ANALYSIS OF COMPUTER MODELS FOR HEAD INJURY INVESTIGATION

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ABSTRACT

Motor vehicle crashes are the most common cause of serious head injury (Healthy People, 2002). Over the past decade, improvements to seat belts and frontal airbags have reduced the incidence and severity of injuries sustained in frontal crashes, but are less effective in side impact crashes.

Prior studies have shown that both excessive linear and rotational accelerations are the cause of head injury. Although the Head Injury Criteria (HIC) has been beneficial as an indicator of head injury risk, it only considers linear acceleration only.

With the rapid increase in computational power, advanced models of the head/brain complex have been developed in order to gain a better understanding of head injury biomechanics. While these models have been verified against laboratory experimental data, there is a lack of suitable real-world data available for validation. Hence, the objective of the current study is to use real-world data to predict injury outcomes using computer models of the head, and to validate the model results against the actual injuries sustained in two real-world crashes. Two computer models of the head were used: The Wayne State University Head Injury Model (WSUHIM) and the NHTSA Simulated Injury Monitor (SIMon). The HIC was also calculated for comparision.

The use of computer models of the brain provide a useful tool for the prediction of brain injury in motor vehicle crashes and may be able to replace criteria such as the HIC in the future.

INTRODUCTION

Head injury, or more specifically, brain injury, is the most threatening form of injuries, both to life and to the quality of life. Motor vehicles are the most common cause of serious head injury, which is the most critical form of impact trauma resulting from car crashes (MUARC, 1993). There is a growing awareness of the incidence of non-fatal brain injuries and their impact on the individual, the family unit and the community. Typically, half of all hospital road crash admissions have a brain injury (Westmead Hospital Trauma Registry, 1985). Over the past decade, improved seat belt design and use of frontal airbags have reduced the incidence and severity of injuries sustained in frontal crashes, but are less effective in side impact crashes.

Brain injury is appropriately called the silent epidemic (Buchanan 1989), and the dramatic increase in brain injury in the last decade has not been a result of an increased number of crashes but of increased survival. The use of ambulances with life support systems, helicopter ambulances, and CT scans to identify haemorrhaging and the location of blood clots contribute to increased survival of crash victims. The long-term consequences and the personal cost of a brain injury are very evident to the victim and their family. Seven million head injuries occur annually in the United States (NHTSA 1989a). The community cost of brain injury is progressively being recognised as a major social issue. Consequently, there is an increased focus on developing strategies for the reduction of both head injury frequency and severity. An improved understanding of the biomechanics of brain injury is a critical first step to the development of improved occupant protection.

Previous research has identified excessive linear and rotational accelerations as the cause of head injury. In testing the hypothesis of linear acceleration as the etiology of head injury, a series of head injury experiments began in 1939 at Wayne State University by Neurosurgeon Dr Elisha S. Gurdjian, and Engineering Professor Herbert R. Lissner. These experiments included dropping metal balls onto dry human skulls, impacts to the foreheads of embalmed cadavers against rigid and padded surfaces, and the application of an air pressure pulse directly onto to the dura of anesthetised animals. The outcome of this research formed the basis of the Wayne State Tolerance Curve (Lissner et al., 1960), which became the HIC with curve fitting analysis of the tolerance curve (Versace, 1971).

In 1943, Holbourn proposed a rotational acceleration theory based on a physical model of the head. He hypothesised that large shear strains produced throughout the brain from rotation could

induce diffuse brain injury. This hypothesis was further tested at the National Institutes of Health and later at the University of Pennsylvania by two Neurosurgeons, Dr Tom Gennarelli and Dr Ayub K. Ommaya, and Engineer Dr Larry Thibault. The group performed experimental studies using live subhuman primates and physical models, and claimed that virtually every known type of head injury could be produced by angular acceleration (Gennarelli et al, 1972, Gennarelli et al, 1982, Thibault and Gennarelli, 1985). However, the level of angular acceleration used in their experiments was inordinately high.

In real-world collisions, head injury occurs from a combination of translational and rotational acceleration, neither of which needs to be extremely high. While the HIC has been beneficial in reducing major forms of head injury by providing some type of tolerance level, new head injury safety standards need to include both types of acceleration. However, the establishment of a safety standard requires an understanding of human responses and tolerances to impact loading. As noted by many researchers, cadaver specimens cannot be used to understand the physiology of head injury and volunteers cannot be taken to injurious levels. On the other hand, ethical issues and differences in anatomy make animal testing difficult to conduct and interpret for human use.

With the aid of rapid advances in computational power, numerical models of the human head have been developed to improve the understanding of head injury biomechanics (Bandak et al, 2001; Zhang et al, 2001a; Klevin et al. 2001). While these models have been validated against laboratory experimental data, there is a lack of real-world injury data for model validation. Without this critical validation step, computer models can only be used as a research tool. Using computer assisted tools, the purpose of this study is to report and judge the accuracy of two sets of head injury data selected from real-world cases for injury investigation. Additionally, it is the intention of this research to make the data publicly available so that any future development of computer head models can be validated against these cases for biofidelity.

METHODS

This study is comprised of three separate components: Crash Investigation, Crash Reconstruction and Head Injury Computer Modelling.

Crash Investigation

The MUARC Accident Investigation Team collects data on real-world crashes in Victoria and New South Wales (NSW), Australia, with the majority of cases being collected in the metropolitan region. The team is comprised of Vehicle Inspectors, Nurses, Accident Scene Investigators, a Case Co-ordinator and a Senior Manager. The study has a hospital-based inclusion criterion. The cases are identified by a Nurse via the hospital system. After a case is identified, the information described below is collected.

Medical data collection: The Nurse interviews the patient about a range of factors pertaining to the collision, such as the crash scenario and their seating position in the vehicle. The medical information pertaining to the crash is then recorded and the injuries are subsequently coded according to the Abbreviated Injury Scale (AIS) 1990 (Revision 1998). CT reports, other diagnostic imaging reports and medical reports are accessed in order to accurately describe and code the injuries.

Vehicle inspection: The vehicle inspection is performed within days of the crash in accordance with international best practice for retrospective examination of crash-damaged vehicles (NHTSA, 1989b). The inspection includes details about the vehicle itself (such as make, model, year, VIN and measurements of the vehicle body and wheelbase) in addition to collision-specific data (such as crush dimensions and seatbelt use). The crush dimensions are recorded according to SAE J224 Collision Deformation Classification (CDC) profile and the delta-V is computed using CRASH3. The Principal Direction of Force (PDoF) is visually determined directly from the vehicle.

Scene inspection: Information from the patient in conjunction with that in police reports and other reliable sources is used to sketch the crash scenario and locate the crash scene. Photographs showing various angles of the crash site are taken and evidence of the crash, such as broken glass or paint marks on the struck object, are identified. If the vehicle impacted into a fixed object, such as a tree or pole, measurements of the object are also recorded.

