

A Semi-Automated Approach to Real World Motor Vehicle Crash Reconstruction Using a Generic Simplified Vehicle Buck Model

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ABSTRACT

Computational finite element (FE) modeling of real world motor vehicle crashes (MVCs) is valuable for analyzing crash-induced injury patterns and mechanisms. Due to unavailability of detailed modern FE vehicle models, a simplified vehicle model (SVM) based on laser scans of fourteen modern vehicle interiors was used. A crash reconstruction algorithm was developed to semi-automatically tune the properties of the SVM to a particular vehicle make and model, and subsequently reconstruct a real world MVC using the tuned SVM. The required algorithm inputs are anthropomorphic test device position data, deceleration crash pulses from a specific New Car Assessment Program (NCAP) crash test, and vehicle interior property ranges. A series of automated geometric transformations and five LS-Dyna positioning simulations were performed to match the FE Hybrid III's (HIII) position within the SVM to reported data. Once positioned, a baseline simulation using the crash test pulse was created. A Latin hypercube sample space (9 variables) of 120 simulations was created to vary occupant safety and restraint properties. Sprague and Geers magnitude and phase error factors were used to identify an optimal set of restraint parameters to reconstruct the HIII kinematic and kinetic responses. Using the tuned SVM, event data recorder pulses from real world crashes, and the Total Human Model for Safety, LS-Dyna simulations were used to reconstruct the occupant-vehicle interactions. In a sample case, stress, strain, and dynamic loads were evaluated to predict rib, sternum, and vertebral injuries sustained by the occupant in the crash.

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INTRODUCTION

Motor vehicle crashes (MVCs) are the eighth leading cause of death globally, with over 1.2 million deaths [1]. Frontal MVCs are the most common crash mode in the United States, and account for 60% of fatal and 54% of injurious MVCs [2]. While anthropomorphic testing devices (ATDs) and post mortem human subject (PMHS) testing in laboratory conditions are valuable to understanding injury, the time and monetary cost of each ATD/PMHS test severely limits the number of imposed boundary conditions that can be evaluated. Analysis of real-world MVC events allow researchers to both investigate injury patterns and evaluate occupant restraint systems in the fleet in real-world injurious conditions. However, even after expert analysis of crashes, there is often still uncertainty on the exact mechanism of injury, and the effects of pre-crash occupant position on injury outcomes. Benefits of finite element human body models (HBMs) include the ability to calculate specific injury risks in body regions that are not instrumented within ATDs and the ability to quickly assess entire body impact events in many loading conditions. One commonly used HBM capable of predicting organ injuries for whole body impact simulations is the Total Human Model for Safety (THUMS) [3].

The Crash Injury Research and Engineering Network (CIREN) database contains real world MVC data and has previously been used for computational MVC reconstructions [4]. Golman et al. analyzed the

HBM response to predict injury risks across the entire body in a side impact CIREN case, but the reconstruction protocol used an open source 2001 Ford Taurus National Crash Analysis Center (NCAC) full vehicle finite element model (FEM). These methods were therefore limited due to the paucity of open source full vehicle FEMs [5, 6]. Another study reconstructed two real world crashes using a methodology similar to this paper, but used a modified Taurus simplified vehicle model (SVM) for reconstruction purposes [7]. While both previous studies reconstructed crashes of sedan vehicles, neither used a vehicle model that was representative of the fleet as a whole.

One challenge of reconstructing CIREN cases is the uncertainty in the occupant's position and posture at the time of the crash [8]. Although CIREN collects information related to the occupant restraint mechanisms and positioning, this data is collected post-crash and is subject to potential error, specifically in occupant restraint parameters. This is due to the priorities of emergency services being focused on occupant safety which often involves moving seat positions to extract the occupant. The objective of this study was to develop a semi-automated approach to reconstruct real world crashes using a standardized buck, information from a CIREN case report, and frontal New Car Assessment Program (NCAP) test data, and subsequently to compare the computed injury risk to a real world crash.

