COMPUTATIONAL ANALYSIS OF REAL WORLD CRASHES: A BASIS FOR ACCIDENT RECONSTRUCTION METHODOLOGY

Vikas Hasija
GESAC, Inc
Erik G. Takhounts
Stephen A. Ridella
NHTSA
United States
Paper Number: 07-0050

ABSTRACT

This paper focuses on an accident reconstruction methodology by estimating the errors introduced into reconstruction analysis as a result of assumptions made due to lack of data availability and other uncertainties. Mathematical models are used to show the sensitivity of their results, i.e., occupant kinematics, injury predictions, etc., to changes in these assumptions. For demonstration purposes, a real world crash involving an occupant with "no brain injury" was selected from NHTSA's Crash Injury Research and Engineering Network (CIREN) database and reconstruction was carried out using the information available from the crash. The crash pulse for the case was obtained using Human-Vehicle-Environment (HVE) software and then applied to a MADYMO (Mathematical DYnamic MOdel) occupant simulation model of the case vehicle and occupant. Head acceleration output from the model subsequently served as an input into the NHTSA-developed SIMon (Simulated Injury Monitor) finite element (FE) head model and used to compute probabilities of various brain injuries. The results of the SIMon predictions were then compared to the brain injuries reported in CIREN. Sensitivity analysis was carried out at each step with respect to various assumed parameters starting with generation of the collision pulse in HVE and ending with SIMon brain injury predictors. Important parameters required for better injury predictions were also identified, and some observations that may be relevant to the CIREN accident investigation team are made. This paper shows that a "no injury" case can become an "injury" case due to the introduction of variability in reconstruction parameters. This paper thus shows the methodology, including important details to be taken into account as well as the additional information that needs to be collected from the real world crashes for better accident reconstruction analysis.

INTRODUCTION

Computerized accident reconstruction analysis is a tool used to investigate crash sequences and to study occupant kinematics during crashes. Information obtained on occupant kinematics can then be used to design better and more efficient safety systems for occupant protection. There are several potential parameters influencing a real occupant's injury risk, but unfortunately many of them are unknown and an accurate accident reconstruction analysis cannot be carried out. As a result, the occupant injuries cannot be predicted correctly. Since assumptions have to be made for these unknown parameters, one set of reconstruction parameters is not sufficient to predict occupant injuries. It becomes imperative to carry out a sensitivity analysis with respect to these assumed parameters to find those critical parameters that affect the injury predictions significantly. These critical parameters need to be controlled better (minimize their range of variation by gathering additional information on these parameters) before injuries are predicted. The predicted injuries can be quite different from the actual injuries if control is not exercised.

In the past, an occupant's injury evaluation based on reconstruction has been carried out using computational models, but with only one set of reconstruction parameters and without any sensitivity analysis. For example, Franklyn et al [1] presented a paper on accident reconstruction in which they physically reconstructed real world accidents, and the information from these physical tests was used as input to finite element head models for predicting injuries and subsequently compared with actual occupant injuries. During experiments, various errors can affect the data. For example, the crush depth obtained from their physical tests do not match up with the real world crash data, and this discrepancy can certainly affect the crash pulse experienced by the vehicle as well as the accelerations experienced by the Anthropomorphic Test Device (ATD) used in their physical tests, which provides input data for the computational models. Sensitivity analysis was not carried out in the Frankyln study to see how the results, i.e., the injury predictions obtained from the finite element head models, were affected due to these errors. This analysis is very important when using computational models to predict injuries as the models are only as good in predicting injuries as the input data driving them.

Also, Mardoux et al [2] presented a paper showing the head injury-predicting capability of HIC (Head Injury Criterion), HIP (Head Impact Power), SIMon FE head model and ULP (Louis Pasteur University) FE head model. Input data for the finite element head models was obtained by experimental reconstruction of real-world cases with the Hybrid-III (H-III) dummy head. The experiments have errors associated with them that can lead to errors in the model's injury predictions. Sensitivity analysis of the model or the model's injury prediction was not carried out in this study either. The effect of these uncertainties must be analyzed. Also in this study, von-Mises stress and global strain energy were used as a measure of brain injuries that have not been shown experimentally to be related to brain injuries. Different injury metrics were studied in this paper (and some were shown to be better than others), but it becomes necessary to first control the reconstruction parameters before showing the effectiveness of the injury metrics, as variability in the parameters can lead to quite different injury metrics.

The objective of this paper is to show a reconstruction methodology that involves sensitivity analysis with respect to the assumed parameters and identify the critical parameters using injury assessment quantities such as HIC and SIMon brain injury metrics [3], namely Cumulative Strain Damage Measure (CSDM), a correlate for diffuse axonal Injury; Dilatational Damage Measure (DDM), a correlate for contusions; and Relative Motion Damage Measure (RMDM), a correlate for subdural hematoma. The methodology is shown by reconstructing a "no brain injury" real world crash selected from the CIREN database [4] and comparing injury predictions with real world injuries. It shows that due to variability of reconstruction parameters, some injury metrics can switch from "no injury" to "injury." Finally, some observations are made for the CIREN crash investigation team on the additional data that needs to be collected on the field, which can be used for accident reconstruction.

METHODOLOGY

The methodology for reconstructing real world accidents using computer simulations starts with selection of real world case from the CIREN database (Figure 1). The Event Data Recorder (EDR) information listed in CIREN is then searched to find the crash pulse. If no EDR information is available, the crash details available from the selected case are used in Human-Vehicle-Environment (HVE) software [5] to generate the crash pulse. This is followed by setting up the occupant simulation model in MADYMO [6] using the information available from the selected case such as occupant information, restraints information, etc. The crash pulse obtained from either EDR or HVE is used for driving this occupant simulation model. During the set up, the unknown parameters are identified and assumptions are made for these parameters (Figure 1). Once this model is set up, the baseline run is obtained by matching the occupant-vehicle contacts happening during the simulation with those listed in CIREN. Sensitivity studies are carried out around this baseline run with respect to the assumed parameters. For all these parametric simulations, the CIREN-listed occupant-vehicle contacts are maintained to ascertain the validity of the selected case. The head accelerations obtained as output from the baseline run and all the parametric runs are then used as input into the SIMon finite element head model [7] to predict brain injuries, which are then compared with the actual occupant injuries. HIC and SIMon brain injury metrics obtained are further analyzed to identify the parameters that affect the output considerably and thus need to be controlled better before running the final simulation for injury predictions. The methodology is demonstrated here by reconstructing a "no brain injury" case.

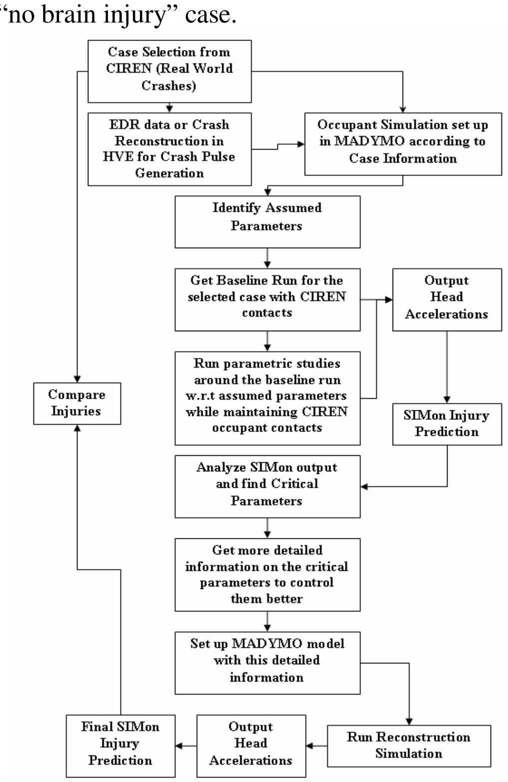


Figure 1. Reconstruction Methodology Diagram.

Case Selection

The case selection matrix was taken from CIREN. Only cases with single event, frontal impact with PDOF of $\pm 10^{\circ}$, with no rollover and having a status of "COMPLETED" were considered. Cases were selected that provided enough information for reconstruction in HVE (vehicle type, collision partner involved, Collision Deformation Classification (CDC), Principal Direction of Force (PDOF), Crush and DeltaV) and also enough information for occupant simulation in MADYMO (age, height, weight of the occupant, occupant role, restraints used, airbag information, seat performance information, etc). One important criterion for case selection was good occupant-vehicle contacts that could be simulated. All cases with airbag failure, seat performance failure and seatbelt failure were ignored. Cases where the occupant was asleep or in an Out-of-Position (OOP) state were also ignored. Based on these selection criteria, the case that had the most information available for reconstruction was a case of moderate crash severity with the case occupant sustaining "no brain injuries."

