustrated in Figure 9 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.

One of the main elements of the CSSM is the NASA MIDAS-based driver model [23], which is indicated as Module 3.6 in Figure 9. This driver model comprises long term memory, sensing/perception, working memory, and motor response functions, as illustrated in Figure 10 and implemented in NASA's APEX programming environment [24]. 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.

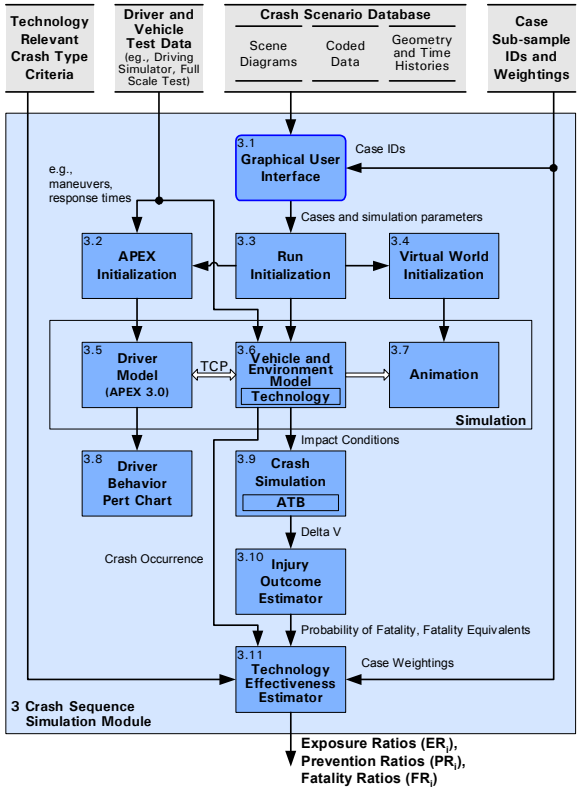

Figure 9. Crash Sequence Simulation Module

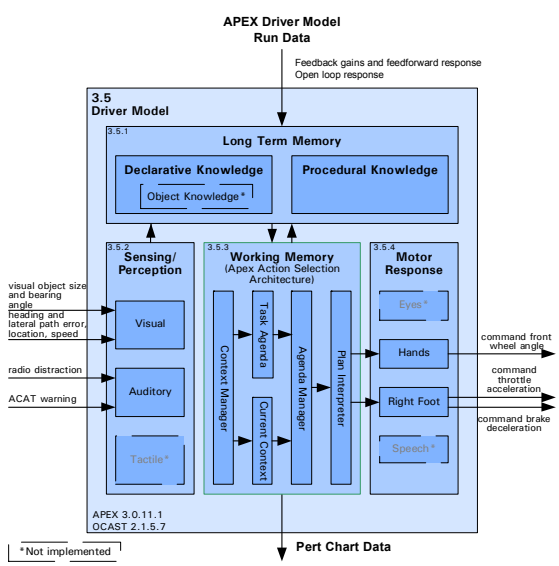

Figure 10. NASA MIDAS-based Driver Model

Other CSSM submodules are the

- ATB crash simulation to compute the crash Delta-V based on the impact speeds and geometry (Module 3.9);
- Injury Outcome Estimator to estimate the Subject Vehicle (SV) and CP driver injury Fatality Equivalents (FE) and Probability of Fatality (POF) (Module 3.10); and a
- Technology Effectiveness Estimator (3.11)