METHODS

Case Selection

One frontal MVC was selected from CIREN with crash characteristics similar to government crash tests. The crash did not have a rollover event, nor did it include large occupant compartment intrusion.

Ford Escape Case Details

The CIREN frontal crash reconstructed involved an 86 year old, 85 kg, 175 cm (5'9"), belted male driver in a 2012 Ford Escape (CIREN ID 359544180). The Ford Escape struck the back of a 2013 Ford F150 at 0° PDOF, with an EDR-recorded longitudinal delta-V of 50 km/h (31 mph) resulting in a maximum crush of 43 cm. The frontal airbag deployed in the non-fatal crash and the occupant was documented to be seated "middle to rear track" with an estimated seat back angle of "slightly reclined". The first and second stages of the airbag deployed at 22.5 and 32.5 msec, respectively. The D-Ring was reported to be in the full down position. The occupant sustained multiple injuries including the following: AIS 3 rib fractures, AIS 3 hemothorax, AIS 2 sternum fractures, AIS 2 lumbar vertebral body fracture, and an AIS 2 cervical spinous process fracture (Table 1) [9].

Table 1. Injuries sustained in 2012 Escape MVC. AIS Codes paired with description [9].

AIS Code	Injury Description
450203.3	Rib fractures (left 3-4 and right 5-7,10)
442200.3	Right hemothorax
450804.2	Central sternum fracture
450804.2	Manubrium fracture
650632.2	L3 compression fracture
650218.2	C4 spinous process fracture

Case Reconstruction Algorithm

The reconstruction process of the CIREN case followed three distinct phases. Phase I involved establishing a vehicle FEM that was suitable for simulating the vehicle environment of a 2012 Ford Escape. This was accomplished by tuning the occupant restraint system of a generic SVM using NHTSA NCAP crash test data. Phase II was completed to automatically position THUMS v4.01 within the previously tuned SVM in a range of pre-crash positions. The seat track, seat back angle, steering wheel angle and telescoping distance, and the D-ring height were the independent variables. Phase III applied the longitudinal EDR pulse from the CIREN crash to each of the previously established potential occupant pre-crash positions. Following these simulations, injury risks for each pre-crash position were assessed using an updated version of the Injury Prediction Post Processor (IPPP), a custom in-house MATLAB GUI (Mathworks Software) [10]. The finite element solver used for each phase was LS_DYNA (MPP, Version 971, R6.1.1., LSTC, Livermore, CA) run on a computer cluster.

Phase I - Simplified Vehicle Model (SVM) Development and Tuning

A FEM of a SVM was adapted, augmented, and tuned to accurately simulate a frontal NCAP crash test of a 2012 Ford Escape. A generic vehicle interior representative of a wide range of modern vehicles was implemented using an adapted version of the vehicle interior developed by Iraeus et al [11]. The generic vehicle geometry developed by Iraeus et al (Umeå University) included a seat cushion, seat pan, dashboard, steering wheel and column, door, A-Pillar, BPillar, and center console which represented an average geometry of laser scan data from 14 modern vehicles in the A2MAC1 database [12]. The measurements of the steering column relative to other interior structures in the Iraeus model were used to implement a previously developed steering column, steering wheel, and airbag assembly as well as a seat back. [6, 7, 13]. The steering column was capable of compressing under user defined axial loads. The steering wheel frontal airbag (*AIRBAG_SIMPLE_AIRBAG_MODEL card in LS-DYNA) was based upon an open source NCAC inflating airbag model [14].