Selected "No Brain Injury" case –Details of the "no brain injury" case that was reconstructed are provided below:

This crash occurred at night with no streetlights while it was raining on a wet roadway surface. The speed limit was posted at 25 mph. Case vehicle one (V1), a 1995 Saturn SL four door sedan, was traveling eastbound on a two lane, two-way roadway that curved right to the south (Figure 2). Vehicle two (V2), a 1988 minivan, was northbound on the same roadway, but was traveling in the opposite lane. As V1 had completed the curve and recognized V2 in the lane, the driver began to apply the brakes and attempted to move right partially on the shoulder. V2 also applied the brakes, leaving lockup evidence prior to striking head-on with V1. Post impact, V1 rotated counterclockwise and was forced rearward into the roadside ditch. This was a moderate severity head-on crash with a delta-V of 34 mph.

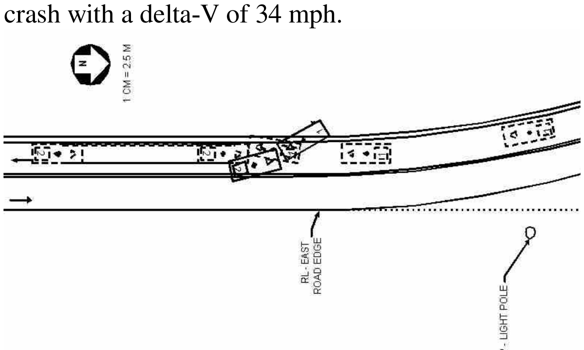


Figure 2. Crash Scene for "no brain injury" case.

In this case, the case occupants were the driver and back center seat passenger in V1. In our study only the driver was considered. The driver (28-year-old female, 173 cm in height and 73 kg in weight) was wearing the lap/shoulder belt and had a frontal airbag deployment. The occupant (driver) did not have any major injuries; all listed injuries were minor skin contusions/lacerations (Table 1).

Table 1.
Occupant Injuries

AIS Code	Description
8906021	Lower Extremity Skin Laceration Minor
4904021	Chest Skin Contusion
7904021	Upper Extremity Skin Contusion
7902021	Upper Extremity Skin Abrasion
2904021	Facial Skin Contusion

The occupant contact points with the vehicle interior (Table 2) were taken from CIREN. During the reconstruction simulations, it was made sure that these contacts were maintained between the occupant and the vehicle interior.

Table 2.
Occupant-Vehicle Contacts

Contact	Component	Body Region
1	Airbag –Driver side	Face
2	Knee Bolster	Knee-Left
3	Steering Column/ Transmission	Knee-Right

Crash Pulse Generation

For the crash pulse (vehicle deceleration pulse during impact), EDR data (if available) should be preferred, but since the EDR data was not available for this case, Human-Vehicle-Environment (HVE) software developed by Engineering Dynamics Corporation (EDC) was used for crash pulse generation. Specifically, Engineering Dynamics Simulation Model of Automobile Collisions (EDSMAC4) module was used for this purpose [5, 8, 9, 10, and 11].

Before using this module for the selected CIREN case, the module's crash pulse generation capability was evaluated by generating the crash pulse for several tests for which the crash pulse was already known. These were vehicle-vehicle compatibility tests that were selected from NHTSA's vehicle database [12]. Two different types of vehicle-vehicle impact tests were selected; one full frontal collinear (Figure 3 - Chevy Venture into Honda Accord), and the other 50% offset frontal (Figure 4 - Dodge Grand Caravan into Honda Accord). Vehicle-vehicle impact tests were evaluated so as to be consistent with the selected CIREN case which involves vehicle-vehicle impact.

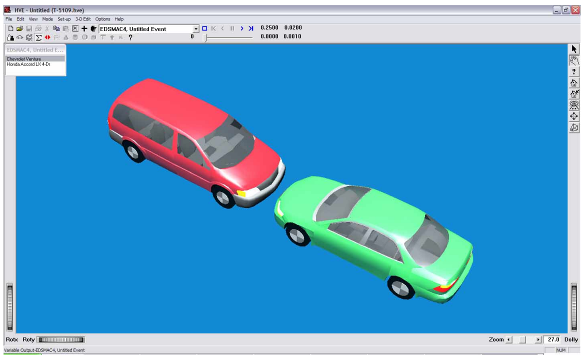


Figure 3. Full frontal case set up.

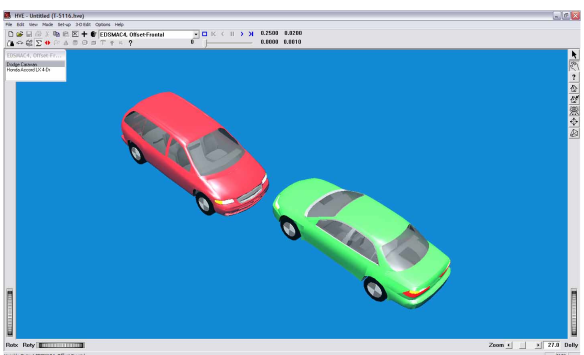


Figure 4. 50% Offset frontal case set up.

For this evaluation study, vehicle models were chosen from the vehicle database and updated with respect to the exterior specifications (overall length, width, wheelbase, front overhang, rear overhang, weight, etc.) as per the test report. The tire model was also updated and was selected from the tire database. Position and velocities were then assigned to the vehicles according to the information in the test report. Delta-V and crush were matched to get the crash pulse.

In HVE, even though only homogeneous and linear stiffness could be defined for any side of the vehicle by specifying parameters A and B (Figure 5), a reasonably good approximation of the crash pulse was obtained (Figures 6 and 7).

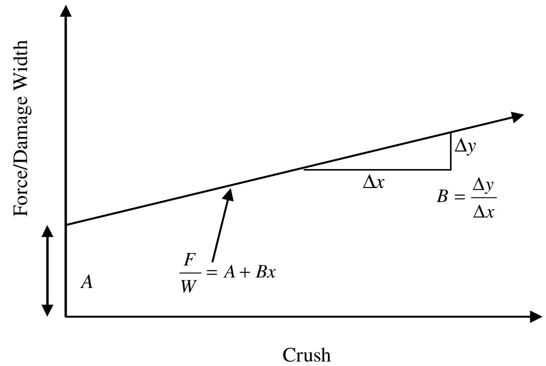
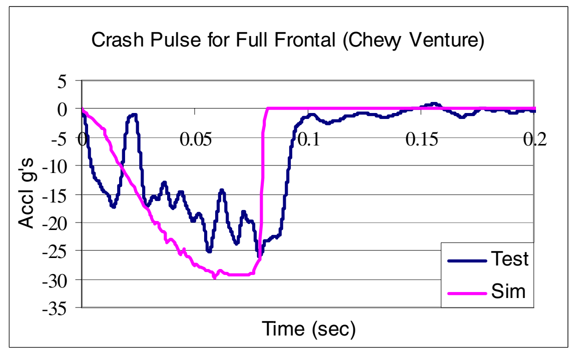
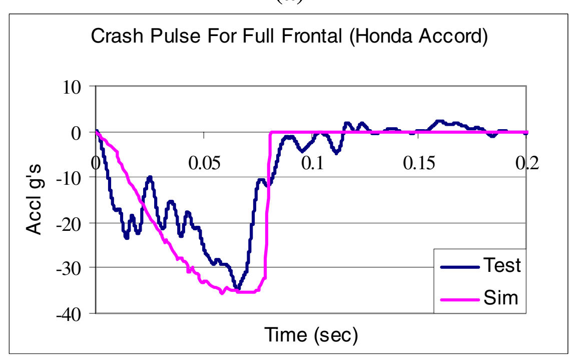


Figure 5. Stiffness used in HVE.

