A METHODOLOGY USING A COMBINED INJURY CRITERIA INDEX TO STUDY THE PERFORMANCE OF VARIOUS DRIVER RESTRAINT SYSTEM CONFIGURATIONS

Jikuang Yang
Hugo Mellander
Per Lövsund
Crash Safety Division, Chalmers University of Technology, Sweden
Yngve Håland
Autoliv Research, Sweden
Henrik Svanberg
Saab Automobile AB, Sweden

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ABSTRACT

The objective of this study was to evaluate the performance of various configurations of a driver restraint system by using a combined injury criteria index and making the restraint system adaptive to different frontal crash coinditions, such as severity of the crash, belt use, sitting position, pre-impact braking and size of the driver.

For this purpose, a mathematical model of a driver restraint system was developed. The study was divided into three steps:

1. A FE-model of the driver airbag was developed by using MADYMO 3D program;
2. The model was validated by comparing the simulations to crash tests;
3. Effects of design changes in an adaptive restraint system on injury parameters were investigated in simulations of frontal car impacts.

It was found that the performance of the restraint system was most influenced by the size of the ventilation hole and the capacity of the gas generator. The best performance of an airbag for an unbelted 50th and 95th dummy can be achieved by choosing a relatively large vent hole diameter in combination with a high mass flow at impact speeds of 48 km/h or higher. For a 5th dummy, a lower level of gas generator was preferable at 25 km/h while a higher performance of the gas generator was desirable at 48 km/h. These effects interfered with the effects of other variables such as the seat belt system including a pretensioner, load limiter. A complete restraint system has to be tuned together to achieve the maximum safety performance. It is preferable, in terms of injury parameters, to absorb the kinetic energy of the belted dummy with the maximum allowable motion. This can be achieved with a lower force level in the load limiter.

INTRODUCTION

Millions of cars have been equipped with airbags as standard equipment since airbag restraint system first came into use in passenger cars. Airbags are life savers in the most common type of vehicle impact - the frontal crash. The combination of the airbag and the seat belt is the best protection available against serious and fatal injuries (Evans, 1991). The first generation of airbags was designed to meet the requirements in FMVSS 208. The main dynamic performance requirements in original FMVSS 208 involves successful crash testing into a rigid barrier with a 50th percentile adult dummy at all speeds up to 30 mph (48 km/h). The tests must be run with unbelted dummies. Therefore, current crash protection systems for cars are developed with the focus on protection for a mid-sized male in crash speeds of certain fixed magnitudes. Most systems are set to perform satisfactory at a 50-60 km/h impact with a fixed, non-deformable barrier. In real life there are, however, a number of variables which may influence the level of effective protection given by a system such as the size and weight of the occupant, his position in relation to the steering wheel or the dashboard, and, of course, the severity of the crash. Therefore, the conventional airbag works very well in certain types of collisions and is not so effective in others (Malliaris et al. 1996).

With the use of restraint systems (including seat belts and airbags) the occupants are avoiding fatal head and chest trauma, but may in some cases sustain injuries associated with airbag deployment (Malliaris et al. 1996). The risk of injuries to out-of-position occupants by deploying airbags have been studied during the last three decades (Patrick et al. 1972, Wu et al. 1973, Aldman et al. 1974, Horsch et al. 1979, Takeda et al. 1980, Mertz et al. 1982, Augenstein et al., 1994, Otte, 1995). The issue of airbag induced injuries gained much attention during 1995-1997 due to a number of fatal incidents in the field. The National Highway Traffic Safety Administration (NHTSA) has investigated the airbag related deaths, many of them occuring at low crash velocities. They found that deploying airbags have played a role in the outcome of these crashes.

To achieve full airbag deployment in the right time to provide a proper protection, airbags must deploy with very high velocities. Due to this requirements, the airbag will transmitt large forces to an occupant being in the deployment zone. This high level of inflation is needed for normally-seated and mid-weighted unbelted occupants or heavier (FMVSS 208). Therefore, when an occupant is seated very close to the airbag module, it is desirable to significantly change the performance of airbag during its deployment (as recently manifested in the modified FMVSS 208).

An intelligent restraint system could adjust its performance based on the circumstances present at the time of a collision, such as crash severity, occupant size, occupant position, and whether the occupant is belted or not. This information can then be used to make decisions on how to adjust the restraint modules. Such a system is to adapt airbag deployment for occupants who are very close to the airbag module and who are heavier or lighter than a middle-sized person.