The Technology Effectiveness Estimator estimates the Exposure, Prevention, Injury and Fatality Ratios (ER, PR, IR, and FR) for each technology relevant crash category based on the simulation results as follows:

$$ER_i = \frac{\tilde{S}_{W_i}}{\tilde{S}_{WO_i}} \qquad (8.)$$

$$ER_i \times PR_i = \frac{\tilde{A}_{W_i}}{\tilde{A}_{WO_i}} \qquad (9.)$$

$$ER_i \times PR_i \times IR_{p,i} = \frac{F\tilde{E}_{p,W_i}}{F\tilde{E}_{p,WO_i}} \qquad (10.)$$

$$ER_i \times PR_i \times FR_{p,i} = \frac{\tilde{F}_{p,W_i}}{\tilde{F}_{p,WO_i}} \qquad (11.)$$

where

$\tilde{S}_{W_i}$ and $\tilde{S}_{WO_i}$ are the estimated number of conflicts with and without the ACAT,

$\tilde{A}_{W_i}$ and $\tilde{A}_{WO_i}$ are the estimated number of crashes with and without the ACAT,

$F\tilde{E}_{p,W_i}$ and $F\tilde{E}_{p,WO_i}$ are the estimated number of injury Fatality Equivalents for person type "p," with and without the ACAT, and

$\tilde{F}_{p,W_i}$ and $\tilde{F}_{p,WO_i}$ are the estimated number of fatalities for person type "p," with and without the ACAT,

ER_i is the estimated Exposure Ratio,

PR_i is the estimated Prevention Ratio,

$IR_{p,i}$ is the estimated Injury Ratio for person type "p,"

$FR_{p,i}$ is the estimated Fatality Ratio for person type "p,"

for TRCT "i." Ratios less than 1 are desirable.

The p person types are the subject vehicle driver and collision partner person, which is either the driver of the other vehicle or a pedestrian (Note: the H-CAAS does not address pedestrian crashes).

In the current example evaluation, it was assumed that the H-CAAS does not affect the number of conflicts (i.e., it is not intended to be a conflict avoidance system), and therefore $ER_i = 1$.

The number of crashes with and without the ACAT in each TRCT was estimated from the CSSM Driver-Vehicle-ACAT-Environment simulation results according to the equations:

$$\widetilde{A}_{W_i} = \sum_{k \in \{TRCT_i\}} w_k \left(\sum_j P_{W_j} n_{W_{k,j}} \right) \qquad (12.)$$

$$\widetilde{A}_{WO_i} = \sum_{k \in \{TRCT_i\}} w_k \left(\sum_j P_{WO_j} n_{WO_{k,j}} \right) \qquad (13.)$$

where

- w_k is the US level case weighting for the *k*th simulated crash scenario,
- P_{W_j} and P_{WO_j} are the probabilities of the *j*th driver-behavior combination occurring (e.g., Driver "273a") with and without the ACAT, determined by Driving Simulator test results,
- $n_{W_{k,j}}$ and $n_{WO_{k,j}}$ are the crash outcomes in the *k*th crash scenario with and without the ACAT for the *j*th driver-behavior combination.

This module is described in further detail in [4][7].

Overall Safety Effects Estimator (Module 4)

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 [3]. The technology effectiveness functions describe the exposure, prevention, and fatality ratios (ER, PR, FR) vs technology relevant category criteria. 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 [25]) expressed as mathematical functions of the relevant human, vehicle, environment and accident factors. Retrospective data sources include FARS and GES accident databases [11][14] and R.L. Polk & Co. National Vehicle Population Profile® vehicle registration data [26].

The results from the OSEE are used to estimate the size of the problem, technology effectiveness, and benefits according to the equations [22]:

$$B = N_{WO} - N_W \qquad (14.)$$

$$B = \sum_i B_i = \sum_i N_{WO_i} \times E_i \qquad (15.)$$

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;
- 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 the 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.
- 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 of the SIM in the ACAT-II Program

The Honda-DRI SIM tools described herein includes several modifications and refinements as part of the NHTSA-DRI-Honda ACAT-II program. These modifications and refinements include initially planned extensions and additional extensions

identified during the program in order support the H-CAAS evaluation.