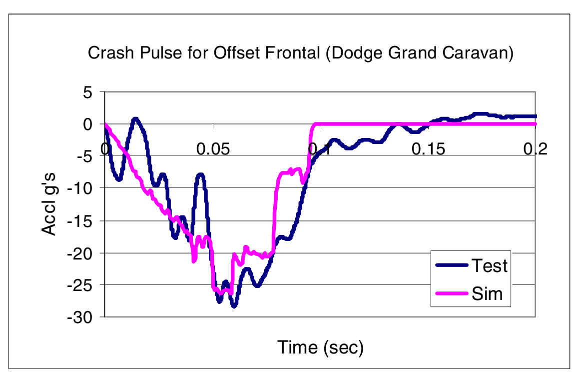


(a)

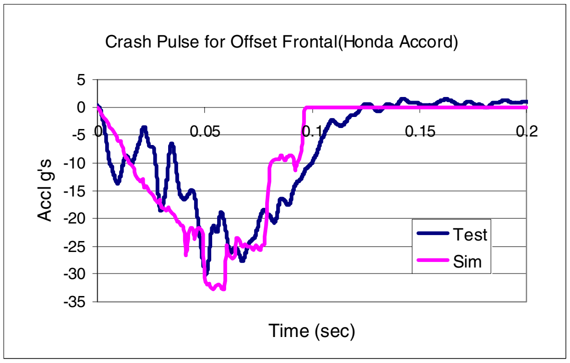


(b)

Figure 6. Crash pulse comparison for full frontal case for (a) Venture and (b) Accord.



(a)



(b)

Figure 7. Crash pulse comparison for offset frontal case for (a) Caravan and (b) Accord.

To generate the crash pulse for the CIREN case, the vehicles involved in the crash were first selected. For the 1995 Saturn SL, which was the case vehicle, a generic passenger car model was used. For the second vehicle (1988 Dodge Caravan) involved in the crash, a generic van model was used. Generic models were used to calculate crush more precisely. Both these vehicle models were then updated with respect to the exterior vehicle specifications: front overhang, rear overhang, overall length and width, wheelbase and weight. The exterior specifications for both vehicles were obtained from the CIREN database. The total weight used was the sum of "Curb weight," "Weight of the Occupants," and "Cargo weight." Since CIREN did not list any information for the occupant in the non-case vehicle (V2), a weight of 150 lbs was assumed for the driver of the non-case vehicle. Vehicle stiffness plays an important role in correct crash pulse generation. Hence, the front, side, rear, top and bottom stiffnesses and the inertias of these generic vehicle models were updated based on the values available from actual vehicle models available in the HVE vehicle database for the case and the non-case vehicle. After these vehicles were set up in the vehicle mode, the crash event was set up in the event mode. The vehicles were positioned (Figure 8) with respect to the global coordinate system according to the heading angles given in CIREN. An estimated initial velocity was then assigned to each vehicle as their velocities were unknown.

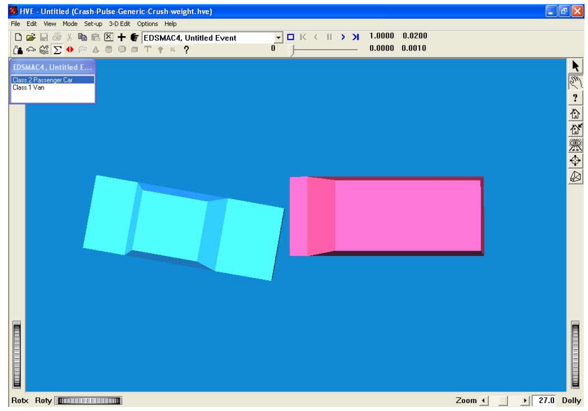


Figure 8. HVE set up for the "no brain injury" case.

To generate a valid crash pulse (Figure 9) for the selected CIREN case, various quantities (i.e., Principal Direction of Force (PDOF), Collision Deformation Classification (CDC), Crush and Delta-V) were matched between CIREN and the HVE simulation by carrying out parametric variations with respect to the impact location, vehicle velocities, inter-vehicle friction, etc. Since CIREN did not report all these quantities for the non-case vehicle, only Delta-V was matched for the non-case vehicle. A good match was obtained for both the case and non-case vehicle (Tables 3 and 4). Post-impact motion obtained for both the case and the non-case vehicle in the HVE simulation was consistent with the information provided in CIREN. The damage photo from CIREN was also compared with the damage profile obtained from HVE (Figure 10). The match seemed to be reasonable coming from an EDSMAC4 module simulation which is a 2D physics program and thus incapable of simulating hood buckling.

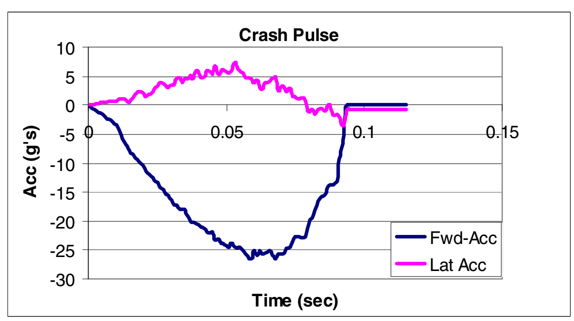


Figure 9. Crash pulse generated using HVE.

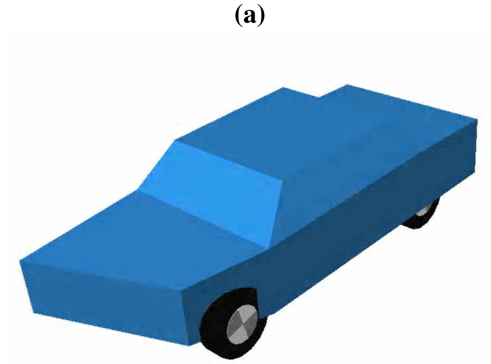
Table 3.
Case vehicle match

Saturn	CIREN	HVE
DeltaV mph	34	35
Crush, in	31	28.62
CDC	12FYEW4	12FYEW5
PDOF (deg)	350	349.6

Table 4.
Non-case vehicle match

Dodge	CIREN	HVE
DeltaV mph	28	28.9

(a)

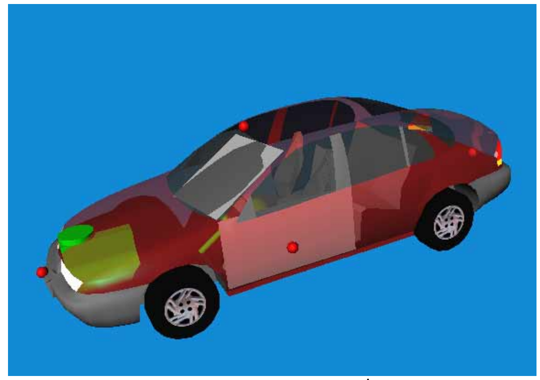


(b)

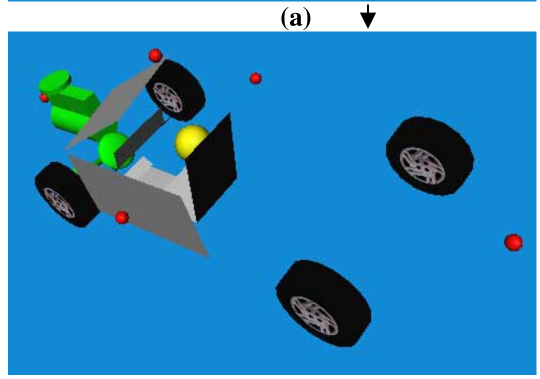
Figure 10. Damage photo from (a) CIREN and (b) HVE.

Occupant Simulation

The occupant simulation was carried out using MADYMO, which is a widely used occupant safety analysis tool that can be used to simulate the response of an occupant in a dynamic environment. The occupant size for this "no brain injury" case was close to a 50th percentile size, and hence the H-III 50th ellipsoid model and the 50th percentile human facet model were used as occupant models in MADYMO. The case vehicle interior surfaces were created in MADYMO. The location of these surfaces was obtained from HVE, which had the actual vehicle model of a 1996 Saturn SL available in its vehicle database. The contact surfaces were first created in HVE (Figure 11), and only the necessary contact surfaces were created based on the contacts listed in CIREN between the occupant and the vehicle interior. This information was then used to create the case vehicle in MADYMO (Figure 12).



(a)



(b)

Figure 11. Contacts Surfaces generated in HVE (a) Full View and (b) No Body View.

The properties for the seat structure, seat back, seat cushion, knee bolster, steering column and the contact characteristics between the occupant model and the vehicle interior were taken from the frontal impact application file [13] available in MADYMO, which has generic but realistic properties. Since the occupant (driver) had an airbag deployment during the crash, a generic airbag model was added to the steering wheel hub. The generic driver airbag model was selected from MADYMO applications [13].