NCAP Test Identification and Data Extraction

The 'sisters and clones' vehicle model list was consulted to arrive at a range of vehicle make, models, and years with matching vehicle properties that were subsequently used to query the NHTSA crash test database [15, 16]. A 2011 Ford Escape XLT 4WD SUV (NHTSA Crash Test 7120) was determined to be the most representative of the CIREN case vehicle, with a delta-V of 56.5 km/h (35.1 mph) [17]. Following the identification of the matching crash test, the following data were extracted: Hybrid III (HIII) ATD positioning, eight crash test signals, and lateral side view test video. The signals extracted were belt anchor lap force, belt upper shoulder force, left femur force, right femur force, T6 resultant acceleration, chest deflection, head resultant linear acceleration, and pelvis resultant acceleration using SignalBrowser [18]. The signals were filtered per SAE J211 [19]. The crash test pulse was extracted from the crash test video from camera #7 using Tracker Video Analysis Software (Open Source Physics, Davidson, NC). The longitudinal pulse is shown in Figure 1. This method preserved the vehicle longitudinal, vertical, and pitching kinematics.

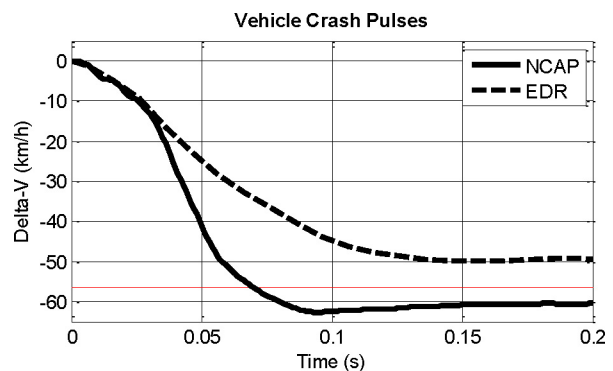


Figure 1. 2012 Ford Escape EDR crash pulse and NCAP longitudinal pulse data (extracted from camera #7, NHTSA Test #7120). Red line indicates transition to rebound for NCAP crash.

FE HIII Positioning

The 50th percentile male HIII ATD FEM (Humanetics, Plymouth, MI) was positioned within the SVM according to the steering column position, seat back angle, pelvis and tibia angles, and nose to rim, chest to steering hub, knee to dash, knee to knee, and ankle to ankle measurements reported in the NCAP report using an algorithmic approach (Figure 2) [20, 21]. The HIII initial positioning was completed by rotating the ATD about the H-point, simulating moving the knees apart, simulating adjustments of the tibia angles, and then simulating the movement of the ankles to the correct position. Next, the SVM steering column angle was adjusted to match the angle specified in the NCAP crash test data by rotating the column about a node at the most forward portion of the part.

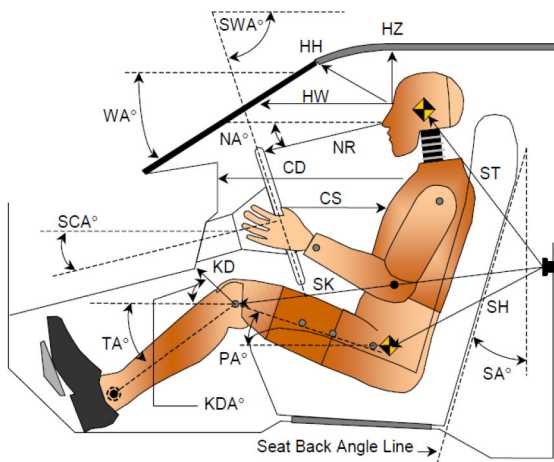


Figure 2. NCAP Positioning Measurements.

The mid-plane of the steering column and the sagittal plane of the HIII model were then aligned. The longitudinal (X) position of the HIII was adjusted to position the lower limbs. The longitudinal (X) position of the HIII was adjusted using an iterative process, due to the complex curvature of the knee bolster surface. During each iteration, a surface to surface measurement was taken between a temporarily created shell element in the knee joint and the right half of the knee bolster. Using this method, the Right Knee to Dash (RKD) distance and Right Knee to Dash Angle (RKDA) were optimized. Once this procedure was completed, a second iterative process was used to match the Left Knee to Dash (LKD) distance. During each iteration, the “separation” measurement was used to determine the shortest distance between the left knee and knee bolster. Based on this distance, the dashboard was rotated about a node on the right side of the knee bolster. This process was terminated when the measured and target distance was less than 0.1 mm.