The refinements that were made to the crash scenario database development tools in Module 1 include:

- Extending the data extraction modules to support more recent data (e.g., 2007 calendar year CDS data);
- Add vehicle parameter data for more recent calendar year vehicles;
- Add Universal Descriptor variables for TRCT description;
- Add "DOCTRAJ" and other variables to the crash scenario dataset, as needed for the reconstructable case criteria;
- Calculate and add the WinSMASH moment arm and other supporting variables to the crash scenario dataset, as needed for the "Delta-V constraint."

Refinements made to the AART (Module 1.3) include:

- Add "DOCTRAJ" check to the reconstructable case criteria;
- Develop a "Delta-V constraint" preprocessor for the NASS 3-DOF AART based on WinSMASH Delta-V, moment arm; integrate solution into the 3-DOF AART; and numerous other minor refinements;
- Develop a new Simplified H-CAAS AART in order to reconstruct head-on crashes involving inadvertent drifting;
- Expansion of Safety Critical Conflict (SCC) Time to include braking and/or steering maneuvers.

Refinements made to Module 2 include:

- Adding support for Universal Descriptors

Refinements made to the CSSM (Module 3) include:

- Extending the vehicle steering model to include steering wheel torque
- Implemented driver behavior data for drowsy and/or impaired drivers;
- Implemented an unintentional lateral drift as determined by the H-CAAS AART
- Added a driver "intended path" feedback control recovery phase after the avoidance maneuver.

Refinements made to the OSEE (Module 4) include:

- Update FARS and GES data to the 2008 calendar year;
- Update vehicle parameters for newer model year Honda and Acura vehicles;
- Develop an MS Excel workbook to extend the OSEE modeled fleet results for a given model year and calendar year to the entire US light passenger vehicle fleet in the same calendar year; and to estimate the technology effectiveness by H-CAAS TRCT and by non-technology specific crash types. (Also used in ACAT-I).

ADVANCED TECHNOLOGY AND SAFETY AREAS THAT THE H-CAAS ADDRESSES

The Head-on Crash Avoidance Assist System (H-CAAS) illustrated in Figure 11 is an active safety technology that automatically predicts particular types of head-on collisions, warns the driver, and applies gentle steering torque in order to help the driver to avoid the collision, as illustrated in Figure 12. The current speed, brake pressure, steering angle, steering torque, and yaw rate of the driver's vehicle are used in combination with radar data giving the position of other objects and vehicles in the environment, to determine whether a collision seems imminent.

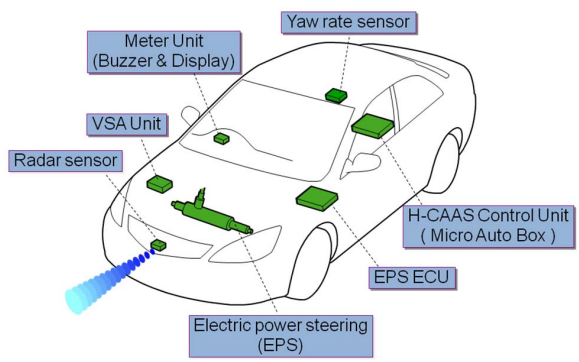

Figure 11. H-CAAS System Configuration

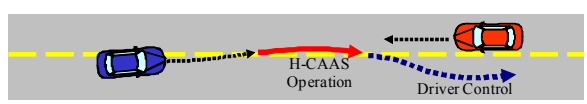

Figure 12. Operation of the Proposed H-CAAS

The operation scenario for the H-CAAS is illustrated in Figure 13. The system differentiates between what it estimates to be intentional driver actions and what it estimates to be unintentional "drifting" of the Subject Vehicle. If the Subject Vehicle begins drifting left into opposing traffic, possibly as the result of inattentive (e.g., distracted, drowsy and/or impaired) driving, and if an oncoming vehicle is sensed, then the H-CAAS applies a small steering

torque to the right (away from opposing traffic) and provides an audible sound, both of these being intended to warn the driver, and which cannot directly control the vehicle. The driver then reacts to these warnings and steers the vehicle back onto its intended path in order to avoid the collision. The H-CAAS also provides steering torque to assist the driver's avoidance maneuver. Note that the system does not operate for drifting rightward into opposing traffic, which is not typical in the US.