Pre-simulation for positioning the occupant model in the seat was carried out for both the H-III 50th ellipsoid model and the 50th human facet model. Gravity loading was applied for a total time of 1 sec. The joint positions obtained from the last time step were used to update the impact-simulation file to position the dummy correctly in the seat (Figure 12). After this positioning was done, the right foot of the occupant was placed on the brake as mentioned in CIREN case file and the hands were positioned in driving mode. Since the occupant was wearing the lap/shoulder belt during the event, an FE lap and shoulder belt was created and wrapped around the occupant (Figure 12). The properties for the belts were taken from MADYMO application file to be close to the realistic properties.

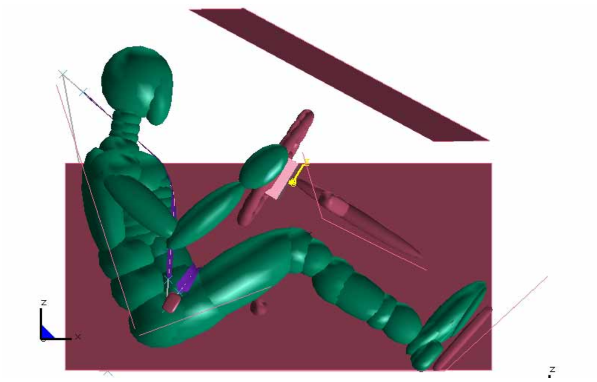


Figure 12. Impact Simulation model for "No Brain Injury" case.

The crash pulse obtained from HVE (Figure 9) was used as a fictitious acceleration field applied on the occupant during the impact simulation. The baseline run was obtained once the occupant-vehicle contacts were matched with those listed in CIREN. Time histories of the head linear accelerations and angular velocities were generated as output to be used for further analysis with SIMon finite element head model. The human facet model took over 15 hours to run as compared to 5 hours for the ellipsoid dummy model on an SGI machine with 1 processor. Because of this time constraint, the human facet model was not used for any parametric studies. The results presented in this paper are thus only from the simulations carried out with the H-III 50th ellipsoid dummy model.

HIC & SIMon Injury Metrics

After the baseline run was obtained in MADYMO, the linear accelerations at the head CG and the angular velocities of the head were obtained in head-body coordinates. These pulses were then input into the NHTSA-developed SIMon finite element head model and the injury metrics were obtained (Table 5), namely CSDM, DDM and RMDM. The HIC values were also calculated (Table 5).

Table 5.
HIC and SIMon Injury Metrics for baseline run

Injury Metrics	Value	Threshold
CSDM (0.15)	0.04628	0.55 *
DDM	0.000185	0.072 *
RMDM	0.8368	1 *
HIC15	424	700
HIC36	564	1000

* Threshold corresponds to 50% probability of injury

The injury metrics CSDM, DDM, RMDM and the HIC values predicted "no brain injury"-below threshold - for the selected case for the baseline run. HIC15, CSDM, DDM and RMDM were further used as assessment quantities to find the critical parameters from the reduced parametric studies carried out with the assumed parameters described in the next section.

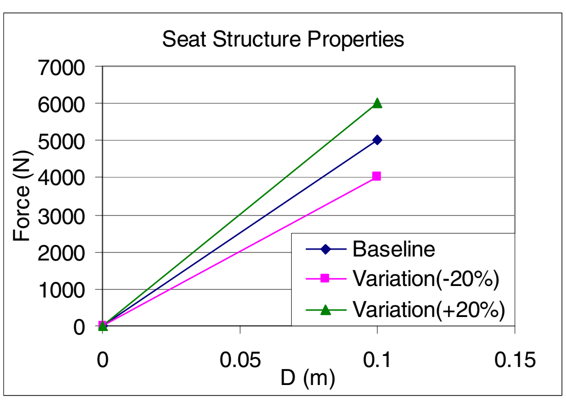
Parametric Studies

Parametric studies were carried out around the baseline run with respect to the assumed parameters to show how the predicted injuries were affected due to changes in these assumed parameters, and to identify the important parameters that need to be controlled better for accurate reconstruction. It was made sure that the CIREN-listed occupant-vehicle contacts were maintained during all these parametric simulations so that the parametric effect could be seen in the valid solution space. Overall, 19 different parameters were studied with an assumed range of variation (Table 6). 9 of these 19 parameters were functions (Figures 9 and 13). Some of the parameter ranges were taken from references [12] and [14].

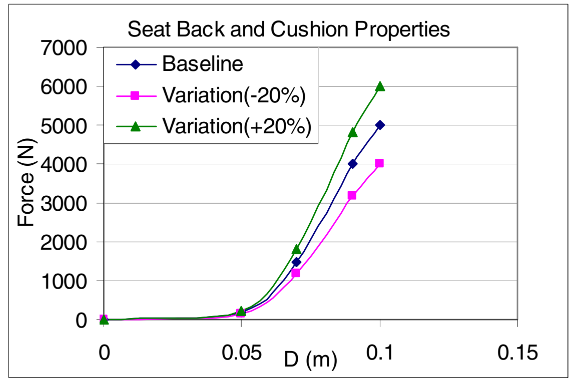
Table 6.
Assumed parameters

	Parameters	Baseline Value	Variations
SEAT	Seat Structure Properties	Figure 13a	± 20%
	Seat Back and Cushion Properties	Figure 13b	± 20%
	Seat Inclination	19	± 5°
	Seat Track Position	Figure 12	56mm 22mm
	Seat Friction	0.3	0.1, 0.6
POSTURE	Seating Posture	Normal	Different positions of left leg
KNEE BOLSTER	Knee Bolster Properties	Figure 13c	± 20%

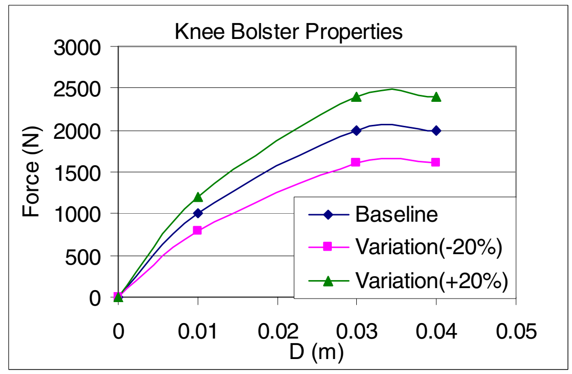
	Knee Bolster Angle	27	$\pm 10^{\circ}$
BELT SYSTEM	Belt Segment Properties	Figure 13d	$\pm$ 20%
	FE Lap/Shoulder Belt Properties	Figure 13e	$\pm$ 20%
	Belt Friction	0.2	0.1, 0.4
	Retractor Properties (film spool effect)	Figure 13f	$\pm$ 20%
	Retractor Locking Time	1 ms	10ms,20ms
DRIVER AIRBAG	Airbag Firing Time	20ms	25ms,35ms
	Airbag Friction	0.2	0.1, 0.6
	Steering Column Angle (Airbag Deployment Angle)	30	$\pm 5^{\circ}$
	Airbag Mass Flow Rate	Figure 13g	$\pm$ 20%
CRASH PULSE SCALING FACTORS	Crash Pulse-X component (Fwd Acc)	Figure 9	0.82,1.11
	Crash Pulse-Y component (Lat Acc)	Figure 9	0.5, 1.5



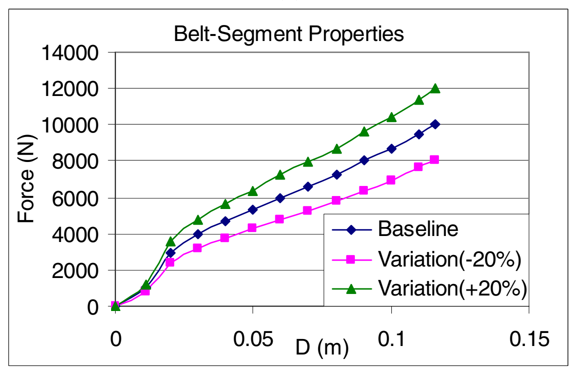
(a)