A number of simulation studies on airbag and occupant restraint systems have been performed since 1980's (Skötte et al. 1985; Fountain et al. 1993; Hou et al. 1995; Miller et al., 1996; Yang and Håland, 1996). Fountain et al. (1993) studied the effect of different parameters in a restraint system with 17 simulations. The authors had not included the dummy size as a parameter, and therefore they could not draw any conclusion concerning what happens if another dummy size than the 50th percentile dummy is used. In a study by Hou et al. (1995) the effect of different crash parameters on injuries was investigated. They found that by adjusting both the airbag and seat belt, the level of overall injury can be reduced by 32%, but, again, the effect of dummy size was not investigated. Miller et al. (1996) showed in a mathematical study that by changing the force level of the load limiter of the belt system and venting characteristics of the airbag, injuries can be reduced. The modelling, however, was focusing on a 50th percentile dummy seated in standard position and only two simulations with each 5th and 95th percentile dummy were performed. In these studies the effect of dummy size has been underestimated. A study was performed for an adaptive passenger side airbag with different dummy sizes and a large number of variables (Yang and Håland, 1996), but the belt restraint system was not fully investigated.

The objective of this study is to evaluate the performance of a driver restraint system by making the restraint system adaptive to different frontal crash conditions, including severity of crash, belt use, sitting position, and driver size.

METHOD AND MATERIAL

For the purpose of this study, a mathematical model of the driver restraint system, including a seat belt and an airbag, was developed and validated against crash tests with a belted and unbelted HIII dummy. The driver restraint system was simulated with coupled Finite Element Model (FEM) of the airbag and Multi Body System (MBS) for car compartment. A numerical procedure has been developed for evaluation of the restraint system. Furthermore, parameter studies were conducted by using the validated model to find out the most promising configurations in which the maximum driver protection from frontal impacts can be achieved.

Mathematical Modeling

Configuration of the Driver Restraint System - A 3-D baseline model to simulate the car frontal crash tests was developed by using the coupled FEM and MBS code MADYMO 3D package. The model consists of a car compartment with dash board, steering system, wind screen, foot well, floor, driver seat, a HIII dummy represented driver, as well as a driver restraint system including an airbag, seat belt, and pretensioner. The driver airbag was developed with the FEM module. The test car compartment and the HIII dummy were simulated with the MBS module. Both belted and unbelted HIII dummies have been used in the model depending on the crash velocity. A 50th percentile HIII dummy was located and adjusted in a normal driver-seating position (Figure 1).

A series of MADYMO runs were conducted to study the effect of different parameters included in a restraint system. The parameters varied in this study were venting size, performance of gas generator, dummy size, sitting position, and crash velocity. The seat belt configuration was held constant.

The feasible technical solutions which will comprise the restraint system have then been assessed. Mathematical simulations have been used to find the most promising configurations using an optimizing process.

The Airbag Models - The airbag model was created based on a prototype of a driver airbag that was equipped on a midsize European car in a full scale crash test. The bag has a standard volume of 50 liter and one venthole measuring 48 mm in diameter. The airbag was modeled by using a three-node triangle membrane element. The FEM bag model consists of 1482 membrane elements and 744 nodes for the 50-liter driver airbag.

A linear elastic isotropic material law was applied to the airbag model. The parameters of the characteristics for the airbag fabrics used in present study is described as follows.

Young's modulus	$E = 2.0E8$ Pa
Poisson's ratio	$\nu = 0.3$
Density of fabrics	$\rho = 850$ kg/m^3

The Compartment Model - The car compartment was modeled based on the midsize car equipped with a driver airbag. The car compartment model consisted of the instrument panel, the steering system, the knee bolster, the windscreen, part of the roof, the footwell, the floor pan, and the driver seat with the belt restraint system.

The Dummy models - The HIII dummy models with three different sizes from the MADYMO database were used in the simulations to represent the dummy used in the crash test.