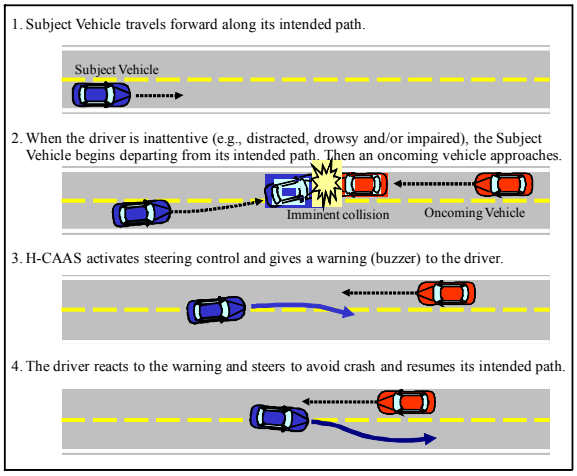

Figure 13. Proposed H-CAAS Operation Scenario

In addition to the steering torque and warnings (audible, visual, and tactile), the H-CAAS can apply automatic braking using an integrated Head-on Collision Mitigation Braking System (H-CMBS). The H-CMBS is a part of the H-CAAS and will be treated as an integrated feature of the H-CAAS. The H-CMBS is designed to apply braking, when it is determined that a collision cannot be avoided, in an effort to reduce the impact speed of the Subject Vehicle.

Note that the H-CAAS is still undergoing pre-production tuning and testing. The specification and performance of the production system may vary from the settings of the pre-production system being evaluated in this project.

For this evaluation the Honda H-CAAS designers have identified one Primary and six Secondary Technology Relevant Crash Types (TRCTs) in terms of coded database variables for which the system is expected to have some benefit. All of the H-CAAS TRCTs are crashes involving:

- two vehicles,
- the Weather is not Snow,
- the Road Condition is not Ice,
- the Initial Speeds of the subject vehicle (SV) and collision partner (CP) (if known) are both greater than or equal to 30 km/h,
- the Attempted Avoidance Maneuver of the subject vehicle is any except no driver present,
- the NASS Accident Type is Same Traffic Way, Opposite Direction, and
- any First Harmful Event.

The Primary TRCT is further specified as:

- the SV Movement Prior to the Critical Event is going Straight, and
- the Critical Precrash Event is the SV traveling over the lane line on the left side of the travel lane.

The six secondary TRCTs are similar to the primary TRCTs, but have more allowable coded values for the SV Movement Prior to the Critical Event, and the Critical Precrash Event, as described in [7].

OBJECTIVE TESTS FOR PREDICTING SAFETY BENEFITS

This section provides an overview of the innovative objective tests proposed for the purposes of ACAT SIM model parameterization, calibration and validation.

Test Case Selection Criteria

The objective of the Driving Simulator and Track tests is to parameterize, calibrate and validate the driver, vehicle and ACAT models over the range of conditions for which the ACAT is expected to function and to be effective. This is accomplished by selecting test cases from within each primary TRCT. The test case selection criteria for driver-not-in-the-loop and driver-in-the-loop tests are based on the value of several key variables at the Safety Critical Conflict time as described in [4] and [5]. However, for the H-CAAS evaluation, the definition of the Safety Critical Conflict time was extended to include steering and braking, such that it is defined herein to be the last time in the period before impact that the subject vehicle can brake and/or steer at 0.75 g x the coefficient of friction (mu) of the road surface and either avoid the collision or stop.