If there is more than one vehicle involved in the crash, the collision partner is located and, where possible, a vehicle inspection of the second vehicle is also conducted. Police reports are obtained and used by the Vehicle and Scene Inspectors to verify details of the vehicles involved and the crash scenario. After all data has been collected, the Case Co-ordinator produces a summary sheet describing the key aspects. The Case Co-ordinator and Senior Manager then check the entire case for consistency and clarify any conflicting information. To complete a case, all members of the Accident Investigation Team attend a case review panel, where any complex or inconsistent

case details are discussed and resolved. All information is de-identified and the case is closed.

Two cases involving Holden VT Commodore models were selected for this study: one AIS 0 head injury case (no head injury) and one AIS 5 head injury case. These cases were selected to firstly provide two extreme sets of data, and secondly on the basis that they were not overly complex and hence could be replicated via crash tests where the injuries could be directly attributed to the impact. Factors considered included a crash speed that was below 85km/hr, adult occupant subjects and the exclusion of crashes where the occupants were out of position.

Collision Reconstruction

Computer Simulations: Before conducting any physical crash tests, computer simulations of the crashes were performed to determine pre-crash speeds and if relevant, crab angles. The crab angles are initially calculated from the estimated speeds of both vehicles prior to the impact (Figure 1).

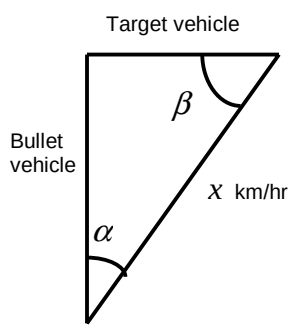


Figure 1: The method used to calculate the crab angles (α and β) and the speed (x) required

The two types of crash simulations are outlined:

1. The first set of simulations utilised the SMAC4 module of the HVE (Human Vehicle Environment) software (Version 4.30), produced by the Engineering Dynamics Corporation (EDC, OR, US). The objective of the HVE simulations was to find the pre-impact speed(s) of the vehicle(s) involved in the crash before conducting the physical crash test. Simulations were conducted until paramaters such as the crash scenario and delta-V (calculated by CRASH3) matched the real-world case.
2. The second set of simulations involved the use of a Finite Element (FE) model of the case vehicle. The model-calculated deformation patterns were compared to those measured during the vehicle inspection.

The information from the FE simulations was used to finalise the parameters used in the physical crash test.

Crash Testing: Vehicles of the same model year as the case vehicles were acquired and prepared for the crash tests. Of the two cases selected, one was a Commodore impacted by another vehicle (AIS 0 Case) while the other was a Commodore which impacted a pole (AIS 5 Case). Specific information related to the vehicle preparation is presented in the Results section. In order to measure angular accelerations in addition to linear accelerations, a specially designed Hybrid III skull, which is arranged to attach up to 12 Endevco accelerometers, was purchased (Figure 2). Nine accelerometers, arranged in the 3-2-2-2 configuration, were mounted to the centre, anterior, left, and superior mounting blocks. All three components of the body-fixed linear and angular accelerations were calculated and used as input to finite element models of the head in order to estimate the risk of brain injury.

In addition to all six components of the head acceleration, standard injury metrics were also measured. These data were filtered according to SAE J211 specifications then compared to the recommended Injury Assessment Reference Value (IARV) in order to assess injury potential for the other body parts.

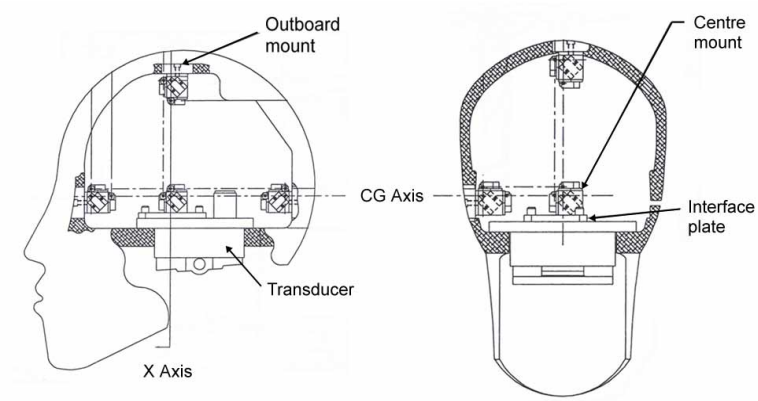


Figure 2: The location of the accelerameters and the dimensions of the skull showing the lateral view (left) and the posterior view (right)

Head Injury Computer Modelling

For prediction of head and brain injuries, the two models used were the NHTSA SIMon Head Injury Model (Bandak et al, 2001) and the Wayne State University Head Injury Model (WSUHIM) version 2001 (Zhang et al., 2001a)

The NHTSA SIMon Model: SIMon, **S**imulated **I**njury **Mon**itor, is a finite element occupant model developed in LS-DYNA by NHTSA. The only model currently available is the beta version of the SIMon head module, which represents a 50th percentile male head. The model simulates the cerebrum, dura, falx, skull and 7-pairs of bridging veins (Figure 3). It does not mesh the cerebellum, brain stem and ventricles. The inferior part of the temporal lobes have been greatly simplified to reduce the computational cost. The total mass of the model is 4.77kg of which the brain comprises 1.36kg and the skull consists 2.93kg. The model contains 8,036 nodes and 5,948 elements, among which 2,288 elements were used to model the skull. The skull is assumed to be a rigid body while the brain is represented by linear viscoelastic material. All other components of the head are assumed to be linear, homogeneous and isotropic.

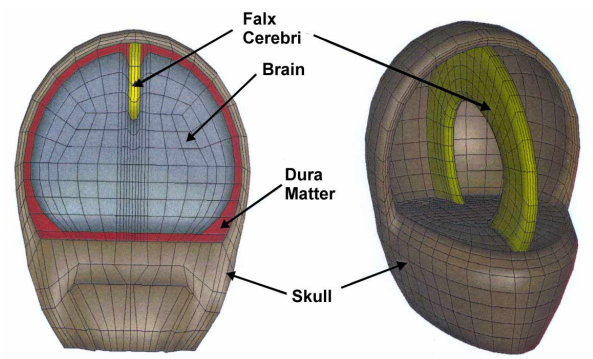


Figure 3: The NHTSA SIMon model of the head/brain complex illustrating the rigid skull and the deformable brain

The NHTSA SIMon Model takes nine linear acceleration measurements using the Hybrid III skull described earlier. Three brain injury predictors are calculated: 1) the Cumulative Strain Damage Measure (CSDM), 2) the Relative Motion Damage Measure (RMDM), and 3) the Dilation Damage Measure (DDM). The CDSM is used for the prediction of diffuse axonal injury (DAI), the RMDM is adopted for the estimation of acute sub-dural haematoma (ASDH), and the DDM is used to predict the damage resulting from intracranial pressure changes in the brain. The SIMon model is designed to be highly computationally efficient in order to handle the large quantity of simulations needed by the automotive industry.