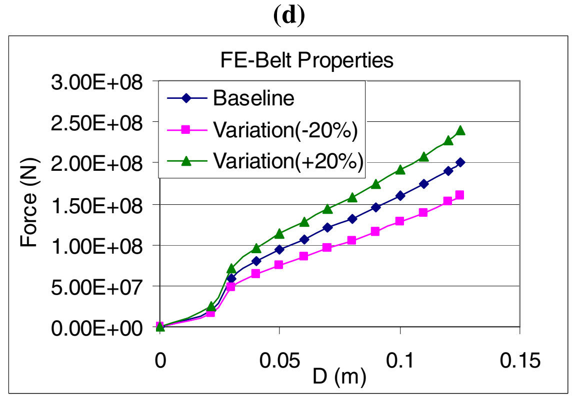
(b)



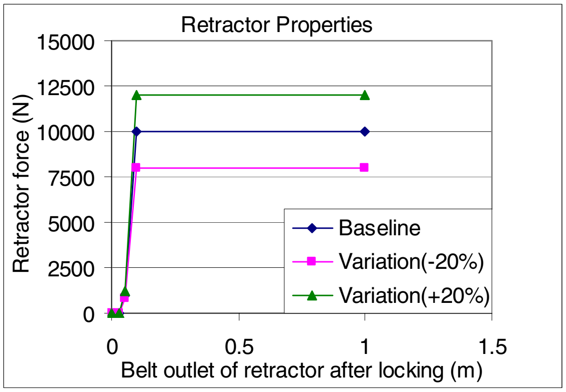
(c)



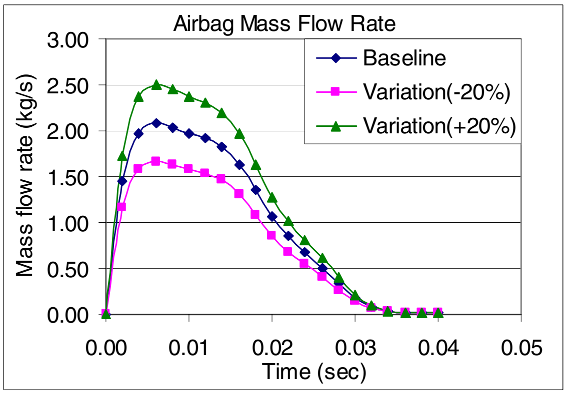
(d)



(e)



(f)



(g)

Figure 13. Plots showing the properties used for different vehicle components.

Even though the knee bolster angle was taken from the HVE vehicle model, it is only an approximate way of obtaining the contact surfaces. Hence, parametric variations were carried out with respect to the knee bolster angle. Also, since the position of the right leg was already known, the position of the left leg was changed to study seating posture effects.

The delta-V reported in CIREN is not exact and an error of $\pm 5\text{mph}$ was assumed in the delta-V value (34 mph) reported in CIREN. Based on this assumption, the scaling factors for the X and Y components of the pulse were obtained. The scaling factor range for the X-component was obtained by making sure that the delta-V obtained by integrating the resultant crash pulse stayed within $34 \pm 5\text{mph}$. Since the Y-component had a much lower magnitude (Figure 9), scaling did not affect delta-V (obtained from the resultant crash pulse) too much. So the scaling factors were selected to produce a change of around $\pm 4g's$.

Since there were a large number of parameters, it was impossible to use the full parametric matrix. Thus, reduced parametric studies were carried out where only a subset was performed to demonstrate the effect of variability/uncertainty.

The reduced parametric studies were carried out first by independently changing each parameter while controlling for the others (fixed to the baseline values). 38 MADYMO simulations were run, two variations for each parameter (Table 6), with each simulation having a run time of 5hrs on a SGI system with one processor. Out of these 19 parameters studied, 14 were found to be critical. The critical parameters were identified by using the following methodology:

First the change in each assessment quantity, i.e. HIC15, CSDM, DDM and RMDM, was calculated for each parameter (Equation 1).

$$\Delta_{HIC15i\,/\,CSDM\,i\,/\,DDM\,i\,/\,RMDM\,i} = Max\,(run1,\,run2,\,run3) - Min\,(run1,\,run2,\,run3);\ i=1\ to\ 19 \quad (1).$$

Once the change was obtained for each assessment quantity for each parameter, normalization was carried out (Equation 2).

$$\Delta^{HIC15}_{normi} = \frac{\Delta_{HIC15i}}{Max\Delta_{HIC15}};\ i=1\ to\ 19 \quad (2).$$

where $Max\Delta_{HIC15}$ corresponds to the maximum value of Δ_{HIC15} obtained for any parameter.

Similar normalization was carried out for CSDM, DDM and RMDM. This normalization was performed because the scales of HIC, CSDM, DDM and RMDM were quite different. Next, the total effect of each parameter on the output was obtained by summing up the normalized values of each assessment quantity (Equation 3).

$$Total\_effect_i = \Delta^{HIC15}_{normi} + \Delta^{CSDM}_{normi} + \Delta^{DDM}_{normi} + \Delta^{RMDM}_{normi}\quad where,\ i=1\ to\ 19 \quad (3).$$

Finally the % effect was obtained for each parameter (Equation 4).

$$\%Effect_i = \frac{Total\_Effect_i}{4};\ i=1\ to\ 19 \quad (4).$$

From the % effect, the critical parameters were identified. As it was impossible to carry out a full cross-effect study due to large number of parameters, around 12 simulations were run by using some of the critical parameters (identified using independent parametric analysis) to study the cross-effects. The limited cross-effect study carried out was in the valid solution space, and was sufficient in the context of this paper. Thus, the reduced parametric study consisted of independent parametric analysis plus some cross-effect analysis.

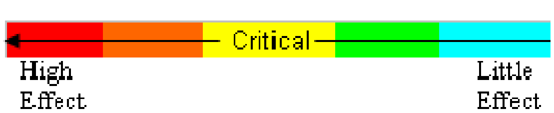
The output from all these occupant simulations was used for driving the SIMon finite element head model to predict brain injuries. 49 FE simulations were run, with each simulation having a run time of around 3hrs on a PC with a Pentium 4 processor. Therefore a total of 100 simulations (51 MADYMO + 49 SIMon) were carried out for this reduced parametric study of the "no brain injury" case.

RESULTS

The results of the first 38 simulations (independent parametric study) were analyzed in terms of the assessment quantities - HIC, CSDM, DDM and RMDM (Table 7) - to show how different parameters affected the output.

Table 7.
Parametric effect (normalized values)

Parameter	HIC 15	CSDM	DDM	RMDM	Total Effect	% effect
Crash Pulse-X component	0.927	1.000	0.343	1.000	3.270	81.76%
Seat Inclination	1.000	0.736	1.000	0.220	2.956	73.91%
Seat Track Position	0.592	0.217	0.564	0.682	2.055	51.39%
Crash Pulse-Y component	0.390	0.495	0.162	0.668	1.716	42.90%
Belt Segment Properties	0.226	0.467	0.475	0.331	1.499	37.48%
Airbag Friction	0.317	0.371	0.204	0.245	1.138	28.44%
Seat Back and Cushion Properties	0.181	0.475	0.060	0.414	1.130	28.25%
Airbag Firing Time	0.160	0.324	0.432	0.150	1.066	26.66%
Seat Friction	0.171	0.532	0.081	0.269	1.053	26.33%
Seating Posture	0.035	0.092	0.565	0.288	0.979	24.48%
Belt Friction	0.240	0.079	0.429	0.171	0.920	23.00%
Steering Column Angle	0.153	0.123	0.174	0.422	0.873	21.82%
Airbag Mass Flow Rate	0.195	0.060	0.295	0.200	0.750	18.76%
Seat Structure	0.042	0.011	0.517	0.039	0.609	15.24%
Knee Bolster Angle	0.031	0.068	0.237	0.232	0.568	14.19%
FE Belt Properties	0.171	0.179	0.019	0.193	0.562	14.05%
Retractor Locking Time	0.049	0.092	0.128	0.176	0.445	11.12%
Knee Bolster Properties	0.035	0.050	0.128	0.149	0.362	9.04%
Retractor Properties	0.000	0.000	0.000	0.000	0.000	0.00%



The assessment quantities for these 38 simulations were also compared with the baseline run (Figures 14 - 17) to show their variation with respect to the assumed parameters.