Description of Objective Tests

There are 3 categories of objective tests, each of which is designed to provide the information needed for the evaluation of the ACAT (Table 2). These

objective tests include laboratory tests, vehicle tests, Track tests, and Driving Simulator tests. For the H-CAAS evaluation, the Driving Simulator test data from a previous study of a similar technology were used.

Table 2.
Summary of Categories, Purposes and Approximate Number of Tests

Category of test	Type of test	Facility	Key indices to be measured	Number of Tests
ACAT Warning	Compo-nent	Lab	Warning locations, magnitudes and spectra	10 tests (5 luminance, 3 audible, 15 steer pulse tactile, 2 safety belt pretension)
Vehicle	Compo-nent	Lab	Vehicle dimensions, weight, etc.	3 tests[a]
	Driver-not-in-The-loop	Track	Vehicle response to driver controls	37 tests[a]
Driver-Vehicle-ACAT	Driver-in-the-loop	Driving Simulator	Typical drivers response delays and magnitudes	20 typical drivers x 5 conditions x 3 repeats = 300 tests

Laboratory Test – A series of laboratory tests were conducted for the ACAT-I program to measure the characteristics of the ACAT warnings as they are experienced by a vehicle driver during a potential conflict event. The results of these tests were used to calibrate and validate the driving simulator setup, as well as to provide parameters for the CSSM warning and display model that is sensed by the CSSM driver model. These tests include audible, visual, and tactile warning tests. These tests are further described in [4].

Vehicle Tests – These tests include vehicle parameter tests, which are designed to measure the vehicle parameters including mass, wheelbase, track, length, and longitudinal CG location. The vehicle tests also include vehicle dynamics tests, which are used measure the vehicle response characteristics to various driver and ACAT inputs. For the H-CAAS evaluation, these tests were expanded to include measurements of steering torque as a function of vehicle speed and steering wheel angle. These tests are further described in [4] and [7].

Track Tests – These tests would typically include driver-not-in-the-loop and driver-in-the-loop test. Driver-not-in-the-loop tests are vehicle/ACAT tests which are used to calibrate the Driving Simulator models. Driver-in-the-loop tests are driver/vehicle/ACAT tests which measure the expert driver's response to the ACAT and are used to calibrate the Driving Simulator. For the H-CAAS evaluation, this testing was not necessary to accomplish because there were no H-CAAS Driving Simulator tests to calibrate. However, the foam vehicle body of the Guided Soft Target (GST) test system was refined to achieve a more realistic vehicle form as show in Figure 14. In addition, the associated inter-vehicle communications network was upgraded so as to have a greater operational range, to at least 1 km.

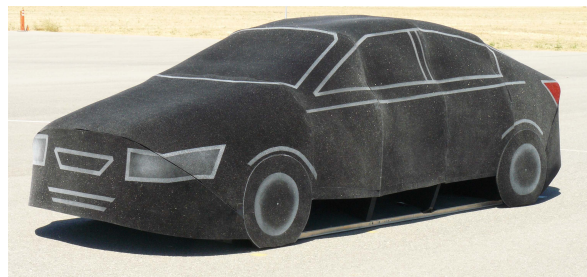

Figure 14. Guided Soft Target Foam Vehicle Body and Dynamic Motion Element

Driving Simulator Tests – In lieu of new Driving Simulator testing based on H-CAAS specific scenarios, Driving Simulator data from a previous study were used to generate driver parameters for use in the CSSM. Honda R&D Company, Ltd. made available the test data and results of a previous Driving Simulator study (Figure 15) for a prototype Collision Avoidance Assist System (CAAS) which operates in a manner similar to H-CAAS and which considered the effects on both distracted drivers and drowsy drivers. Since the CAAS and H-CAAS systems are very similar, the previous Driving Simulator study provided the best available data for identifying emergency driving parameters for use in the CSSM.