The relative positions of the HIII upper body were determined based on the steering wheel diameter and reported nose to rim distance, nose to rim angle, chest to steering hub distance, and steering wheel angle. The necessary relative horizontal distance and angle between the chest and nose were calculated and the neck joint was rotated about the local Y-axis in the LS-PrePost Dummy Positioner until the relative horizontal distance was matched. After the upper body segments of the HIII model were repositioned, the steering wheel and column positions were refined by translating the entire steering column and wheel assembly.

The HIII was then translated upwards until there was no penetration with the seat and allowed to settle into the seat by locking the joint movement and applying gravity. At each d3plot state of the settling simulation, the angle of the head with respect to the horizon was measured. Once this initial angle deviated by more than 1.5°, the model was determined to be in the correct position and node locations were saved. This corresponded with the H-point location that minimized the distance to the floor during this phase (Figure 3).

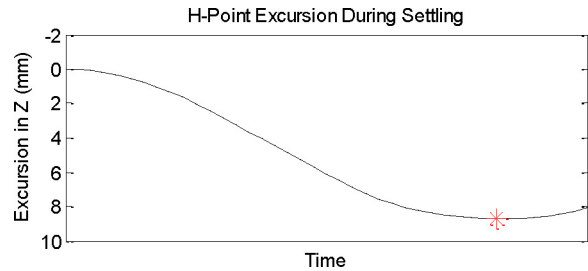


Figure 3. H-point excursion during z-settling step. The red star marks time point at which model nodes were saved and exported.

Following this step, the seat back was rotated from the fully reclined position upwards 75° over a period of 300 ms. A node on the occupant's upper back and a node of the upper seat back cushion were tracked, and the state at which this distance was less than 10 mm was used for the final node locations. This ensured that the seat was in a position similar to a crash test using a published positioning procedure [22]. The occupant was then automatically belted within the SVM. The positioned HIII model in the pre-crash state is shown in Figure 4.



Figure 4. Belted FE HIII within the SVM following the pre-crash positioning algorithm.

Latin Hypercube Design of Experiments

The occupant restraint parameters were subsequently used in a variation study using a Latin Hypercube Design (LHD) of experiments. The LHD is an effective space filling design used in

experimental parameter studies [23]. In a LHD, each parameter has as many levels as there are experiments in the design. The levels are spaced evenly from the lower bound to the upper bound of the parameter. The Latin Hypercube optimization method used in this study was the optimumLHD function in R (The R Foundation). The previously described SVM and HIII set up was used in 200 different simulations with 9 different independent variables. The model's kinematics were driven by the video tracker data. The nine independent occupant restraint variables were divided into five systems: frontal airbag, seatbelt, knee bolster, steering column, and seat cushion. For the belt, maximum pretensioner force, belt buckle dynamic friction coefficient, and load limiting force were varied. For the frontal airbag, both the mass flow rate and vent area were included as independent variables. The mass flow rate was a function of time with a right skewed shape (Figure 5). A scale factor on the ordinate of this mass flow rate was used as an independent variable. The knee bolster had two independent variables: right and left knee bolster surface thickness. The seat cushion modulus was varied to account for potential different seat stiffnesses from various assemblies. Additionally, the shear bolt fracture force in the steering column was also varied.