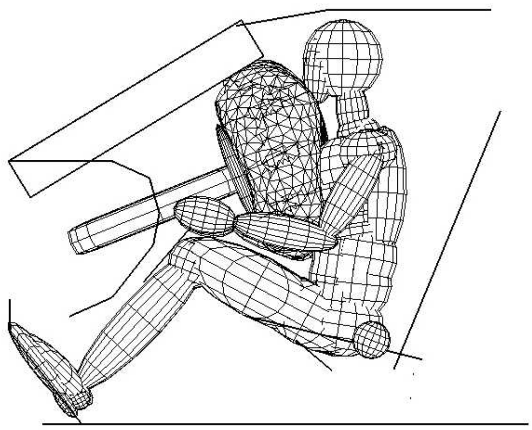

Figure 1. The configuration of the MADYMO model to simulate crash test with a belted 50th percentile HIII dummy and an airbag.

The Load Pulse - The recorded acceleration pulses from 10g to 30g in crash tests were used as the acceleration field for the HIII dummy model in the simulations at impact speeds of 25 km/h, 48 km/h and 56 km/h.

VALIDITY OF THE MATHEMATICAL MODEL

Validation with Full Scale Crash Test

The model was validated against an existing full scale car crash test at 56 km/h. The injury-related parameters calculated in the simulations are: HIC36, chest deceleration, chest viscous criterion (VC), neck moments and forces, and axial femur force.

Validation with Sled Crash Tests

Table 1 (APPENDIX I) shows three configurations of the sled tests with driver airbag and belted/unbelted HIII dummies, which were used to further verify the mathematical model.

Test Set-up - The sled tests were performed on an HYGE-sled at Autoliv Safety Centre, Sweden. Sled tests were performed using the same car body.

The car body equipped with a steering wheel with driver airbag module, steering column, front seat, seat belt etc was placed on the test sled. Crash test dummies of different sizes were placed in the car and the tests were performed.

The driver airbag modules were equipped with either one of two types of different gas generators. One which was downloaded to about 80% of a standard gas generator's output, another which was uploaded to about 120 % of a standard gas generator. The different gas generators were used to create different mass flow into the airbag.

The driver airbag modules were equipped with one of the three following types of airbag ventilation. There were one, two (standard) or four ventilation holes with a diameter of 28 mm. The different ventilation sizes were used to allow different mass flow out of the airbag.

The seat belt retractor was equipped with two different types of force limiters, with either a limiting force of 3 or 5 kN. The force limitation is achieved by using different torsion bars mounted in the retractors.

The crash test dummies used were Hybrid III-type with three different sizes, 5th female, 50th male and 95th male.

The tests were filmed with high speed camera (1000 frames/s) and the measured data were: head acceleration, upper and lower neck forces, upper and lower neck torques, chest acceleration, chest compression, pelvis acceleration, femur force, shoulder belt force, lap belt force, and airbag pressure.

PARAMETER STUDIES

Parameter studies were carried out with the validated baseline model.

In the parameter study, eight parameters were taken into account for every crash condition. The levels are presented in Table 2 (APPENDIX I).

To investigate the influence of varying the selected parameters on injury parameters in the baseline model with a load limiter added, 240 simulations in different configurations were performed.

Injury Thresholds

The most important aim of an adaptive restraint system is to protect occupants with different height and weight in all crash conditions. Different occupant sizes probably imply various injury thresholds. The current status of the knowledge about the injury crieria and threshold limits to impact has been investigated for body regions of face, cervical spine, thorax, abdomen, and lower extremities. Each computer simulation creates a matrix containing different dummy responses. The dummy responses should be compared to injury thresholds to assure that no injury limit has been exceeded. Table 3 (APPENDIX I) shows injury limits to impact in frontal collisions for different dummy sizes used in this study (Nahum et al. 1994).

Approach to Evaluate the Results

Several approaches were reviewed to interpret the overall performance and injury risks of restrained occupants in a crash (Oberdieck et al. 1982; Gustafsson et al. 1985; Viano et al. 1990; Norin et al. 1997). The preferred method was found to be a relative injury risk assessment which was calculated as the sum of the relative risks. Relative risk is calculated as the relation between the measured dummy responses in the different body parts divided with the conventional threshold level (Nahum et al. 1994). This enables injury risk in each body region to be assessed by comparing it with the maximum acceptable threshold level from applicable biomechanical criteria.

Equation 1 (APPENDIX II) shows the derived formula for the evaluation. The head injury criterion (HIC36), chest deceleration, femur loads, and neck forces and moments were used in the evaluation procedure. The Combined Injury Risk (CIR) is based on all these injury parameters.