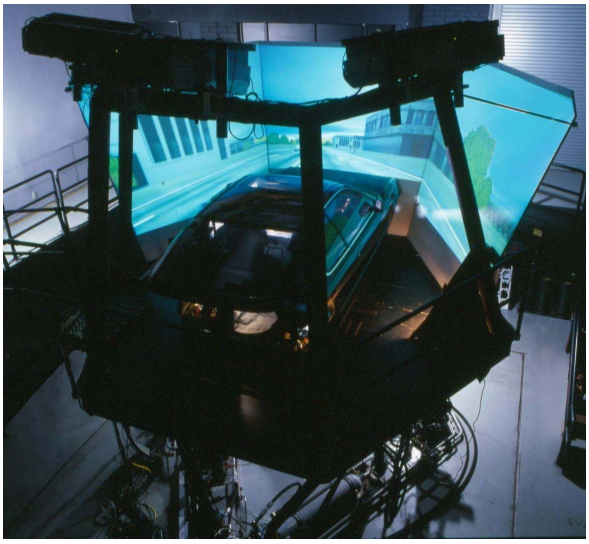

Figure 15. DRI Driving Simulator

The CAAS Driving Simulator study consisted of a sample of 20 typical driver participants. Half of the participants were in the "distracted" driver group and the other half were in the "drowsy" driver group. Both distracted and drowsy driver participants experienced the same conflict scenario, in which the subject vehicle is leaving the lane into oncoming traffic, on a trajectory which would lead to a head-on collision. This lane departure was induced by instantaneously re-positioning the subject vehicle while the participant was inattentive. The CAAS operation would then alert the driver to the impending collision and the driver would react accordingly as illustrated in Figure 16.

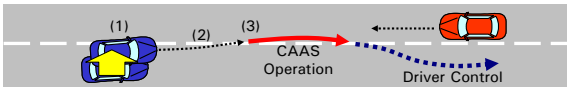

Figure 16. CAAS Conflict Scenario

<u>Driver Behavior Model Parameter Extraction</u> – The emergency braking and steering maneuvers for the Driving Simulator participants were parameterized in order to implement them into the CSSM in a repeatable manner. This was accomplished by first parameterizing the braking and steering maneuvers as illustrated in Figure 17 and Figure 18. The typical steering emergency maneuver consisted of an emergency steering response and then a recovery phase during which the driver re-positioned the vehicle in the center of the initial travel lane. This response is the reason for the asymmetric steering profile in Figure 18.

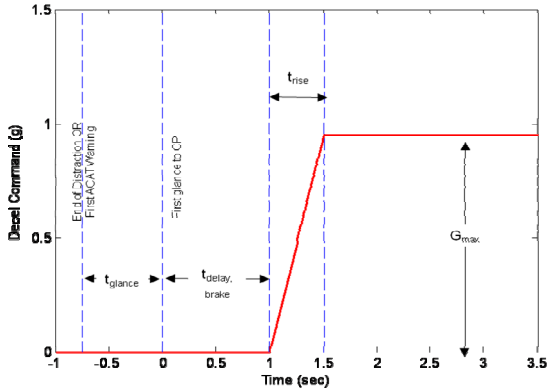

Figure 17. Parametric Form of the Assumed Driver Emergency Braking Procedure

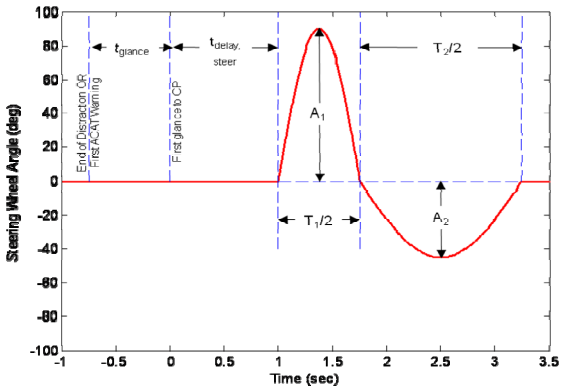

Figure 18. Parametric Form of the Assumed Driver Emergency Steering Procedure

After the responses were parameterized, the responses for the first two valid exposures for each participant were selected to be used in the H-CAAS evaluation. An exposure was classified as invalid if the participant glanced at the roadway before the CAAS warning, or if the parameterized fit was poor ($r^2 < 0.85$). If a driver did not have two valid exposures, the results from that driver were not used. This process resulted in 26 emergency responses consisting of two runs each for 8 of the distracted participants and 5 of the drowsy participants.

