CAR DRIVER PROTECTION AT FRONTAL IMPACTS UP TO 80 KM/H (50 MPH)

Bengt Pipkorn
Autoliv Research
SWEDEN

Hugo Mellander
Traffic Safety Research and Engineering AB
SWEDEN

Yngve Håland
Autoliv Research
SWEDEN
Paper Number 05-0102

ABSTRACT

The structures of modern passenger vehicles are designed to maintain integrity up to an impact velocity of about 64 km/h (40 mph). The occupant protection system is likewise designed to efficiently protect the occupant up to an impact velocity of 64 km/h. However, there are highways with a 90 km/h (56 mph) speed limit without separation of the lanes and many car occupants still die in severe frontal crashes.

To investigate the level of occupant protection at very high impact velocity a full frontal full vehicle rigid wall crash test with a mid size passenger vehicle was carried out. The impact velocity was 80 km/h (50 mph). A 50%-ile Hybrid III crash test dummy was positioned on the driver side. The dummy results show that the possibility of survival of an occupant in that particular vehicle in such a crash was minimal.

With the goal to develop a protection system that in an 80 km/h (50 mph) crash test would result in dummy reading below the FMVSS 208 injury criteria levels a mathematical sled model was developed and a mechanical sled mock-up was set up. The mathematical model was validated by means of results from the mechanical sled tests.

To identify the parameters of the occupant restraint system with the greatest influence on the efficiency of the restraint system factorial analysis was used in which a number of parameters were varied at two levels. The parameters were preloading of seat belt, load limiting of seat belts, gasgenerator output, steering column yield distance and airbag volume.

Using the results from the factorial analysis a mathematical sled simulation and a mechanical sled test were carried out with a restraint system that was designed give reasonable protection to an occupant at an 80 km/h (50 mph) impact. The restraint system consisted of a large volume airbag, a significantly longer ride down distance than what is available in the vehicles today, diagonal and lap belt pretensioning and load limiting. Efficient occupant driver protection in 80 km/h (50 mph) full front rigid wall crash seems to be possible. However, the interior ride down distance needs to be greater than what is available in the vehicles on the market today.

INTRODUCTION

Modern passenger vehicles are being extensively tested for the ability to protect vehicle occupants in the event of a crash. Regulatory as well as rating tests are carried out all over the world. The results from these tests are publicly available and receive great attention. For the consumer the results from these tests are an important factor that influences the choice of vehicle when buying a new passenger vehicle. The impact velocities at which these tests are run have been increasing over time. The rating tests carried out at present in the US and in EUROPE (USNCAP and EUNCAP) are run at impact velocities of 56 km/h (35 mph) and 64 km/h (40 mph). It has even been proposed to run crash tests at 80 km/h impact velocity to evaluate compartment integrity [1].

The structures of modern passenger vehicles are designed to maintain integrity at an impact velocity of 64 km/h (40 mph) and lower. The occupant protection system is likewise designed to protect the occupant up to an impact velocity of about 64 km/h (40 mph). However, there are highways with a 90 km/h (56 mph) speed limit without separation of the lanes and many car occupants still die in severe frontal crashes. In Sweden alone approximately 150 fatalities occurred in frontal collisions in 2003 which is about half of all car occupant fatalities [2].

Crash protection in high-speed barrier crash tests with up to 80 km/h (50 mph) impact velocity was studied in the seventies in the Experimental Safety Vehicle (ESV) program [3]. Since then there seems to be a gap in research efforts in this area. However, recently another study was published in which different driver restraint system configurations were studied in a mathematical model with the goal to achieve interior crash protection at 80 km/h [4]. In the study potential for good driver protection in an 80 km/h frontal crash was shown. The aim of this study was to analyze the theoretical and technical possibilities to design an efficient crash safety system for the driver of a passenger car subjected to fully distributed frontal crashes at 80 km/h (50 mph).

METHODOLOGY

To investigate the level of protection the restraint system of a vehicle offers an occupant at high impact velocity a full frontal rigid wall crash test was performed. The test was run with a mid size passenger vehicle and with an impact velocity of 80 km/h (50 mph). A 50%-ile Hybrid III crash test dummy was positioned in the driver seat according the FMVSS 208 specifications.

To analyze the theoretical and technical potential to design an efficient crash safety system for passenger vehicle occupants in a frontal crash at high impact velocity models were developed. A mathematical sled model and a mechanical sled mock-up were set up based on the geometry of the vehicle used in the crash test. The mathematical model was validated by means of results from the mechanical impact sled test. In order to limit the scope of this study only the interior restraint system was analyzed.