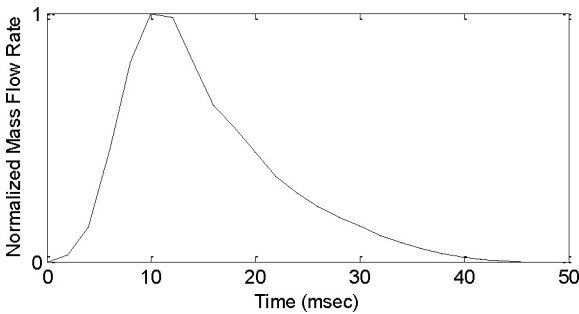


Figure 5. Normalized mass flow rate for the airbag model. Scale Factor on ordinate used as independent variable.

Following the completion of the 200 simulations, signals were extracted from locations in the FE HIII representing the eight extracted from the NHTSA crash test. Sprague and Geers error analysis was used to compare the paired signals [24]. This analysis calculates both the magnitude (M) and phase (P) error for each signal. The comprehensive (C) error was also calculated for each signal according to equations 1, 2, 3, 4, 5.

$$C_{metric} = \sqrt{M_{metric}^2 + P_{metric}^2} \quad (1)$$

$$M_{metric} = \sqrt{\frac{\theta_{mm}}{\theta_{ee}}} \text{ and } P_{metric} = \frac{1}{\pi} \cos^{-1} \left(\frac{\theta_{em}}{\sqrt{\theta_{mm}\theta_{ee}}} \right) \quad (2)$$

$$\theta_{mm} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} m^2(t) dt \quad (3)$$

$$\theta_{ee} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} e^2(t) dt \quad (4)$$

$$\theta_{em} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} e(t)m(t) dt \quad (5)$$

Where $m(t)$ corresponds to the metric data for the simulation model and $e(t)$ corresponds to the metric data from the experimental test. The M and P error factors were calculated over a time period from $t_1 \leq t \leq t_2$. For this study, the time range was from 0 to 100 ms. Data after this time period described the ATD motion during the rebound phase.

Based on these definitions, M, P, and C were standardized measures of the difference between the signals of the experimental tests and simulation models. Smaller values represent more similar signals. P can range from 0 to 1, while M can theoretically range from -1 to ∞ . However, typical values range was from -1 to 1. The IPPP was used to batch this operation for all 200 simulations. In order to arrive at an overall metric of similarity of the SVM to NCAP data, a total body comprehensive error factor was developed: $C_{TotalBody}$ (Eq 6). This metric was developed by averaging the right and left femur errors and the seat belt errors and then weighting the results equally to the head, T6, and pelvis C_{metric} values.

$$C_{TotalBody} = \sqrt{\frac{\left(\frac{C_{R\ Femur} + C_{L\ Femur}}{2} \right)^2 + \left(\frac{C_{Lap\ Belt} + C_{Shoulder\ Belt}}{2} \right)^2}{C_{Head}^2 + C_{T6}^2 + C_{Pelvis}^2}} \quad (6)$$

The top three simulations were then further analyzed with each parameter across the three simulations averaged to arrive at a hypothesized "optimal" tuned SVM. A final simulation with the tuned SVM was subsequently performed to test this hypothesis.

Phase II - THUMS Scaling and Variation Study

After tuning the SVM to have a similar frontal crash response as a 2012 Ford Escape, the next step in the crash reconstruction was to implement THUMS into the SVM and run a positioning variation study. Because the pre-crash position is typically uncertain in real world crashes, a set of 120 pre-crash occupant positions and adjustable vehicle parameters were created.

THUMS Occupant Scaling

Since the occupant in the CIREN case and THUMS v4.01 are neither the same weight nor height, the model was scaled. One option was to scale THUMS to the correct height by equally scaling the lengths of the HBM. However, this would ultimately lead to incorrect mass (12.6% error). Similar efforts to scale the mass would yield a large height error. Thus, a set of equations were derived to calculate a length-scaling factor that minimized both the length and mass errors without compromising the model geometry and properties (Eq 7-9).

$$\text{height factor} = \frac{\text{case occupant height}}{\text{THUMS model height}} \quad (7)$$