The WSUHIM: The WSUHIM, which consists of more than 300,000 elements, represents the other extreme of a numerical tool to estimate the risk of head injury (Zhang et al, 2001a). All essential components of the head including the scalp, skull, brain stem, cerebellum, bridging veins, and a detailed face were modeled. The grey and white matter were defined separately using linear viscoelastic material (Figure 4).

Unlike the NHTSA SIMon model, the WSUHIM does not provide predetermined metrics to predict the risk of brain injury. For example, the user needs to 1) check the magnitude of the bridging vein strain in order to predict the potential of sustaining an ASDH, 2) check the location of maximum stress/strain in order to determine if the stress/strain exceeds the laboratory produced tissue level injury threshold, and 3) check the intracranial pressure in order to determine if any focal injury has occurred.

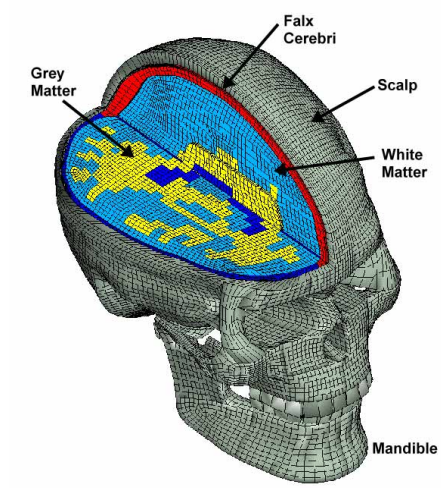


Figure 4: The WSUBIM brain injury model showing the various components of the head

The compromise for including a detailed brain structure in the WSUHIM is obviously the computational cost involved. A typical simulation using the SIMon model on a personal computer can be completed in less than 4 hours compared to 24 hours for the WSUHIM on a high-end workstation. On the other hand, a strain of 10% in the brain stem region may be interpreted very differently to a strain of 10% in the grey matter. The cumulative measure used in the SIMon to predict brain injury may underestimate the regional difference existing in the complex brain whereas the WSUHIM takes into account the region where the injury is observed.

RESULTS

Crash Investigation

A summary of the two cases selected for this study is provided below. The cases will be referred to as AIS 0 Case and AIS 5 Case for the remainder of the paper.

1. AIS 0 Case

Case description: A 1993 Toyota Paseo struck a 2000 Holden VT Commodore on the drivers's side (right) after running a red light. The Commodore rotated almost 180 degrees and impacted a pole on the front of the vehicle on the passenger's side (left). The secondary pole impact was not reconstructed because the injuries to the occupants were sustained in the primary impact. Figures 5 and 6 illustrate the residual deformation of the Paseo and the Commodore respectively.

Figure 5: The frontal damage to the Toyota Paseo involved in the AIS 0 case

Figure 6: Photograph of the Holden Commodore in the AIS 0 Case depicting the lateral impact

Vehicle Occupants: There were two occupants seated in the Holden Commodore: a male driver and a female front seat passenger (FSP). The male occupant was 56 years old, 1.79m and 80kg while the female occupant was 51 years old, 1.59m and 65kg. Both occupants were wearing seatbelts. Frontal and side airbags were fitted to the vehicle and both deployed in the crash. The Toyota Paseo had one occupant only (driver), who was a female. Medical details pertaining to the Paseo driver were not collected as she was in the non-case vehicle. The driver of the Commodore sustained 5 rib fractures with haemopneumothorax in addition to multiple contusions and abrasions. The FSP of the Commodore suffered minor contusions.

2. AIS 5 Case

Crash Description: The driver of a Holden VT Commodore lost control of his vehicle and clipped a parked vehicle on the front passenger side (left). He then struck a telegraph pole on the driver's side (right), which resulted in extensive cabin intrusion. The damage to the vehicle is depicted in Figures 7a and 7b. Only the pole impact was reconstructed as this impact resulted in the injuries sustained.

(a)

Figure 7 (a and b): The damage to the Holden Commodore after impact with a pole

Vehicle Occupants: There were two occupants in the vehicle, a driver and a FSP. The driver, who was the case occupant, was a 39-year-old male, 1.80 metres in height and weighed 80kg. The FSP was a male of similar anthropometric dimensions. The driver suffered extradural haematoma, temporal bone fractures and contusions, flail chest, haemopneumothorax and several fractures. The FSP was addmitted to a non-study hospital, hence his injuries were not coded.

Crash Reconstruction

1. Computer Simulated Crash Reconstructions

HVE Simulations: As the HVE software contains US vehicles only, a Commodore and a Paseo were created using a Chevrolet Impala SS and a Toyota Celica respectively as base vehicles. Modifications to the base vehicles were made so that parameters such as the drive axle, vehicle weight, number of doors, type of vehicle (sedan) and stiffness matched the vehicles required for the analysis. Using the police-reported description of the crash scenario, a number of SMAC4 simulations were performed. The simulation was deemed accurate when the CDC profile from the vehicle inspection and the delta-V from the CRASH3 calculation were comparable to those from the HVE simulation.

For the AIS 5 Case, the collision partner was a fixed object (a pole). Consequently, the impact speed determined in the simulation was used for the physical crash test. However, in the AIS 0 Case, there were two moving vehicles, and the crash test facility could only use one moving vehicle. Hence, the crash test was conducted using a stationary target vehicle (the Commodore), and a moving bullet vehicle (the Paseo). Further HVE simulations were performed to find the impact speed required for the bullet vehicle to produce the equivalent damage that the two moving vehicles would have produced.

FEM Simulations: Because the HVE software includes only the stiffness data for vehicles available in the US, an LS-DYNA finite element model of a Holden vehicle, which has a similar underbody structure to a Commodore, was used to perform additional simulations of the crash. Input for the model was taken from results determined by SMAC4 and the model-calculated deformation patterns were compared to those measured during the vehicle inspection. The initial contact point and the impact speed were varied through several iterations until the deformation patterns were similar to those measured in the real-world crash. These data were then used to finalise the parameters used in the reconstruction of the collision.

AIS 0 Case: Using CRASH3 software, the delta-V from the real-world crash was calculated to be 27 km/hr for the lateral impact and 49 km/hr for the (secondry) frontal pole impact. The CDC was recorded as part of the vehicle inspection. Table 1 shows these measurements, while the real-world vehicle deformations have previously been shown in Figures 5 and 6. HVE SMAC4 simulations were performed to match the kinematics of the real-world crash and were continued both until the damage on the simulated vehicles (Figure 8) matched the damage seen on the real-world vehicles (Figures 5 and 6) and the damage measurements were similar to those in the real-world crash (Table 1). The crash circumstances were known from the police report and patient interview and final vehicle rest positions were derived from the police reports and vehicle inspections.