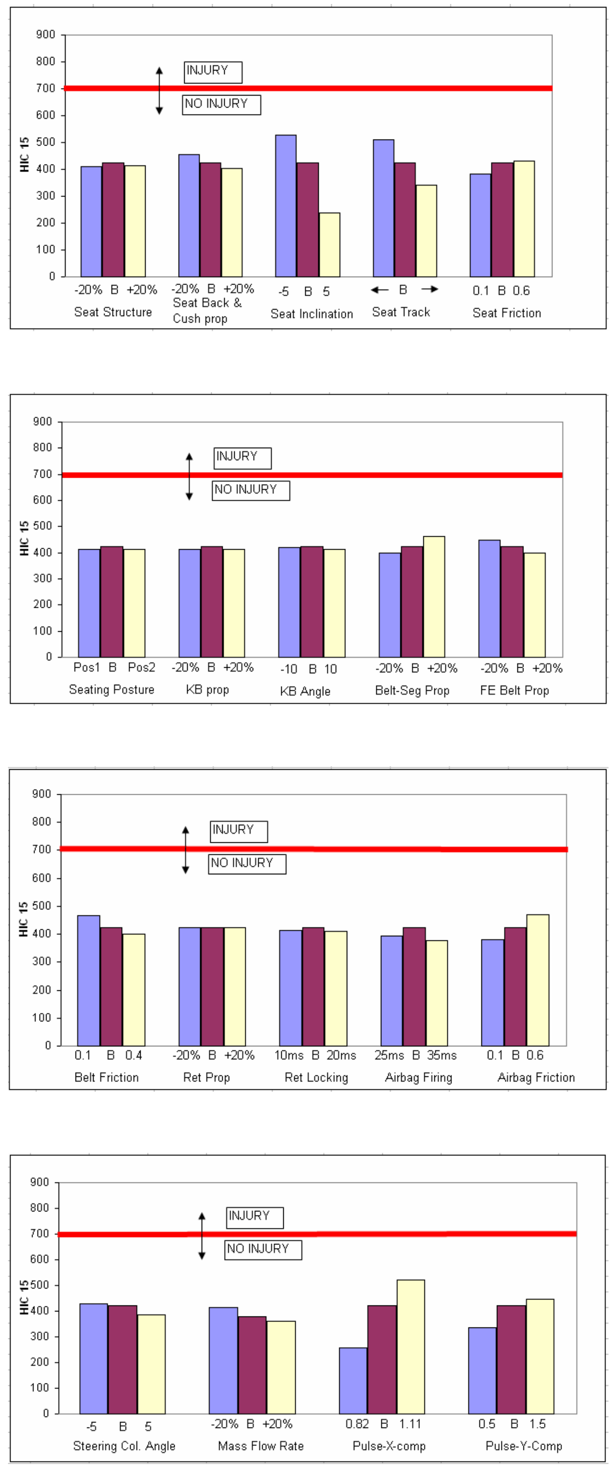


Figure 14. Plots showing the variations in HIC15.

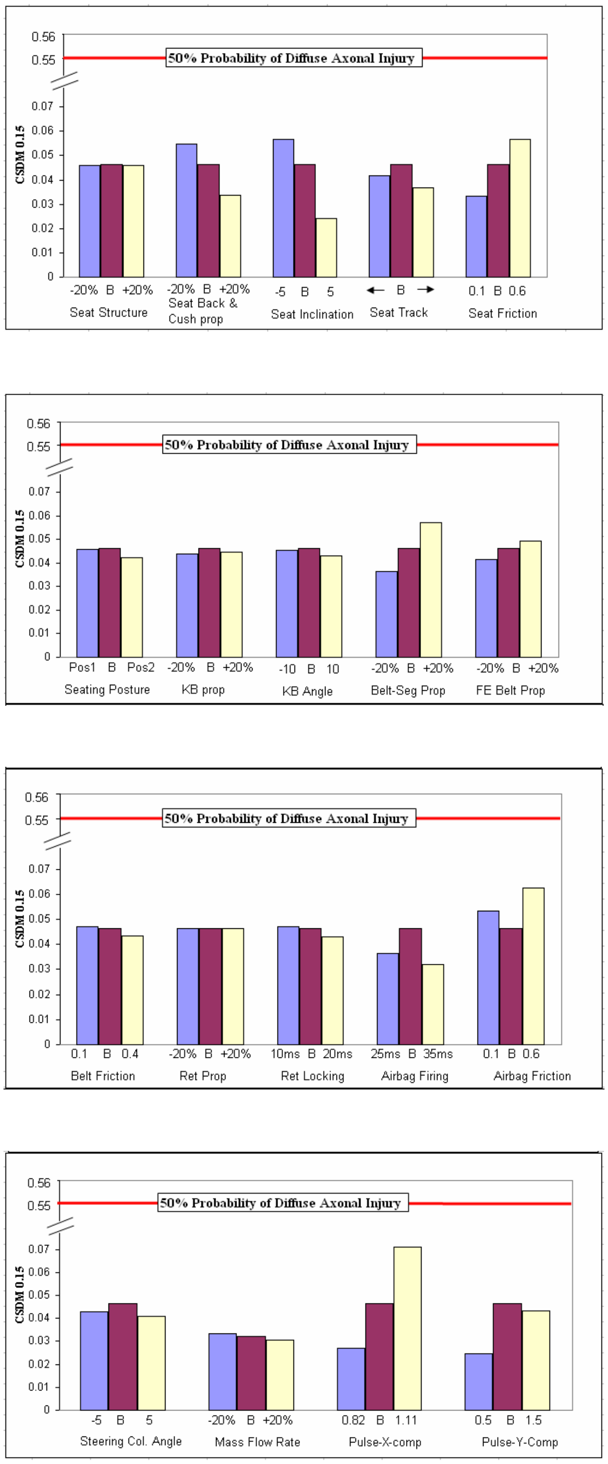


Figure 15. Plots showing the variations in CSDM.

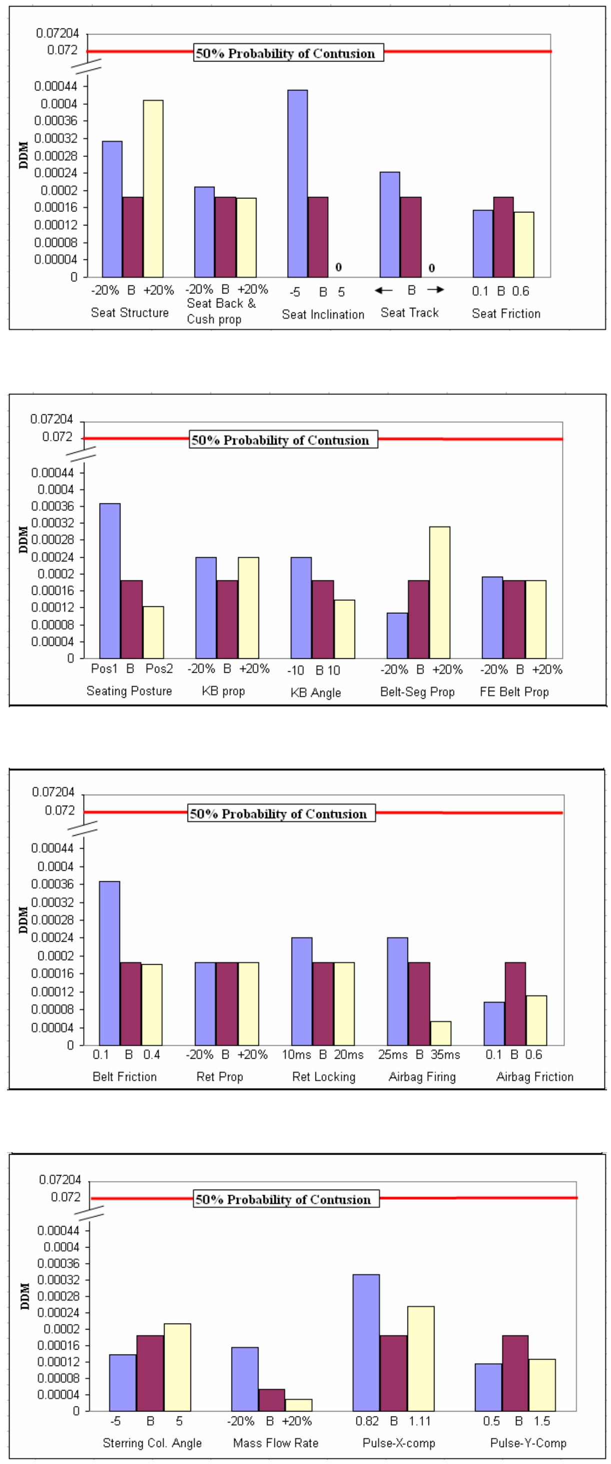


Figure 16. Plots showing the variations in DDM.