A review of published literature was also conducted in order to determine the feasibility of determining parameters for an alcohol impaired driver. This review concluded that there was insufficient published data available to determine the driver parameters with the detail required for the CSSM.

CONCLUSIONS

The Advanced Crash Avoidance Technology (ACAT) programs are proof-of-concept efforts that seek 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. The progress to date in this ACAT-II program has substantially extended and refined the methodology that could be used to estimate the safety benefits of the particular crash countermeasure evaluated in this research project.

The extended and refined Safety Impact Methodology (SIM) tool is planned to provide an estimate of safety benefits of a prototype Honda Head-On Crash Avoidance Assist System (H-CAAS) in terms of reduction in crashes and fatalities. The SIM methodology and overall safety benefits and effectiveness results are planned to be described in more detail in the ACAT-II final report [7].

REFERENCES

[1] Anon., Traffic Safety Facts 2006.

[2] Sugimoto, Y., and Sauer, C.W., "Effectiveness Estimation Method for Advanced Driver Assistance System and its Application to Collision Mitigation Brake System," Paper No. 05-0148-O, 19th International Technical Conference on the Enhanced Safety of Vehicles, Washington, June 6-9, 2005.

[3] Suzuki, H., et al., "Development of a Prototype Safety Analysis System to Assess and Forecast Vehicle Safety," Technical Paper 2006-01-0718, SAE, Warrendale, PA, 2006.

[4] Van Auken, R.M, et al., Advanced Crash Avoidance Technologies (ACAT) Program – Final Report of the Honda-DRI Team, Volume I: Executive Summary and Technical Report, DOT HS 811 454, Accomplished by Honda and DRI for the National Highway Traffic Safety Administration, Washington, Forthcoming.

[5] Zellner, J.W., et al., "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," Technical Paper 2009-01-0781, SAE, Warrendale, PA, 2009.

[6] Van Auken, R.M., et al., "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," Technical Paper 2011-01-0581, SAE, Warrendale, PA, 2011.

[7] Zellner, J.W., et al., Advanced Crash Avoidance Technologies (ACAT) II Program – Volume I: Executive Summary and Technical Report, Accomplished by Honda and DRI for the National Highway Traffic Safety Administration, Washington, Forthcoming.

[8] Dingus, T. A., et al., The 100-Car Naturalistic Driving Study, Phase II – Results of the 100-Car Field Experiment, DOT HS 810 593, Accomplished by Virginia Tech Transportation Institute, for National Highway Traffic Safety Administration, Washington, April 2006.

[9] Kelly, J., Broen, P., Silberling, J., Bozin, N., Zellner, J., "Development of a Guided Soft Target for Crash Avoidance Technology Evaluation," SAE Technical Paper 2011-01-0580, 2011.

[10] Carter, A.A., Burgett, A., Srinivasan, G., Ranganathan, R., "Safety Impact Methodology (SIM): Evaluation of Pre-Production Systems," Proceeding of the 21st International Technical Conference on the Enhanced Safety of Vehicles, Paper Number 09-0259, Stuttgart, June 2009.

[11] Tessmer, J.M., FARS Analytic Reference Guide 1975 to 2006, National Highway Traffic Safety Administration, Washington, DC, 2006

[12] Anon., National Automotive Sampling System Crashworthiness Data System, 2000 Coding and Editing Manual, National Highway Traffic Safety Administration, Washington, 2000.