The validated mathematical sled model was used for a parameter sensitivity analysis of the restraint system. A test matrix was created with design of experiment technique (fractional factorial analysis at two levels).

Using the results from the factorial analysis the mathematical model was modified to incorporate a restraint system that was designed to provide the occupant with protection in high impact velocities. This restraint system was also evaluated mechanically by a sled test. The mathematical simulation and mechanical sled test were carried out an impact velocity of 80 km/h (50 mph). The results were compared to the FMVSS 208 injury criteria levels.

Mechanical Full Vehicle Full Frontal Crash Test

In the mechanical crash test carried out a mid size passenger vehicle was impacting at a 0 degree angle full front into a rigid wall. The closing speed was 80 km/h (50 mph). The vehicle was equipped with a standard 3 point belt system and a driver side airbag. The initiation of airbag inflation was done by the existing sensor and triggering system in the vehicle. A 50%-ile Hybrid III crash test dummy was positioned according to FMVSS 208 specification in the driver side of the vehicle (Figure 1). In the dummy, head acceleration, chest acceleration, upper neck force, upper neck moment, chest deflection and femur force were recorded. In addition both lap and shoulder belt forces were recorded. Vehicle acceleration was measured on the tunnel, trunk and the left and right b-pillar.

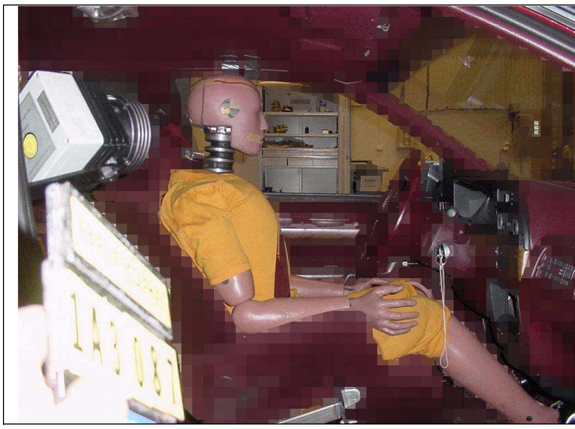

Figure 1. Occupant position in full vehicle crash Test

Development and Validation of Mathematical Model

To design and evaluate a restraint system for occupant protection at high impact velocity a mathematical sled model was developed and a mechanical sled mock-up was set up. The geometry of the occupant compartment in the mathematical model and mechanical sled mock-up was based on the geometry of the occupant compartment of the vehicle tested. The mathematical model was a multi-body dynamics model (MADYMO) that incorporated a 50%-ile HIII-dummy, a windscreen, a ceiling, a seat, a knee bolster, a belt system, an airbag, a steering wheel and a energy absorbing collapsible steering column (Figure 2). The mechanical mock-up of the driver environment was mounted on an impact sled. The mock-up was incorporating a windscreen, ceiling, seat, steering wheel with column, airbag, knee restraints and seat belt (Figure 2).

In the mathematical model and in the mechanical sled test the acceleration from the full frontal rigid barrier crash test at 80 km/h was used. However, the effect of occupant compartment intrusions was not included in the study.

The model was validated by means of results from mechanical sled tests. The predictions and results that were used for validation were head acceleration, chest acceleration, chest deflection, pelvis acceleration, femur force, belt forces, steering column yield distance and airbag pressure.