As Table 1 demonstrates, the simulation appears to be an realistic representation of the real-world crash. For the Commodore, the CRASH3 delta-V for the real-world lateral impact was 27 km/hr while the delta-V from the HVE simulated impact was 31 km/hr. Conversely, for the secondary pole impact, these figures were 49 km/hr and 51 km/hr respectively. The CDC profiles for both the Commodore and the Paseo were analogous. For the Paseo, there was some variation between the delta-V calculated using real-world data and the delta-V resulting from the HVE simulation. This variation may be due to the assumption made by CRASH3 that the target vehicle (the Commodore) was stationary or that the stiffness values for the Paseo were softer than those in the real-world Paseo. However, as crash circumstances and crash measurements were very similiar, the HVE simulation crash was deemed to be an accurate representation of the real-world crash. Using the speeds from this simulation, the crab angle was initially calculated using the method shown earlier in Figure 1. The initial pre-impact speed for the Paseo was calculated at 85 km/hr while the crab angles were computed to be 43 degrees for the Commodore (α) and 47 degrees for the Paseo (β).

Table 1: Comparison of real-world measurements and HVE simulation measurements for both cases.

Case/ vehicle	Impact	Parameter	Real World	HVE
AIS 0				
Holden	Lateral	Delta-V	27 km/hr	31 km/hr
		CDC	03RPEW3	02RYEW3
	Pole	Delta-V	49 km/hr	51 km/hr
		CDC	12FLEN6	11LFEW4
Toyota	Front	Delta-V	48 km/hr	64 km/hr
		CDC	12FDEW3	12FDEW3
AIS 5				
Holden	Pole	Delta-V	43 km/hr	45 km/hr
		CDC	03RPAW5	03RPAW5

The second set of simulations was completed using a stationary Commodore and a moving Paseo in order to replicate the conditions for the physical crash test. The crab angles from Figure 1 were used as a starting point to determine the Paseo pre-impact speed necessary to produce the same damage profile as the initial HVE Simulation (Table 1). The crab angles remained at 43 degrees and 47 degrees for the Paseo and Commodore respectively, while the pre-

impact speed for the Paseo was computed to be 85 km/hr.

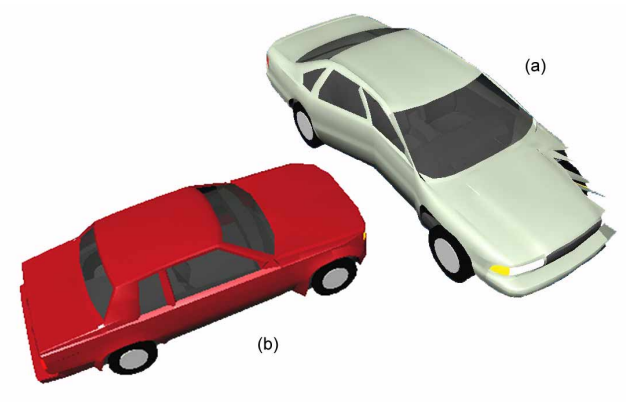


Figure 8: The HVE SMAC4 simulations of the Holden Commodore (a) and Toyota Paseo (b).

AIS 5 Case: Table 1, which was presented previously, shows the delta-V calculation and CDC profile from both the real-world crash and the HVE simulation. The delta-V compuations were similar, being 43 km/hr and 45 km/hr for the real-world crash and the HVE simulation respectively. Furthermore, the CDC profiles were identical; hence, the simulation was considered a close representation of the real-world crash.

2. Physical Crash Test Reconstruction

AIS 0 Case: The Paseo was mounted onto a trolley to assist its motion towards the Commodore. To compensate for the trolley weight of 200kg, the equilavent weight in vehicle parts was removed from the vehicle. Both on and off-board cameras recorded the motion of the vehicle and the Anthropomorphic Test Devices (ATD's). The camera positions are illustrated in Figure 9. As the crab angle was too large to replicate at the test facility, a double crab configuration was adopted.

To represent the two occupants in the crash, the ATD's used were a 50th percentile BioSID for the driver and a SIDIIs for the FSP. There were 50 signals for the BioSID that measured the head, neck, T1, T4 and T12 vertebrae, the shoulder, the ribs the pelvis, the pubic region, the iliac region, the sacrum and the lumber regions. The SIDIIs had 26 channels that included the head and neck, the T1, T4 and T12 vertabrae, the shoulder, the ribs the pelvis and the lumbar regions. The Hybrid III in the Paseo was not instrumented as the injuries to the occupant of the bullet vehicle were not recorded. A total of 9 contact switches was installed. Airbag and pretentioner fire times were recorded. Including the target and bullet signals, a total of 101 channels was used.

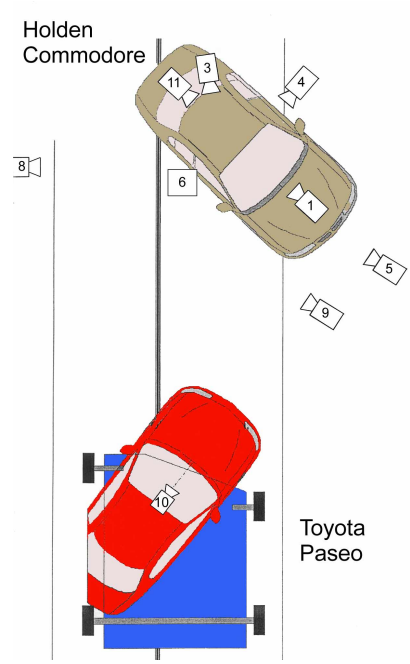


Figure 9: The final physical crash test configuration. Positions 1-10 indicate camera positions (cameras 2 and 7 were located inside the Commodore and are not shown)

AIS 5 Case: The reconstruction involved pulling the Holden Commodore laterally into a fixed pole. The vehicle available had the reverse configuration (driver on the left side), hence the crash test was conducted on the opposite side. There was a small crab angle used to simulate the 255 degree PDoF required to impact the vehicle at 9 o'clock.

The driver ATD used was a 50th percentile BioSID, while the FSP was a 50th percentile SID. The BioSID was instrumented to 50 signals (similiar to the driver in the AIS 0 Case), while the FSP was not instrumented. There were 7 cameras installed to record the motion of the Commodore and 5 contact switches. Airbag and pretentioner fire times were recorded. A total of 57 channels was used for the entire crash test.

3. Post Crash Test Measurements

AIS 0 Case: Vehicle inspection measurements from the real-world crash against the dimensions measured after the physical crash test are displayed in Tables 2 and 3, with Table 2 showing the vehicle parameters for the Commodore and Table 3 for the Paseo. The CDC gives an indication of the overall damage, but does not capture accurate measurements of the damage profile. In the case of the Commodore, they were identical, indicating that the damage produced in the crash test was a reasonable outcome.

A comparison of damage measures such as the maximum crush depth and the energy produced indicate that the crash test damage underestimated the real-world crash damage, but not greatly. The damage profile from the crash test was slightly wider and the maximum crush was further towards the rear of the vehicle (comparing C3 and C4). Similar analysis for the Paseo (Table 3) shows that the damage produced in the crash test was reasonably accurate, although, as this vehicle was not the case vehicle, the accuracy of the damage profile was not as important as for the Commodore.