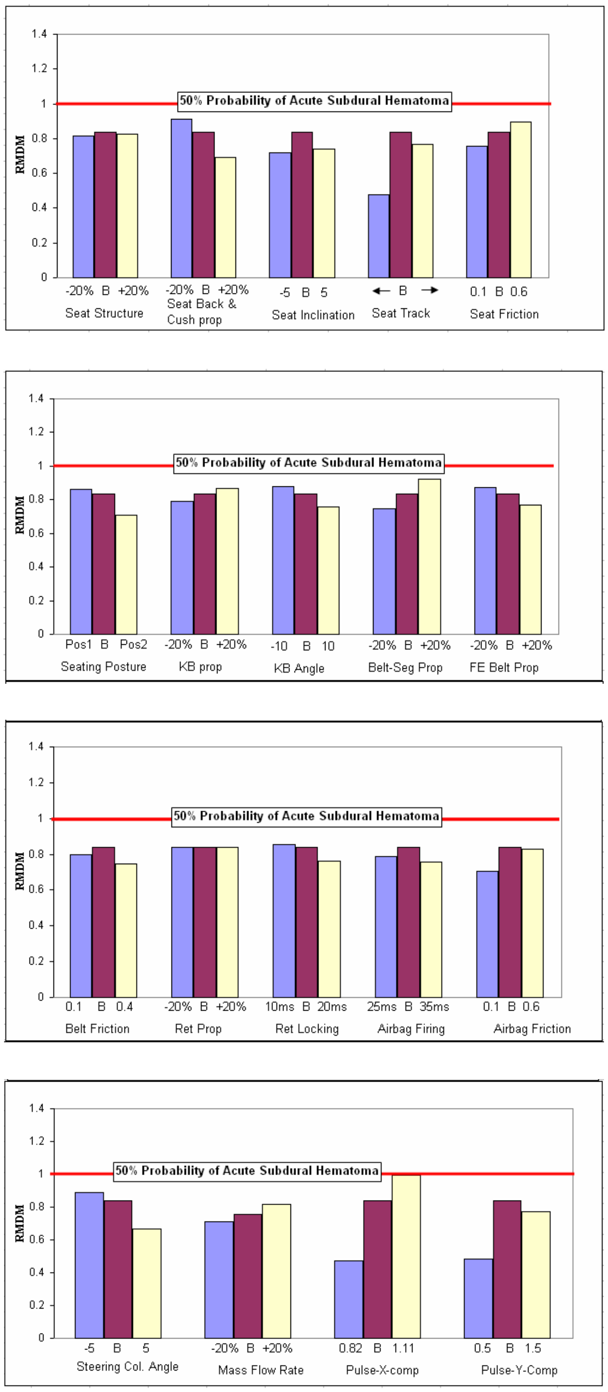


Figure 17. Plots showing the variations in RMDM.

The results (table 7 and figures 14 - 17) showed that the assessment quantities varied more with some parameters and less with other parameters. Hence from this first run we could identify the critical parameters which were: (a) Seat Track position; (b) Seat inclination; (c) Belt Friction; (d) Airbag Friction; (e) Airbag mass flow rate; (f) Airbag firing time; (g) Crash Pulse; (h) Belt segment properties; (i) Seat back and cushion properties; (j) Seat friction; (k) Seating Posture; (l) Seat Structure properties; and (m) Steering Column Angle (Airbag deployment angle). These critical parameters were the ones that produced 25% or more change in any one of the assessment quantities. This 25% change in assessment quantities corresponded to a % effect of more than 15%.

The highest CSDM, DDM, RMDM and HIC15 obtained from the independent parametric study were 0.0709, 0.000431, 0.9958 and 526 respectively. None of the injury metrics exceeded the threshold, thus predicting "no brain injury."

Also as part of the reduced parametric study, around 12 simulations were run (Figure 18) using some of these critical parameters while maintaining the range of these parameters and the CIREN contacts to study the cross-effect of parameters.

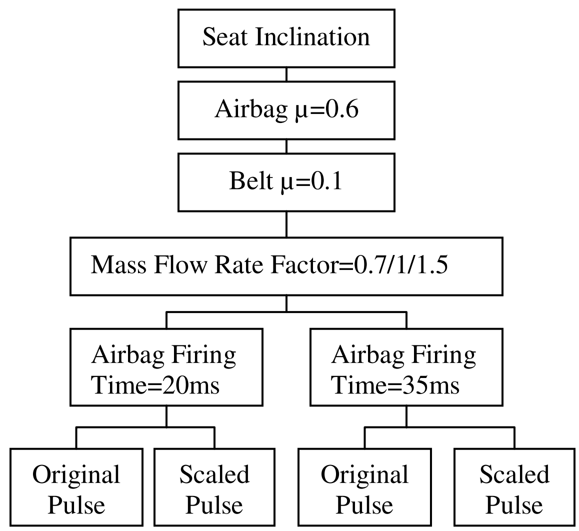


Figure 18. 12 Cross-effect simulations.

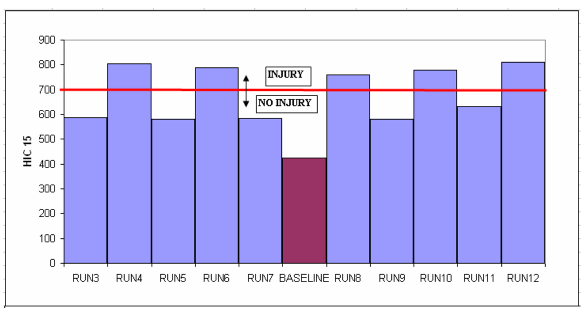
The seat inclination, airbag and belt friction coefficients used above were the ones that produced high HIC value (based on the independent parametric study). These were used in combination along with variations in mass flow rate, airbag firing time and applied pulse to see the effect on the results. Cases that violated CIREN contacts were eliminated (table 8).

Table 8.
Details of the 12 simulations

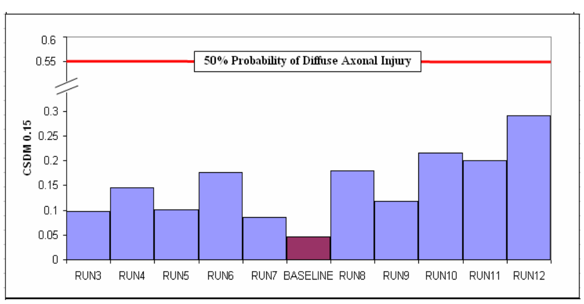
	Seat Inclination	Airbag μ	Belt μ	MFR Factor	Airbag time, ms	Pulse	Validity
RUN1	Incline 1	0.6	0.1	0.7	20	Original	×
RUN2	Incline 1	0.6	0.1	0.7	20	Scaled	×
RUN3	Incline 1	0.6	0.1	0.7	35	Original	√
RUN4	Incline 1	0.6	0.1	0.7	35	Scaled	√
RUN5	Incline 1	0.6	0.1	1	20	Original	√
RUN6	Incline 1	0.6	0.1	1	20	Scaled	√
RUN7	Incline 1	0.6	0.1	1	35	Original	√
RUN8	Incline 1	0.6	0.1	1	35	Scaled	√
RUN9	Incline 1	0.6	0.1	1.5	20	Original	√
RUN10	Incline 1	0.6	0.1	1.5	20	Scaled	√
RUN11	Incline 1	0.6	0.1	1.5	35	Original	√
RUN12	Incline 1	0.6	0.1	1.5	35	Scaled	√

Two cases (run1 and run2) were eliminated as they produced head-steering wheel contact, which was outside of the valid solution region.

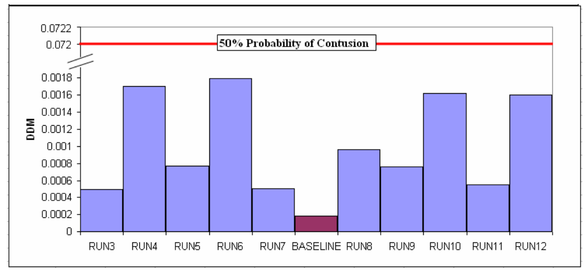
The assessment quantities HIC15, CSDM, DDM and RMDM for the valid runs were compared with the baseline run (Figure 19). The highest CSDM, DDM, RMDM and HIC15 obtained were 0.2901, 0.0018, 1.38 and 812 respectively. Even though CSDM and DDM values did not reach the 50% probability of injury limit, HIC15 and RMDM values exceeded the threshold, and thus predicted "brain injury."