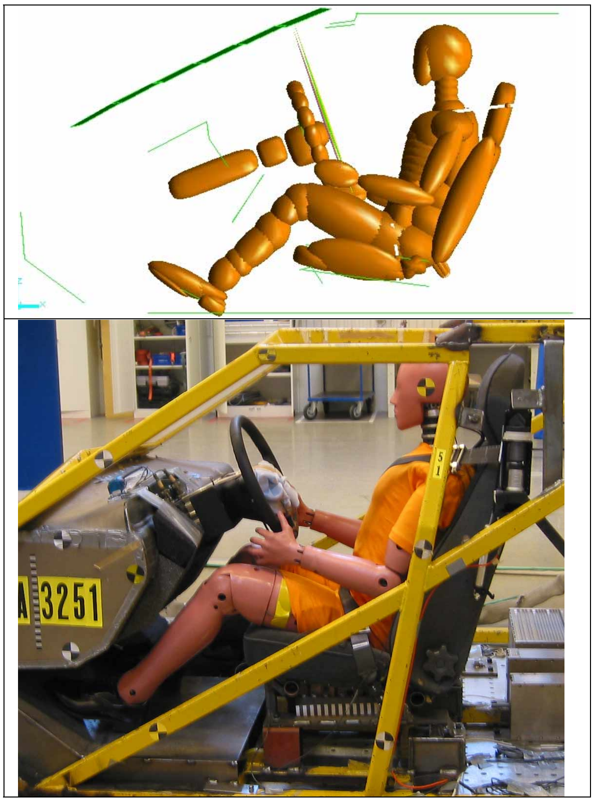

Figure 2. Principal layout of the computer model and the sled test geometry

Design of Experiments (DOE)

In order to limit the number of computer runs and mechanical tests factorial analysis technique was used to identify the restraint system parameters with the greatest effect on the dummy response. A resolution Ⅲ design was chosen with seven two level variables (Table 1). A resolution III design is a fraction of the full 2^7 factorial (128 runs) namely a 2^{7-4}_{III} design that results in 7 different combinations of the variables to be tested in 8 experiments or as in this study 8 computer runs. The following layout of the test matrix was chosen. Minus sign means low level of the parameter and plus sign means high level (Table 2).

Table 1.
Design of Experiments Matrix

Variable **Run**	A	B	C	D	E	F	G	***Result***
1	-	-	-	+	+	+	-	
2	+	-	-	-	-	+	+	
3	-	+	-	-	+	-	+	
4	+	+	-	+	-	-	-	
5	-	-	+	+	-	-	+	
6	+	-	+	-	+	-	-	
7	-	+	+	-	-	+	-	
8	+	+	+	+	+	+	+	
Design pattern				A B	A C	B C	A B C	

The parameters selected for variation at two levels were airbag volume, gasgenerator output, ventilation area, diagonal belt pretensioning force, diagonal belt load limiting force, lap belt load limiting force and steering column yield force (Table 2). The alteration of the gasgenerator output was achieved by modification of the temperature of the gas.

Table 2.
Design of Experiments Variables

Parameter	-	+
Airbag volume	60 liter	72 liter
Gas generator	Original	Temp x 2
Vent area (cm^2)	1,7 cm^2	7,8 cm^2
Pretensioner force	2 kN	4 kN
Load limiter diagonal belt	5/3 kN	8/5 kN
Load limiter lap belt	3 kN	6 kN
Steering column yield force	5 kN	8 kN

A reduced factorial design always results in confounding patterns where interactions between two or several variables may result in responses that can not be distinguished from the main effects. However in this study the effect of interactions were considered to be of minor importance and have not been further studied.

Mathematical Sled Simulations and Mechanical Sled Test Based on DOE Results

Based on the results from the factorial analysis the mathematical model and sled mock-up were modified with a restraint system that was designed to restrain an occupant at an 80 km/h crash. The driver restraint systems consisted of a three-point seat belt with an upper B-pillar mounted retractor and a dual chamber 72-litre airbag mounted in a state of the art steering wheel. The seat belt system consisted of a dual stage load-limiter with a force level of approximately 5.5 and 3.5 kN. Initially prior to contact between occupant and airbag the load-limiter force was 5.5 kN and after occupant to bag contact the force level was reduced to 3.5 kN. There was no limitation to the spool out due to load limiting. In all tests there were dual pretensioning devices. One pretensioner on the diagonal belt and one on the lap belt. All pretensioners and the airbag were all fired at various times into the crash sequence. The applied pre loading force was approximately 2 kN. The quasi-static elongation of the seat belt webbing was 10% at 10 kN. The airbag mounted in the steering wheel was inflated from a tank with stored gas. The valve of the stored gas tank was opened prior to impact. Therefore inflation of the airbag was initiated before impact. The steering column had a special collapse mechanism to allow for a stroke of maximum 200 mm at predetermined force levels (in the computer model there was no restriction to the stroke). The deformable element consisted of aluminum honeycomb. The yield force of the steering column was, based on the results from the factorial analysis, set at a force level of 7 kN. Two load cells were installed to register the yield force. A reinforced standard seat was used in all tests. As string potentiometer was used to register the yield distance of the steering column. A steel plate was built in under the seat cushion in order to avoid excessive seat cushion deformation and seat chassis deformation during testing. The seat was positioned in the mid position with a 26° seat back angle. The knee bolsters consisted of energy absorbing polypropylene (density 40 kg/m^3).