[13] Anon., National Automotive Sampling System (NASS) Pedestrian Crash Data Study, 1996 Data Collection, Coding, and Editing Manual, National Highway Traffic Safety Administration, Washington, 2002.

[14] Anon., National Automotive Sampling System (NASS) General Estimates System (GES), Analytical Users Manual (1988-2008), National Highway Traffic Safety Administration, Washington, 2009.

[15] Tsongos, N., Crash 3 Technical Manual, National Highway Traffic Safety Administration, Washington, 1986.

[16] Fleck, J.T., and Butler, F.E., Validation of the Crash Victim Simulator, Vol. 1: Engineering Manual – Part 1: Analytical Formulation, DOT HS 806 279, US DOT, Washington, 1981.

[17] Obergefell, L.A., Gardner, T.R., Kaleps, I., and Fleck, J.T., Articulated Total Body Model Enhancements, Harry G. Armstrong Aerospace Medical Research Laboratory, AAMRL-TR-88-009, January 1988.

[18] Anon., "Special Issue: Speed," Status Report, Vol. 43, No. 1, 31, Insurance Institute for Highway Safety, January 2008.

[19] Bundorf, R.T., and Leffert, R.L., "The Cornering Compliance Concept for Description of Vehicle Directional Control Properties," Technical Paper 760713, Society of Automotive Engineers, Warrendale, PA, 1976.

[20] Bryson, A.E., and Ho. Y.C., Applied Optimal Control, Revised Printing, Hemisphere Publishing, Washington, 1975.

[21] Young, L.R., "On Adaptive Manual Control," Ergonomics, Vol. 12, No. 4, pp. 635-675, 1969.

[22] Burgett, A., Srinivasan, G., and Ranganathan, R., A Methodology for Estimating Potential Safety Benefits for Pre-Production Driver Assistance Systems, DOT HS 810 945, National Highway Traffic Safety Administration, Washington, May 2008.

[23] Hart, S.G., Dahn, D., Atencio, A., and Dalal, K.M., "Evaluation and application of MIDAS v2.0," Technical Paper 2001-01-2648, SAE, Warrendale, 2001.

[24] Anon., APEX Reference Manual 3.0 Beta, NASA Ames Research Center, 2005.

[25] Braver, E., Kyrychenko, S., Efficacy of Side Airbags in Reducing Driver Deaths in Driver-Side Collisions, Insurance Institute for Highway Safety, August 2003.

[26] Anon., "National Vehicle Population Profile®," Source: Copyright © 2002, R. L. Polk & Co., 2004.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AART	Automated Accident Reconstruction Tool
ACAT	Advanced Crash Avoidance Technology
APEX	NASA software for human behavioral modeling
ATB	Articulated Total Body (computer program)
CAAS	Crash Avoidance Assist System (a predecessor to the H-CAAS)
CDS	Crashworthiness Data System (accident database)
CP	Collision Partner
CSSM	Crash Sequence Simulation Module
Delta-V	Change in velocity
ER	Exposure Ratio
FARS	Fatality Analysis Reporting System (fatal accident database)
FE	Fatality Equivalent (injuries)
FR	Fatality Ratio
GES	General Estimates System (accident database)
GST	Guided Soft Target
H-CAAS	Head-on Crash Avoidance Assist System
H-CMBS	Head-on Crash Mitigation Braking System
IR	Injury Ratio
MIDAS	Man-machine Integration Design and Analysis System (NASA human operator model)
OSEE	Overall Safety Effects Estimator
PCDS	Pedestrian Crash Data System (accident database)
POF	Probability of fatality
$POI^{(-)}$	Point-of-impact
$POI^{(+)}$	Point-of-separation
POR	Point-of-rest
PR	Prevention Ratio
NASS	National Automotive Sampling System
SIM	Safety Impact Methodology
SV	Subject Vehicle
TRCT	Technology Relevant Crash Type