Figure 10 illustrates the damaged vehicles from the crash test, which can be compared to the real-world crash vehicles previously shown in Figures 5 and 6 and the HVE SMAC4 simulation presented in Figure 8.

Table 2: Comparison of vehicle measurements between the real-world crash and the crash test for the Holden Commodore (case vehicle) in the AIS 0 Case.

Parameter	Commodore: Real World Crash	Commodore: Crash test
C1	0 cm	5.0 cm
C2	19.0 cm	15.0 cm
C3	33.0 cm	20.0 cm
C4	31.0 cm	23.0 cm
C5	25.0 cm	20.0 cm
C6	0 cm	5.0 cm
Maximum crush depth	33.0 cm	23.0 cm
Height taken from ground	33.0 cm	45.0 cm
Direct damage width	177.0 cm	190.0 cm
Length of vehicle offside	428.0 cm	485.0 cm
Length of vehicle nearside	464.0 cm	474.0 cm
Wheelbase vehicle offside	249.0 cm	274.0 cm
Wheelbase vehicle nearside	288.0 cm	284.0 cm
Width of vehicle	176.0 cm	180.0 cm
CDC	03RPEW3	03RPEW3
Distance rear to C1	190.0 cm	75.0 cm
Distance front to C6	90.0 cm	150.0 cm
Distance C1 to C6	240.0 cm	260.0 cm
Offset	+34.6 cm	+39.6 cm
Delta-V	26.4 km/hr	35.0 km/hr
Energy	45.3 kJ	34.3 kJ

Table 3: Comparison of vehicle measurements between the real-world crash and the crash test reconstruction for the Toyota Paseo (non-case vehicle) in the AIS 0 Case.

Parameter	Paseo: Real World Crash	Paseo: Crash test
C1	63.0 cm	103.5 cm
C2	41.0 cm	74.5 cm
C3	32.0 cm	64.5 cm
C4	33.0 cm	68.5 cm
C5	34.0 cm	78.5 cm
C6	45.0 cm	79.5 cm
Maximum crush depth	63.0 cm	103.5 cm
Height taken from ground	47.0 cm	65.0 cm
Direct damage width	166.0 cm	165.0 cm
Length of vehicle offside	324.0 cm	335.0 cm
Length of vehicle nearside	347.0 cm	#
Wheelbase vehicle offside	233.0 cm	231.0 cm
Wheelbase vehicle nearside	240.0 cm	#
Width of vehicle	166.0 cm	165.0 cm
CDC	12FDEW3	12FDEW4
Distance left to C1	0 cm	0 cm
Distance right to C6	0 cm	0 cm
Distance C1 to C6	166.0 cm	165.0 cm
Offset	0 cm	0 cm
Delta-V	45.2 km/hr	67.6 km/hr
Energy	80.2 kJ	24.5 kJ

The rear corner of the vehicle was removed for test instrumentation.

(a)

(b)

Figure 10: Post crash test photos of the Commodore (a) and the Paseo (b).

<u>AIS 5 Case:</u> Table 4 displays the vehicle inspection data from the real-world crash against the vehicle measurements resulting from the crash test reconstruction. A comparison of the CDC profiles from both vehicles indicates that the type of damage was similar (03RPAW5 compared to 09LPAW4). The damage produced was similar, but the crash test damage underestimated the real-world crash damage. This is evident when comparing parameters such as the delta-V, the energy, the direct damage width and the C1-C6 measurements.

Photographs of the Commodore impact with the pole, taken after the crash test, are shown in Figures 11a and 11b (recalling that a reverse configuration was used for the crash test). These can be compared to the photographs of the real-world crash in Figure 7.

Table 4: Comparison of vehicle measurements between the real-world crash and the crash test reconstruction for the AIS 5 Case.

Parameter	Commodore: Real World Crash	Commodore: Crash test
C1	0 cm	5.0 cm
C2	40.0 cm	13.0 cm
C3	95.0 cm	38.0 cm
C4	49.0 cm	64.0 cm
C5	20.0 cm	32.0 cm
C6	0 cm	5.0 cm
Maximum crush depth	95.0 cm	64.0 cm
Height taken from ground	75.0 cm	50.0 cm
Direct damage width	55.0 cm	40.0 cm
Length of vehicle offside	412.0 cm	455.0 cm
Length of vehicle nearside	450.0 cm	405.0 cm
Wheelbase vehicle offside	210.0 cm	235.0 cm
Wheelbase vehicle nearside	291.0 cm	295.0 cm
Width of vehicle	150.0 cm	180.0 cm
CDC	03RPAW5	09LPAW4[#]
Distance rear to C1	130.0 cm	130.0 cm
Distance front to C6	65.0 cm	140.0 cm
Distance C1 to C6	200.0 cm	185.0 cm
Offset	+79.6 cm	+22.1 cm
Delta-V	38.6 km/hr	31.3 km/hr
Energy	131.7 kJ	66.9 kJ

[#] Note that the crash test was performed in reverse

(a)

(b)

Figure 11 (a and b): Post crash test photos of the AIS 5 Case showing the Commodore involved in the pole impact

4. Injury Measurements

AIS 0 Case: The injuries sustained by the Commodore occupants and the Injury Assessment Functions (IAF's) from the AIS 0 crash test are demonstrated in Table 5. The raw data was filtered using Diadem Versions 7.2 (AIS 5 Case) and 8.0 (AIS 0 Case). The driver of the Commodore suffered no head injury (AIS 0), although it should be noted that the ambulance report recorded LOC as a possible injury but it was not coded because the medical personnel were not certain if LOC had in fact occured (during the interview with the FSP, she stated that the driver had a short period of LOC). The %IARV (Injury Assessment Reference Value) ATD HIC was low (the HIC_{36} value was 73.28 and the HIC_{15} value was 47.58), indicating little, if any, damage to the head/brain complex. The high %IARV's were measured from the shoulders and ribs of the ATD, which was an accurate reflection of the driver's injuries in the real-world crash, as he suffered a contusion to the upper arm, 5 rib fractures and associated haemopneumo-thorax. The %IARV's at the iliac and pelvic regions of the ATD predicted injuries slightly more severe than the contusion to the right hip (AIS 1) sustained by the driver. To give an overall view of the injury outcome, results for the FSP are also presented.

AIS 5 Case: The injuries sustained by the driver in the real-world crash against the percentage of Injury Assessment Reference Value (%IARV) in the AIS 5 Case are presented in Table 6. The driver ATD was subjected to two impacts: the first with the B-pillar and the second with the head of the FSP ATD. This was confirmed by high speed video footage. The driver sustained a bilateral extradural haematoma (AIS 5), which was reflected in the %IARV's of about 178% for the head to B-pillar contact and 315% for the head to head contact. Interestingly, the highest HIC value was due to the head-to-head contact rather than the driver ATD contacting the B-pillar. The impact with the B-pillar resulted in a HIC of 1789 for both 15ms and 36ms duration, while the impact with the other occupant produced a HIC of 3159.