The idea behind Eq.(1) was that with an adaptive restraint system we would like to give a general high level of protection to all body parts. By dividing neck injury responses by 4 and the axial femur loads by 2, all body regions have received the same priority in the evaluating approach. Then, every parenthesis has been squared to intensify the effect of dummy responses which come closer to the injury criteria. Another effect of squaring the parentheses is that the sum of insignificant dummy responses might not be as significant as a high dummy response.

Tibia index is not included in Eq. 1 because the foot plane in the MADYMO model was not designed to be deformable.

The upper extremities are not included in Equation 1 due to the fact that no accepted injury criterion is available. The viscous injury criterion for the chest (VC-criterion) has been excluded from Equation 1 because all the calculated and measured VC-values were below the criterion level.

RESULTS

Comparison of Results from Sled Tests and Simulations

Results from the full-scale test and the computer simulation of the reference model are shown in Table 4.

A comparison of results from sled tests and computer simulations was made in terms of injury related parameters for peak values (Table 5, 6, and 7, APPENDIX III). Figure 2 shows an example of the initial head-airbag contact at 50 ms from test and corresponding simulation. The time history plots from the test and the simulation are presented in Figure 3 (APPENDIX III). The main injury related parameters from simulations agreed well with the results from sled tests.

Table 4
Comparisons of simulation results with full-scale car crash test results

Injury Values	Full Scale Test	Simulation
HIC36	750	740
Chest deceleration 3ms(m/s^2)	520	527
Chest VC	0.28	0.22
Femur Axial Load	3300	3100
Neck Flexion (Nm)	84	87
Neck Extension (Nm)	24	23
Neck Shear Force (N)	300	303
Neck Compression (N)	-	2000

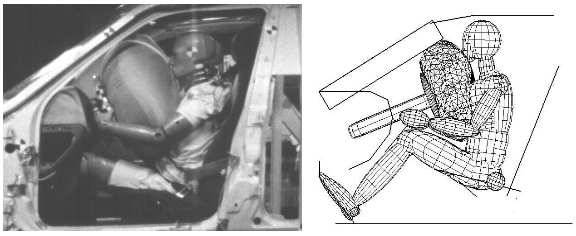

Figure 2. Comparison of the initial head-airbag contact at 50 ms from test and simulation.

Results from Parameter Study

The computer simulations were carried out with different combinations of the parameters (Table2, APPENDIX I). Based on the dummy responses from each simulation, a CIR value was calculated using Eq. (1). CIR was 1.1 for the baseline model at the crash velocity of 56 km/h and with belted dummy without any load limiter. In cases where one or several of the dummy responses have exceeded the injury threshold no CIR value has been calculated.

Table 8: The calculated lowest CIR value

	5^{th} HIII		50^{th} HIII		95^{th}HIII	
Parameters	*V25	V48	V25	V48	V25	V48
VHD(mm)	50		50		50	
GGE (%)	120	80	80	160	120	160
BLL (kN)	3	3	3	3	5	5
SEP	normal		normal		normal	
CIR	0.22	0.4	0.14	0.62	0.13	0.63

Table 8 shows the lowest CIR values found from 108 runs at speeds of 25 and 48 km/h. In the Table 8 through 10, VHD=vent hole diameter, GGE=gas generator, BLL= belt load limit, SEP=seating position, V25=impact speed 25 km/h:

Table 9 shows the lowest CIR values found from 36 runs at speeds of 56 km/h.

Table 9: The calculated lowest CIR value

	5th HIII	50th HIII	95thHIII
Parameters	V56	V56	V56
VHD(mm)	40	50	50
GGE (%)	80	160	160
BLL (kN)	3	3	5
SEP	normal	normal	normal
CIR	0.41	0.64	0.68

The calculated lowest CIR values from 36 runs with 50th percentile dummy in full forward position are shown in Table 10.

Table 10: The calculated lowest CIR value

	50th HIII	
Parameters	V25	V48
VHD(mm)	50	50
GGE (%)	120	80
BLL (kN)	3	3
SEP	full forward	full forward
CIR	0.14	0.48

From 12 runs at speed of 56 km/h with a 50th percentile dummy sitting in full forward position, the lowest CIR 0.64 was received in the run with the vent hole diameter of 50 mm, a 120% gasgenerator, belted dummy, and a load limiting level of 3 kN.

From 12 other runs with an unbelted 5th percentile dummy sitting out of position, the lowest CIR was 0.4 at 25 km/h. In this simulation the gas generator had its lowest possible performance, i.e. 80%, and the vent hole had its value 50 mm.