RESULTS

Results Mechanical Full Vehicle Barrier Test

For the vehicle acceleration measurements the tunnel acceleration was less than 30 g until 35 ms into the crash. At 35 ms the acceleration increases rapidly to 55 g (Figure 3). Thereafter the acceleration decreases slowly until 0 which was reached at approximately 120 ms. Significant deformation of the vehicle was observed. A global dynamic deformation of the vehicle of 1,06 m was obtained. In addition there was intrusion of the firewall into the vehicle.

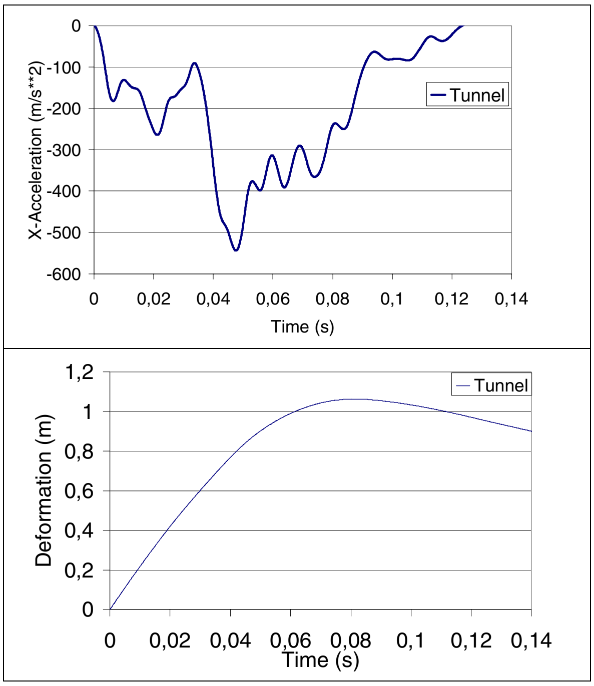

Figure 3. Vehicle acceleration and deformation

For the steering wheel there was significant displacement (Figure 4). The steering wheel intruded into the vehicle and moved upwards. In addition the wheel rotated from the initial 25 degrees to a horizontal position. The rotation started at 50 ms and at 70 ms into the crash the horizontal angle for the wheel was reached.

Due to the translation and rotation of the steering wheel the occupant was not protected by the airbag. The airbag was trapped under the chin of the occupant and the chin was pushed upwards. In addition deployment of the airbag was observed to be initiated after about 15 ms. Such rather late deployment resulted in that the pressure in the bag was not at a sufficient level to protect the occupant when the airbag was reached by the head of the occupant.

Figure 4. Steering wheel, airbag and occupant at 70 ms (computer graphics for enhanced visualization)

For the vehicle occupant all injury measures but chest deflection and femur left force were greater than the FMVSS 208 injury criteria levels (Figure 5 and 6) (Appendix A) [3]. HIC_{15} was 352% greater than the FMVSS 208 injury criteria level.

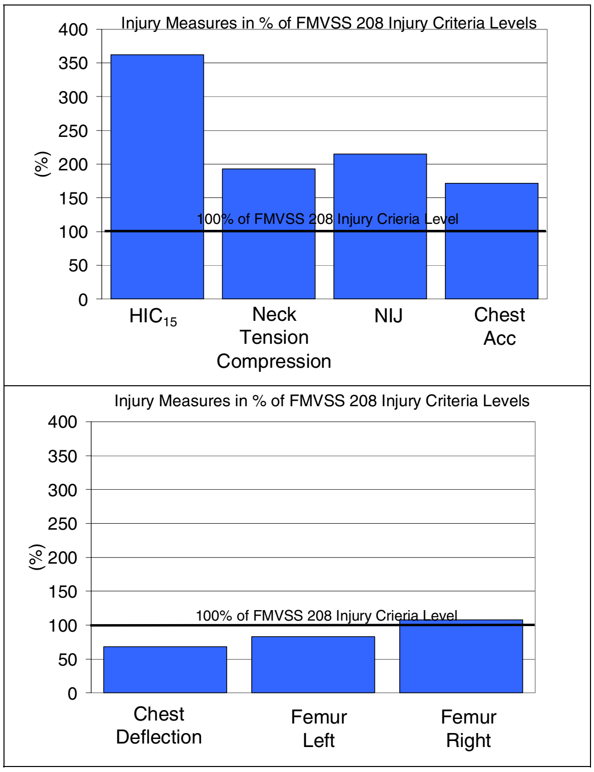

Figure 5. Injury reading in full vehicle crash test

Results Development and Validation of Mathematical Model

The mathematical model was validated by means of results from the mechanical sled tests. Generally good agreement between predictions from the model and results from the sled test was obtained.