Table 5: Comparison between injuries sustained by the real-world crash occupants and the injury assessment values derived from the ATD's in the crash test reconstruction in the AIS 0 Case

Real World Crash	AIS	Measured Quantity	Magnitude	IARV	%IARV
Driver (Case occupant)					
No head injury[#]	0	HIC limited to 15	47.58	1000	4.8
		HIC limited to 36	73.28	1000	7.3
Contusion to upper left arm	3	Shoulder lateral force	3.18 kN	4	79.5
		Shoulder lateral deflection	21.97 mm	75	29.3
		V*C shoulder rib	0.40 m/sec	0.9	44.2
Fractures to the right ribs (5 fractures) and haemopneumothorax	4	Thoracic rib #1 deflection	27.35 mm	42	65.1
		V*C thoracic rib #1	0.64 m/sec	0.9	70.7
		Thoracic rib #2 deflection	26.03 mm	42	62.0
		V*C thoracic rib #2	0.62 m/sec	0.9	69.1
		Thoracic rib #3 deflection	27.03 mm	42	64.4
		V*C thoracic rib #3	0.64 m/sec	0.9	70.6
		Abdominal rib #1 deflection	44.20 mm	39	113.3
		V*C abdominal rib #1	1.02 m/sec	1.2	85.1
		Abdominal rib #2 deflection	57.17 mm	39	146.6
		V*C abdominal rib #2	1.49 m/sec	1.2	124.0
Contusion to right hip	1	Iliac crest force	3.48 kN	6	58.0
		Pelvis lateral acceleration	78.62 g	130	60.5
		Scarum force	0.98 kN	6	16.3
		Pubic symphysis peak force	1.28 kN	6	21.3
		Lumbar bending moment	121.39 Nm	1125	10.8
Multiple abrasions to left femur	1				
Abrasions to left thumb	1				
FSP					
Contusion to left and right hips	1				
Contusion to left tibia	1				
Contusion to right thigh	1				
Contusion to sternum and right ribs	1	Thoracic rib #2 deflection	3.00 mm	42	7.1
		V*C thoracic rib #2	0.03 m/sec	0.9	3.9
Contusion to pelvis	1				
Contusion to left shoulder	1	Shoulder lateral force	0.45 kN	4	11.2
		Shoulder lateral deflection	4.02 mm	75	5.4
Contusion to left elbow	1				

[#] Note that although injury coding for the head was AIS 0, the patient may have suffered a brief period of unconsciouness. See text for further details.

Table 6: Comparison between injuries sustained by the real-world crash occupants and the injury assessment values derived from the ATD's in the crash test reconstruction in the AIS 5 Case

Real World Crash (driver)	AIS	Measured Quantity	Magnitude	IARV	%IARV
Bilateral extradural haematoma (temporal)	5	HIC limited to 15 (head to B-pillar)	1788.82	1000	178.9
Temporal lobe contusion	3	HIC limited to 36 (head to B-pillar)	1788.82	1000	178.9
		HIC limited to 15 (head to head)	3158.54	1000	315.8
		HIC limited to 36 (head to head)	3158.54	1000	315.8
Bilateral temporal bone fracture	3				
Bilateral spheroid bone fracture	3				
		Shoulder lateral force	3.40 kN	4	85.0
		Shoulder lateral deflection	41.11 mm	75	54.8
		V*C shoulder rib	0.84 m/sec	0.9	93.0
Fracture of right anterior ribs (4th,5th and 6th)	3	Thoracic rib #1 deflection	36.61 mm	42	87.2
Flail chest	3	V*C thoracic rib #1	0.54 m/sec	0.9	60.2
Haemopneumothorax (L and R)	3	Thoracic rib #2 deflection	33.27 mm	42	79.2
		V*C thoracic rib #2	0.52 m/sec	0.9	57.8
		Thoracic rib #3 deflection	30.60 mm	42	72.9
		V*C thoracic rib #3	0.54 m/sec	0.9	60.4
		Abdominal rib #1 deflection	40.25 mm	39	103.2
		V*C abdominal rib #1	1.26 m/sec	1.2	105.1
		Abdominal rib #2 deflection	56.48 mm	39	144.8
		V*C abdominal rib #2	1.83 m/sec	1.2	152.8
Fracture of right inferior and superior pubic rami		Iliac crest force	2.03 kN	6	33.8
		Sacrum force	10.50 kN	6	175.0
		Pubic symphysis peak force	7.82 kN	6	130.3
		Lumbar bending moment	417.38 Nm	1125	37.1
		Pelvis lateral acceleration	212.27 g	130	163.3
Fractured L femur (comminuted transverse in the mid to lower third of shaft)	3				

Head Injury Computer Modelling

1. Head Kinematics

A total of 9 components of acceleration were measured from the skull during the crash test. The accelerometer attached to the middle of the skull measured the x, y and z accelerations (3 components) at the centre of gravity. Other accelerometers inside the front, top and side of the skull measured the other 6 accelerations required for angular acceleration calculations.

2. Head Injury Results

The results from evaluating the two head injury models are presented below:

The NHTSA SIMon Head Injury Model: The NHTSA Model bases its head injury for DAI by associating the cumulative volume of the brain matter experiencing tensile strains over a critical specified level, and is based on the maximum principal strain. The volume of elements that has experienced a strain greater than the prescribed level is computed at each time increment.

In 1982, Gennarelli et al. tested 45 Rhesus monkeys to head angular acceleration in three different directions: sagittal, oblique and lateral. Angular acceleration was achieved by moving the animal head through a 60-degree angle with time intervals varying from 11 to 22 ms. During these experiments ASDH, cerebral concussion, and DAI were produced in these animal subjects. The authors concluded that angular acceleration of the head causes DAI and is proportional to the degree of coronal motion. The type of axonal injury and distribution seen in animals was found to resemble that found in severe head injury in humans.

The SIMon program uses Hobourn's inverse 2/3-power law to scale the response of the Rhesus monkey to human, based on head mass. At a 15% strain level, a CSDM value of 5.5% indicates mild DAI while a CSDM of 22.7% represents severe DAI (Eppinger and Takhounts, 2001). A nine-accelerometer package (NAP) comes with the PC beta version of the SIMon. This package calculates the angular acceleration needed for running the FE model based on the SAE sign convention. However, the current PC version of the SIMon model uses the NHTSA sign convention, which is different from the SAE sign convention thus adding complexity to the procedure. Subsequently, all simulations reported in this study were performed directly using the same SIMon FE model running in Unix version of LS-DYNA. The input head linear and angular accelerations for AIS 0 and AIS 5 cases are shown in Figures 12 and 13. The total simulation time was 150 ms for the AIS 0 Case due to longer contact time and 50 ms for the AIS 5 Case.