Another 36 runs were carried out with a 50th percentile dummy sitting in a pre-impact braking position. To avoid any contact of the dummy with the steering wheel or/and exceeding any threshold limit in pre-braking cases the dummy had to be belted. The run with a venthole diameter of 50mm, 120% gasgenerator, and a load limit of 3 kN was the best choice at impact speed 48 km/h.

DISCUSSION

In the design of adaptive restraint systems it is necessary to identify important parameters of the restraint system and to determine appropriate characteristics of parameters for the different configurations. The feasible technical solutions which will comprise the restraint system shall then be assessed.

The chosen approach for interpretation of the overall performance and injury risks of restrained occupants in a crash has to be considered as a first step towards a more sophisticated method that should be developed in further study, incorporating the current injury risk function theory.

The models used in this parameter study are based on a validated 3D-MADYMO model called baseline model. The baseline model did not include a load limiter. This implies that the models used in the parameter study are not validated against a car crash test. Another comment to the models including a belted dummy (both baseline model and those which have been used in the parameter study) is that the seat belt is modelled by sliding springs instead of a finite element belt to reduce computing time. In frontal car crash simulations, the effect of using a seat belt modelled by sliding springs instead of a FE–belt has been investigated by Fratterman et al. (1993). They found that the differences in the dummy responses in two simulations were negligible.

Performance of Airbag

<u>The Size of the Venthole</u> - The size of the venthole had a significant effect on the CIR in a crash velocity of 25 km/h, i.e. the larger venthole the lower CIR. An increased crash velocity means that a larger amount of inertial energy has to be extracted from the dummy. This is in conflict with a larger venthole size and consequently a larger outflow from the airbag which makes the airbag softer. Therefore, at a crash velocity of 48 km/h or higher, a larger venthole is not preferable without having a larger gas inflow to avoid exceeding the threshold limits.

<u>The capacity of the gas generator</u> - The effect of the time-history characteristics of the gas generator is also very significant. Producing more gas during inflation process without allowing more gas outflow will generally increase CIR especially in simulations with the 5th percentile dummy. However, in a few simulations with the 95th percentile dummy with a crash velocity higher than 25 km/h, the results show that it is necessary to have a gas generator with larger capacity to be able to protect the 95th percentile dummy.

Sitting position and the size of the dummy

The results show that if the dummy is seated inside the deployment area of the bag, all injury parameters have larger values compared to the cases where the dummy is seated in a normal sitting position (Huelke et al. 1992; Miller et al. 1996; Schulte et al. 1994).

The 5th percentile occupant has lower mass than both 50th and 95th percentile. As a result, in simulations with 5th percentile dummy, lower mass flow rate and larger vent holes were desirable in lower crash velocities (25 km/h).

However, the 95th percentile dummy has a higher mass and therefore a gas generator with higher gas outflow and a bag with smaller venthole was desirable.

Influence of seat belt usage

In the crash velocity of 48 km/h for all dummy sizes CIR have received lower values if the dummies are belted than in the cases with the unbelted dummies. For the 95th percentile dummy the reduction in CIR value is more significant than for the two other dummy sizes. The reduction in CIR value is not as significant in 25 km/h cases as in cases with the crash velocity of 48 km/h and in some cases with 5th percentile dummy the effect is even negative. Cases with unbelted dummies in higher velocities than 48 km/h have been eliminated because at least one of the injury parameters has been exceeded the threshold limit. The benefits of seat belt are even more recognisable in cases with OOP and Full Forward seated dummy (Melvin et al. 1996 and Schulte et al. 1994).

Influence of level of the load limiter

The level of the load limiter is insignificant for all dummy sizes at the 25 km/h crash velocity. This can be explained by considering the low crash severity combined with the high load limit levels. Despite this fact, a general pattern is recognisable in all cases with different crash velocities and dummy sizes. A higher force level for the load limiter implies a larger CIR. A lower force level in the load limiter leads to less chest compression compared to a higher level of load limiter. This even implies a lower HIC value and less neck flexion, which all result in a lower CIR.

In the present study, no attempt has been made to find the optimum level of the load limiter for different cases to limit the number of simulations.

Recommendations for a Driver Restraint System

New sensor systems should be developed that can measure occupant size, occupant position and crash severity. This study shows that different performance levels on airbag and belt force limiter, could reduce the load on different sized occupants, in low and high crash severities.