(a)



(b)



(c)

(d)

Figure 19. Plots showing (a) HIC15, (b) CSDM, (c) DDM and (d) RMDM results for the valid cross-effect simulations.

DISCUSSION

This paper shows on one hand the potential of computational tools for reconstructing real world accidents, but on the other hand the difficulty of accurately carrying out the reconstruction as a result of assumptions made due to lack of data availability.

Reconstruction of the "no brain injury" case shows that there are several parameters that have to be assumed in order to obtain a solution. Overall, 19 parameters were assumed for this case. The variability in these parameters can produce quite different results in the valid solution space, as can be seen from the variations in the assessment quantities - HIC, CSDM, DDM and RMDM.

Due to variations in the assessment quantities, one set of reconstruction parameters is not sufficient to evaluate occupant injuries, and it is imperative to identify the critical parameters affecting the results. Parametric analysis can be used to identify the main parameters influencing the occupant response.

The reduced parametric analysis carried out in this paper for the "no brain injury" case shows the process of selecting critical parameters that need to be controlled better. Overall, 14 out of 19 parameters were found to be critical. Lack of parameter control can lead to considerable changes in the injury predictions. The "no brain injury" case reconstructed in this paper went from "no injury" prediction to "injury" prediction due to introduced variability. Out of four injury assessment quantities, two (HIC and RMDM) switched from "no injury" to "injury." Although CSDM and DDM did not switch, they did show considerable variation in their values. Depending on the crash scenario, some or all assessment quantities may change from "no injury" to "injury" if control is not exercised.

The results indicated that crash pulse has a considerable affect on the occupant's injuries. The crash pulse in this study was obtained using HVE, as EDR data was not available. HVE has its own limitations, insofar as the stiffness of the vehicle, which plays an important role in generating the right crash pulse, can only be defined as linear and homogenous for any given side of the vehicle. Additionally, hard spots cannot be defined. As a result the crash pulse obtained from HVE is not precise but approximate. Therefore, EDR data, if available, should be preferred to reduce the variability issues of the crash pulse.

In this study, neither full finite element nor human facet models that better define human geometry and material properties were used for any parametric analysis because of the prohibitive run times. For better reconstruction, human models should be preferred if the run time can be reduced.

All critical parameters substantially affecting reconstruction results were identified using the injury assessment quantities: HIC, CSDM, DDM and RMDM. HIC is based only on the translational accelerations, whereas the SIMon FE model is driven using both translational and angular accelerations. Hence the critical parameters were identified based on changes in both linear and angular components, which were reflected by changes in the injury metrics. Some parameters had more effect on the linear accelerations, and others had more effect on the angular accelerations, thus justifying the use of SIMon injury metrics (CSDM, DDM and RMDM) in addition to HIC for critical parameter identification.

This study only concentrated on identifying critical parameters that affected head injury criteria. These might be different for different body regions and an analysis such as the one presented in this paper can help identify those critical parameters which need to be controlled better before running the final simulation for predicting injuries.

Based on this study some general observations, not limited to the reconstructed case, may be relevant for the CIREN crash investigation team. These are:

1. If possible, CDC, Crush, PDOF and the weight of the occupants for the non-case vehicle should be listed so that a better reconstruction analysis can be carried out to generate the crash pulse.
2. An estimate of the range of variation in the measurement of delta-V, CDC, PDOF and Crush listed in CIREN should be included. Protocols could be developed to eliminate the subjectivity involved in the measurement of CDC, PDOF and Crush.
3. The distances between the seat and vehicle interior surfaces with which the occupant has contacts at different seat track positions obtained from an undamaged, exemplary vehicle should be listed. Protocols could be developed for these measurements.
4. The seat model used in the vehicle should be listed so that the properties can be taken directly from the source. If possible, the seat cushion properties should also be listed.
5. The range of seat back angle (seat inclination) and the value of the seat back angle corresponding to different positions (upright, slightly reclined, etc) obtained from an undamaged, exemplary vehicle could be listed.
6. The seat material could be included to get an idea of the friction coefficient.
7. The knee bolster inclination angle obtained from the undamaged, exemplary vehicle could be listed. If possible, the knee bolster properties (stiffness) could also be mentioned.
8. The belt system model used in the case vehicle should be listed so that the properties can be taken directly from the source, and if possible, the properties (lap/shoulder belt properties, retractor characteristics, etc).
9. The airbag model used should be included so details can be obtained from the source.
10. The range of steering column angle and the value of the angle corresponding to the different positions of the steering column (full up, center, etc., as mentioned in CIREN) obtained from an undamaged, exemplary vehicle could be listed.
11. More details could be mentioned on the seating posture. For example, if the person is asleep, what posture would generate the occupant-vehicle contacts being seen for that case.

The information based on these observations, if made available, may help control the critical parameters and help in a better reconstruction analysis.

Future work may involve, among other things, reconstructing more real world crashes with brain injuries, expanding the parameter matrix, carrying out a more detailed parametric analysis and using human FE or facet models for better occupant simulations.

CONCLUSION

The reconstruction methodology used in this paper and demonstrated by reconstructing a real world crash with "no brain injuries" shows that there are several parameters that have to be assumed during crash reconstruction. The variability in these parameters can change the predicted injury output significantly. The paper indicates the importance of carrying out a sensitivity analysis, identifying the critical parameters and better controlling them before attempting to predict injuries. It was shown that injury predictions for a simulated case can go from "no injury" to "injury" if the analysis is not carried out properly. In essence, sensitivity analysis and parameter control are important steps to improving the injury predictive capabilities of any reconstruction process.

AKNOWLEDGEMENT

The authors would like to thank Mr. Mark Scarboro of NHTSA and Lauren Shook of GESAC, Inc for their help with CIREN, Mr. Terry Day and Mr. Joe Canova of Engineering Dynamics Corporation and Mr. Wesley Grimes of Collision Engineering Associates, Inc for their Insights on HVE, MADYMO technical support and Aida Barsan-Anelli of ISSI, Inc for their helpful comments on MADYMO.

REFERENCES

[1] Franklyn, M., Fildes, B., Zhang, L., Yang, K. and Sparke, L. 2005. "Analysis of Finite Element Models for Head Injury Investigation: Reconstruction of Four Real-world Impacts." Stapp Car Crash Journal, Vol.49, November: 1-32

[2] Marjoux, D., Baumgartner, D., Deck, C., Willinger, R. 2006. "Head Injury Prediction Capability of the HIC, HIP, SIMon and ULP Criteria" IRCOBI conference, September: 143-157

[3] Takhounts, E.G., Eppinger, R.H., Campbell, J.Q., Tannous, R.E., Power, E.D., Shook, L.S. 2003 "On the Development of SIMon Finite Element Head Model" Stapp Car Crash Journal, Vol. 47, October: 107-133.

[4] Crash Injury Research and Engineering Network (CIREN), National Highway Traffic Safety Administration, Department of Transportation Washington, D.C., United States.

[5] Human-Vehicle-Environment (HVE), Version 5.10, March 2006, Engineering Dynamics Corp.

[6] MADYMO, Version 6.2, 2004, TNO, Delft, The Netherlands.

[7] SIMon Software, Version 3.051, June 2004, National Highway Traffic Safety Administration, Department of Transportation, Washington, D.C, United States.

[8] Day, T.D., 1999, ''An Overview of the EDSMAC4 Collision Simulation Model", SAE 1999-01-0102, Engineering Dynamics Corp.

[9] HVE User's manual, Version 5, January 2006, Engineering Dynamics Corp.

[10] Validation of Several Reconstruction and Simulation Models in the HVE Scientific Visualization Environment," SAE 960891, Engineering Dynamics Corp., Beaverton, OR, 1996

[11] Grimes, W., Lee, F.D. 2000 "The Importance of Crash Pulse Data When Analyzing Occupant Kinematics Using Simulations," HVE white paper

[12] Vehicle Crash Test Reports, Vehicle Database, National Highway Traffic Safety Administration, Department of Transportation, Washington, D.C., United States.

[13] MADYMO Application manual, Version 6.2, 2004, TNO, Delft, The Netherlands.

[14] Bosch, M., Brandse, J., Lemmen, P., Neale, M., Couper, G., Frampton, R. 2005. "Development and evaluation of Smart Restraints: EC PRISM" 5th European MADYMO User Conference, Cambridge, September: 62-71