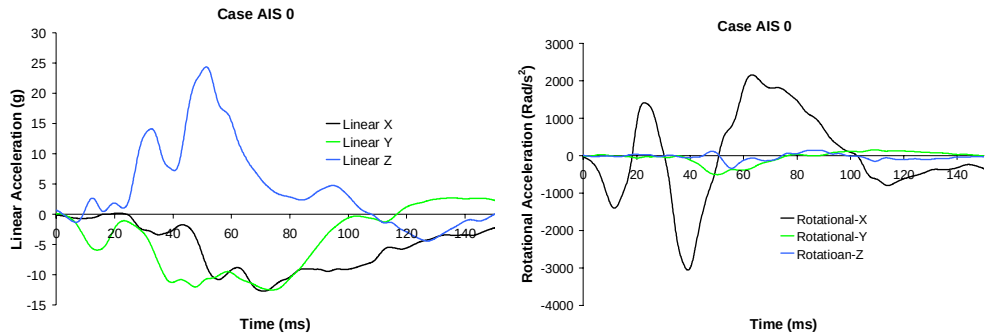


Figure 12 (a and b): Linear and angular acceleration for the SIMon Model in the AIS 0 Case

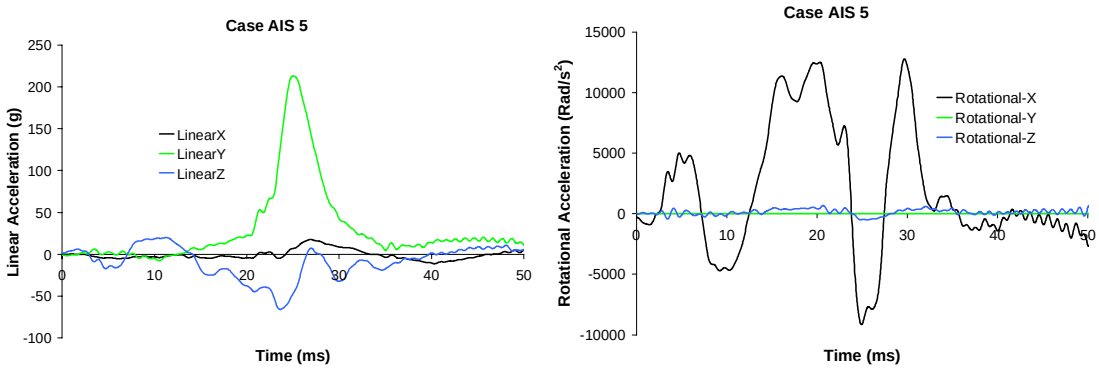


Figure 13 (a and b): Linear and angular acceleration for the SIMon Model in the AIS 5 Case

<u>AIS 0 Case:</u> At 40 ms, after the head angular acceleration reached its peak, the CSDM predicted by the SIMon model shows that about 0.4% of the brain volume experienced a strain level 15% or higher (Figures 14a and 14b). Based on the report by Eppinger and Takhounts (2001) and Gennarelli and Thibult (1982), the injury threshold for mild DAI was 5.5%. Results from the current simulation show that the occupant was well below this proposed injury threshold.

<u>AIS 5 Case:</u> Only the first impact (head to B-pillar) was simulated for two reasons: firstly, it cannot be certain that the head to head contact occurred in the real-world crash and secondly, if head to head contact did occur in the real-world crash, the force generated by the ATD to ATD head contact in the crash test would be much higher than that in the real-world crash due to the stiffness of the ATD's.

At 28 ms, after the peak linear acceleration has passed, 24% of the brain volume (CSDM) exceeded a strain magnitude that is 15% or higher (Figures 15a and 15b). Again, based on studies by Eppinger and Takhounts (2001) and Gennarelli and Thibault (1982), the occupant in this case would suffer severe DAI.

<u>The WSU Brain Injury Model:</u> The same three translational and three rotational accelerations shown in Figures 13a and 13b were applied to the CG of the WSUHIM. Because the CSDM was not available in the code used to run the WSUHIM, the CSDM was checked manually by counting the number of elements that exceeded 15% of strain at a time increment of 2 ms throughout the entire brain.

<u>AIS 0 Case:</u> The model predicted that 3% of the brain elements experienced a strain of 15% or higher. The maximum principal strain contours in a para-sagittal and a coronal section are displayed in Figures 15a and 15b. Regions of high strain were located in the upper brain stem for the non-head injury (AIS 0) case with the majority of brain elements sustaining a strain of 10% or below.

<u>AIS 5 Case:</u> The high maximum principal strains were concentrated in the central core region of the brain, more specifically, in the midbrain, upper brain stem, most of the diencephalon and the inferior portion of the occipital lobe. The corpus callosum region also experienced high strain in the current model simulations. These results are shown in Figures 17a and 17b.

DISCUSSION

In this research, real-world crashes were reconstructed using the same model year vehicles. Crash test ATD's were used to obtain the occupant kinematics. Furthermore, the measured linear and angular accelerations of the head were used as input for two currently available head injury FE models.

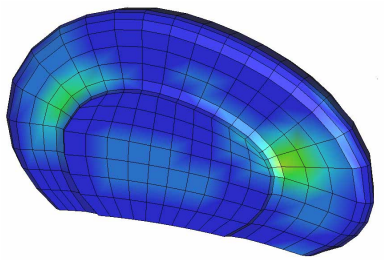


Figure 14a: AIS 0 Case - SIMon Model saggital view at 40 ms

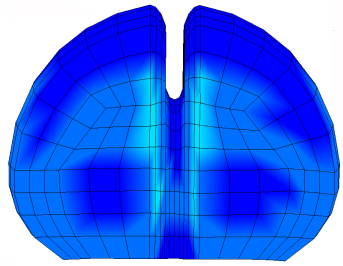
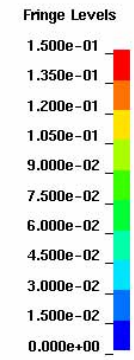


Figure 14b: AIS 0 Case - SIMon Model coronal view at 40 ms



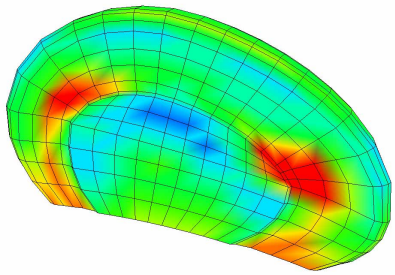


Figure 15a: AIS 5 Case – SIMon Model saggital view at 28 ms

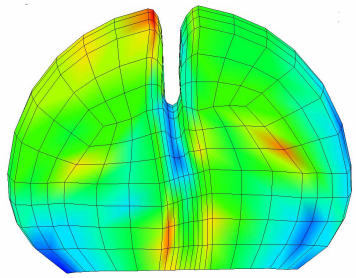
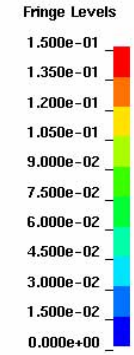