It is very important to couple the occupant to the vehicle very early in the crash event, to reduce the relative velocity between the occupant and the vehicle interior. The best performance of an airbag for an unbelted 50th and 95th percentile dummy can be achieved by choosing a relatively large vent hole diameter in combination with an excessive mass flow.

The 95th percentile unbelted dummy appears to be very difficult to restrain. The vent hole diameter and the gas-generator output that was used in this study, was not enough to get below the injury thresholds for 95th percentile dummy. The output from gas-generator has to be increased above the 160% level that was used in this study.

The scenario is completely different for a 5th percentile dummy for which a lower level of gas-generator is preferable at 25 km/h whence a higher performance of gas-generator is desirable at 48 km/h.

The use the seat belts influenced the results significantly in most cases. In the simulations we see a significant difference, especially for the large occupants in severe collisions.

A dummy which is sitting close (Full Forward and OOP cases) to an airbag module is subjected to higher forces than a dummy in normal sitting position.

It is preferable in terms of injury parameters to absorb the kinetic energy of the belted dummy within a maximum allowable forward movement i.e using belt force limiters.

CONCLUSION

The best performance of an airbag for an unbelted 50th and 95th percentile dummy can be achieved by choosing a relatively large vent hole diameter in combination with a high mass flow. The opposite was found true for a 5th percentile dummy for which a lower level of gas generator is preferable at 25 km/h and a higher performance gas generator is desirable only at 48 km/h.

A dummy which is sitting close (Full Forward and OOP cases) to an airbag module is subjected to higher forces than a dummy in normal sitting position and consequently a reduced gasgenaration is prefered.

A formula to calculate the Combined Injury Criteria (CIR) has been developed as an interim approach but further research in this area is imperative.

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APPENDIX I: TABLES

Table 1: Configurations of sled crash tests

Test No.	Dummy (%)	Speed (km/h)	GGD (%)	Volume (l)	Vent-hole (mm)	Belt (kN)	Position
2	50	56	100(Std)	Std 2175	40	Std	Center/Down
6	95	56	120	50	40	5	Reward/Down
7	5	25	80	50	50	No	OOP

Table 2. Parameters and levels used in simulations.

Parameter	Level
VHD=Venthole Diameter (mm)	40, 50
BVO=Bag Volume (liter)	50
GGE=Gasgenerator	80%, 120%, 160%
BEL=Belt Usage	Yes, No
BLL=Belt Load Limiter (N)	3000, 5000
CVE=Crash Velocity (km/h)	25, 48, 56
DUS=Dummy Size (percentile)	5, 50, 95
SIP=Sitting Position	Normal*, OOP*, Full Forward*, Pre-Braking*

* Normal sitting position for a 5^{th} percentile dummy is full forward and up, for a 50^{th} percentile dummy is mid forward and for a 95^{th} percentile dummy is full backward and down. OOP (Out Of Position) means that the distance between the nose tip of the dummy and the steering wheel is 200 mm. Full forward sitting position means that the dummy, regardless its size, has been moved forward so that the knees are in contact with the knee bolster. Pre-Braking means that the dummy has been moved forward due to a braking before the crash. The braking rate has been 10 m/s^2 and the dummy has not been holding the steering wheel during the braking process.

Table 3. Injury Thresholds for different dummy sizes

	5^{th} HIII	50^{th} HIII	95^{th} HIII
HIC36	1113	1000	957
Flexion Moment in Neck (Nm)	104	190	258
Extension Moment in Neck (Nm)	31	57	78
Shear Force in Neck (N)	2200	3300	4000
Axial Force in Neck (N)	2200	3300	4000
Femur Axial Force (N)	6100	9000	11000
3ms Chest acceleration (m/s**2)	720	590	530

APPENDIX II: Evaluation Formulation

$$CIR = \left(\frac{HIC\ 36}{HIC\ 36\_Th}\right)^2 + \left(\left(\frac{1}{4}\right)\times\left(\frac{Mf}{Mf\_Th}+\frac{Me}{Me\_Th}+\frac{Fs}{Fs\_Th}+\frac{Fa}{Fa\_Th}\right)\right)^2 + \left(\left(\frac{1}{2}\right)\times\left(\frac{Fl}{Fl\_Th}+\frac{Fr}{Fr\_Th}\right)\right)^2 + \left(\frac{a3ms}{a3ms\_Th}\right)^2 \quad (1)$$

where CIR is a index for assessment of Combined Injury Risk,

HIC36 = the value of head injury criterion,
HIC36_Th* = the head injury threshold,
Mf, Me = flexion and extension moments in the neck, respectively,
Mf, Me_Th* = flexion and extension moment injury thresholds, respectively,
Fs, Fa = shear and axial force in the neck, respectively,
Fs, Fa_Th* = neck force injury thresholds,
Fl, Fr = femur forces in the left and right femur, respectively,
Fl,Fr_Th* = femur injury threshold,
a3ms = 3ms-acceleration of the chest,
a3ms_Th* = 3ms-acceleration injury threshold of the chest,