Figure 15b: AIS 5 Case - SIMon Model coronal view at 28 ms



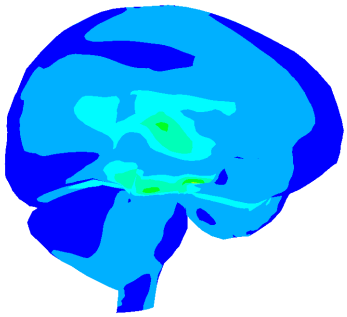


Figure 16a: AIS 0 Case - WSU Model saggital view at 40 ms

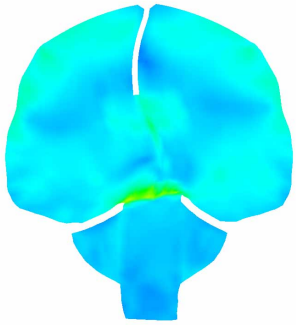
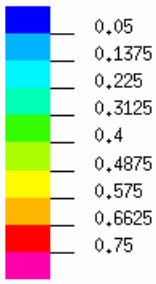


Figure 16b: AIS 0 Case – WSU Model coronal view at 40 ms



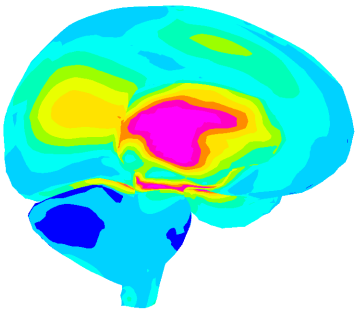


Figure 17a: AIS 5 Case -WSU Model saggital view at 28 ms

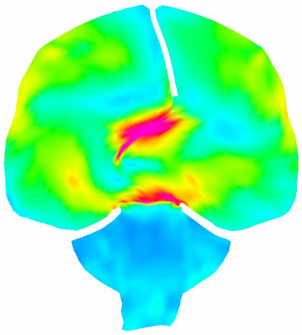
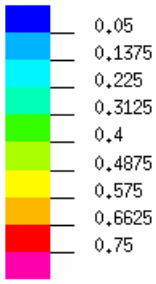


Figure 17b: AIS 5 Case -WSU Model coronal view at 28 ms



By using real-world crashes, the biofidelity of the model predictions could be calibrated since actual patient injuries rather than injury criteria were compared with model predictions. In the two extreme cases reconstructed and simulated, both models were able to demonstrate significant differences between the no head injury (AIS 0) and critical head injury (AIS 5) cases.

It is difficult to perform a physical crash test that replicates the real-world crash. In this study, the computer modelling conducted prior to the crash test was used to predict the crash speed required to produce similar crush profiles and consequently analogous injury outcomes to those in the real-world crash. However, the crash test precision is limited by the accuracy of the prior vehicle computer simulations. The HVE software depends on the assumed stiffness values for the determination of delta-V. Unlike finite element modelling of a vehicle, the stiffness can be prescribed for front, back, side panels, roof and base of vehicle in the HVE but point-by-point stiffness values for any structure cannot be defined. In addition, the vehicles in the crash were not part of the HVE database and had to be designed using the software, hence, they are less accurate. To compensate for these shortcomings, an FE model of a Commodore was used to provide an alternative way to model the crash prior to the physical crash test. FE models have the advantage of being more accurate since the stiffness and other characteristics of the vehicle can be defined on a point-by-point basis. However, the disadvantages include the time required both to prepare each simulation in addition to the long computational time needed. Using both methods enabled as much information to be obtained about the pre-crash circumstances before performing the physical crash test.

Another disadvantage of the current method is that crash ATD's used in the reconstruction do not necessarily represent the actual occupants. The physical ATD's are limited to only several standard sizes, which may not accurately represent the occupants in the cases selected for reconstruction.

Analysis of the AIS 0 Case showed that the NHTSA SIMon model predicted that the driver had no head injury, while the WSUHIM showed a hot spot or high strain location in the upper brain stem region, an area known to play a vital role in basic attention, arousal, and consciousness. According to the FSP, the driver suffered loss of conscious (LOC) for a short period of time following the collision. The ambulance report also mentions that LOC may have occured. However, if LOC had indeed occurred, it could not be verified by medical personnel attending the crash and consequently was not coded. Hence, it is possible that the minor hot spot in the WSUHIM was related to the LOC, but this cannot be verified.

For the AIS 5 case, the SIMon Model predicated that the occupant suffered severe DAI. The WSUHIM agreed with this prediction, but further localised the injury regions to the inferior portion of the occipital lobe, the corpus callosum inferior to the falx, the tentorium cerebellum junction, the midbrain, and the upper brain stem. As previously demonstrated in Table 6, the head injuries sustained by the occupant were a temporal bilateral extradural haematoma (AIS 5), a temporal lobe contusion (AIS 3), bilateral temporal bone fractures (AIS 3) and bilateral sphenoid bone fractures (AIS 3). The WSUHIM was able to capture the bilateral nature of the brain injury but the locations seemed to be more posterior than those reported in the medical records. This is partly due to the fact that the contact point of the crash reconstruction was further towards the rear of the vehicle than in the real-world crash.

The results from these models are promising. However, it is clear that more data is needed for model validation. For instance, the nature of the injury cannot always be predicted, such as in the case of a fracture. In the current study, the driver in the AIS 5 Case suffered a severe fracture at the base of the skull, but neither model could predict this fracture. This was partly due to the fact that neither of the models included boundary conditions at the neck. Subsequently, forces and moments near the occipital junction are not represented accurately.

As noted in the strain magnitude, the SIMon model predicts significantly lower values compared to those predicted by the WSUHIM. This is primarily due to the selection of brain material properties. The shear modulus used in the SIMon model was three times that used in the WSUHIM even though the value selected for the WSUHIM was almost 10 times that measured *in vitro* as reported by Arbogast and Margullies (1997). Zhang et al. (2002b) rationalized that an increase in the material property is needed because the effect of blood vessel tethering is not recognized during *in vitro* testing. However, to what extent the cerebral vasculature contributes to the shear modulus in a living person is yet to be determined.

The two head models were used in this study to determine how well different models predict real-world head injuries. Each model has advantages: the SIMon Model is more user friendly and requires less computational time, enabling many simulations to be performed in a relatively short time period. On the other hand, the WSU model can be modified by the user and is able to pinpoint the region of injury more precisely.

In this study, two extreme cases of head injury severity were used to provide data for FE model validations and/or calibrations. The next stage of this study is to select and reconstruct cases where the occupant sustained AIS 1 (mild) to AIS 4 (severe) head injuries to allow these models to be validated. Data obtained in our study complement another study jointly conducted by Biokinetics (Ottawa, Canada) and WSU, which emphasized concussive brain injury cases observed in American football fields (Zhang et al, 2001b). If both low severity and high severity brain injury can be predicted accurately by a numerical model, it is anticipated that in the future, models such as those presented in this paper will replace criteria such as the HIC. The HIC has been useful in that it has provided a benchmark on which to base injury predictions. However, it is not a criterion based on brain responses. With a better understanding of the mechanisms of head injury and improved tools to predict these injuries, it is feasible that FE models will replace the HIC to provide guidelines for designing countermeasures for head injury protection.

ACKNOWLEDEMENTS

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