*Threshold levels have different value for different dummy sizes (Table 3).

APPENDIX III: Validation Results from Sled Tests and Simulations

Table 5: The results from simulation and test 2 with 50th percentile HIII at 56 km/h

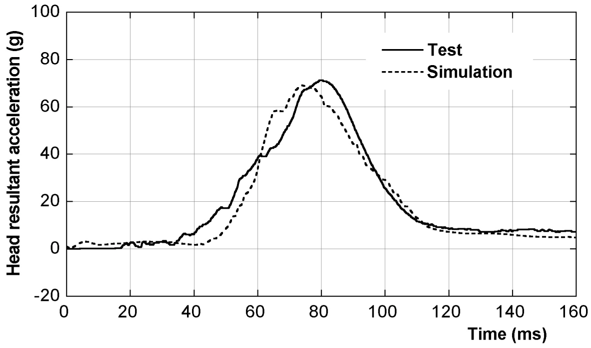
Parameters	Test	Refined model
HIC36	825	853
Head acc.(g)	70	69
Chest acc (g)	58	52
Pelvis acc (g)	63	48
Chest D (mm)	42	56
Chest VC	0.23	0.29
Femur F (kN)	2.67/0.25	2.0/2.4
Sh. belt F (kN)	9.0	7.8
Lap belt F (kN)	8.6	5.7
Neck FX (kN)	0.2	1.5
Neck FZ (kN)	1.6	2.7
Neck MY (Nm)	-36/+33	-20/+44
CIR	1.84	1.79

Table 6: The results from simulation and test 6 with 95th percentile HIII at 56 km/h

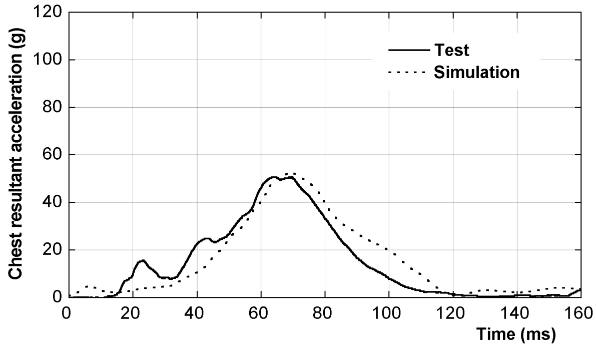
Parameters	Test	Refined model
HIC36	732	627
Head acc.(g)	68	60
Chest acc (g)	47	42
Pelvis acc (g)	50	53
Chest D (mm)	46	55
Chest VC	0.24	0.145
Femur F (kN)	0.22/0.27	1.9/0.4
Sh. belt F (kN)	6.7	5.7
Lap belt F (kN)	9.9	7.3
Neck FX (kN)	0.88	1.5
Neck FZ (kN)	1.69	1.5
Neck MY (Nm)	-15/+78	-27/34
CIR	1.38	1.13

Table 7: The results from simulation and test 7 with 5th percentile HIII at 25 km/h

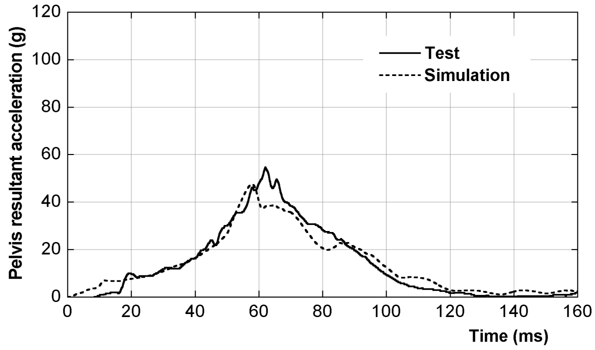
Parameters	Test	Refined model
HIC36	114	89
Head acc.(g)	36	33
Chest acc (g)	19	28
Pelvis acc (g)	19	22
Chest D (mm)	19	18
Chest VC	0.18	0.07
Femur F (kN)	2.12/1.20	1.8/1.6
Sh. belt F (kN)	-	-
Lap belt F (kN)	-	-
Neck FX (kN)	0.42	0.21
Neck FZ (kN)	1.25	1.04
Neck MY (Nm)	-11/+15	-9/+18
CIR	0.32	0.29



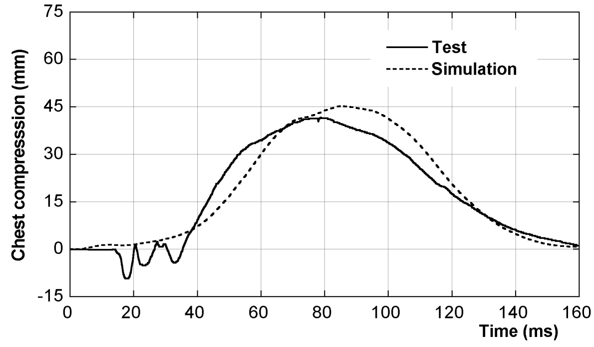
(a) head acceleration



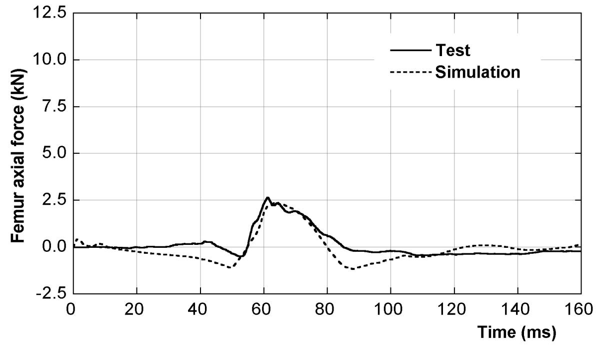
(b) chest acceleration



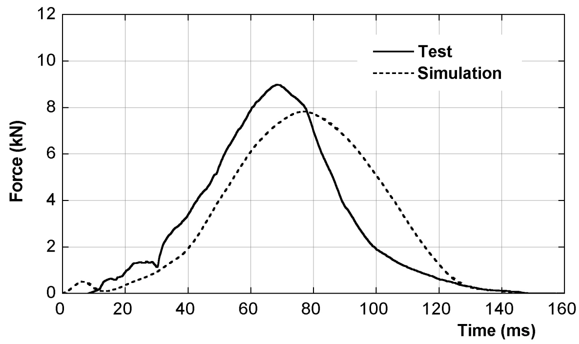
(c) pelvis acceleration



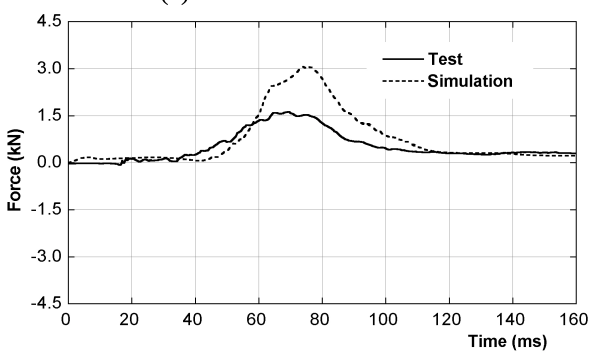
(d) chest deflection



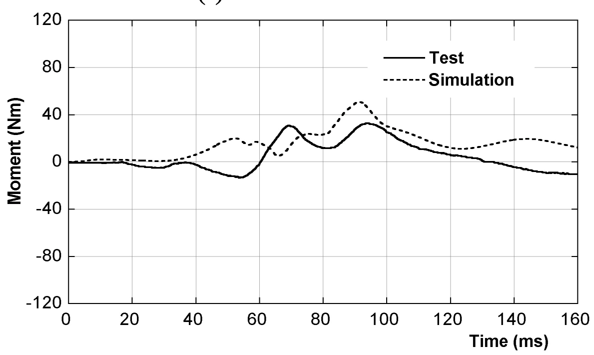
(e) femur force



(f) shoulder belt force



(g) neck force



(h) neck moment

Figure 3. A comparison of the time histories of injury parameters from simulation and sled test 2 with 50^{th} percentile HIII at 56 km/h.