In addition to validation at an impact velocity of 80 km/h (50 mph) the model was validated for an impact velocity of 56 km/h (35 mph).

Results Design of Experiments

In the factorial analysis it was found that the greatest effect on head acceleration was from the steering column yield force with the higher force level increasing head acceleration with 184 m/s^2 (Figure 6). This leads to the conclusion the force level in the energy absorbing mechanism is an important parameter influencing head acceleration. However, all runs with a low force level were associated with a column stroke between 230-400 mm. Since it was considered that such a stroke would be extremely difficult to realize the higher force level of 7 kN was selected to be realized in the sled tests. This force level produced strokes between 61-160 mm. The higher load limiting level in the lap belt had an effect of 84 m/s^2 in reducing the head acceleration. The lower level of force in the load limiter in the lap belt had the highest effect on the chest acceleration and reduced it with 76 m/s^2 (Figure 7). It had the second largest effect on chest deflection with a reduction of 4,5 mm. Then largest effect on chest deflection had the load limiting force in the diagonal belt with the higher force level increasing chest deflection with 7,5 mm (Figure 8). The second largest effect on chest acceleration had the load limiting force level in the diagonal belt with the higher force level increasing the chest acceleration with 72 m/s^2. The higher column force had an effect of 41m/s^2 and increased the chest acceleration but had only a minor effect on the chest deflection with an increase of 2 mm. The larger air bag decreased chest acceleration with an effect of 41 m/s^2. Taking all this information into account further computer analysis was made to design a restraint configuration that would result in dummy injury values below FMVSS 208 injury criteria levels.

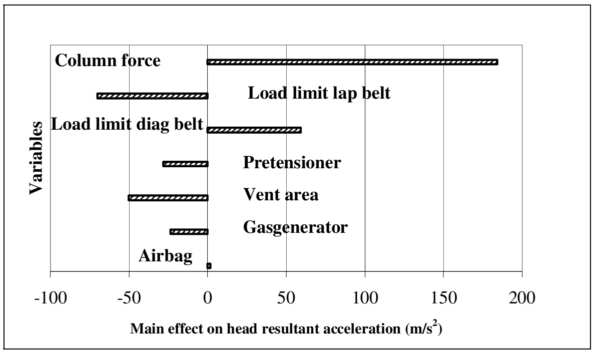

Figure 6. Effect on head resultant acceleration

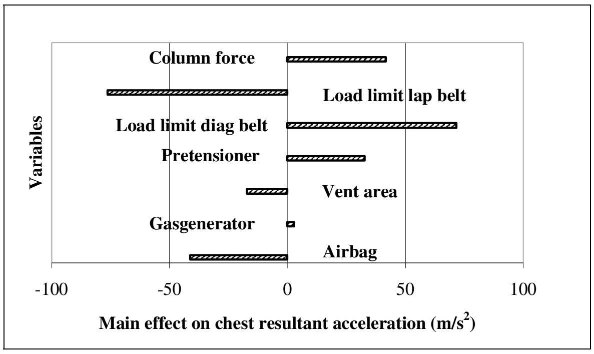

Figure 7. Effect on chest resultant acceleration

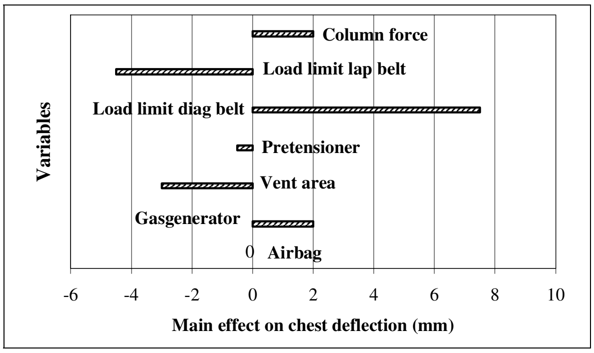

Figure 8. Effect on chest deflection

Results Mathematical Sled Simulations and Mechanical Sled Tests Based on DOE Results

The restraint system of the mathematical model was modified based on the results from the DOE to efficiently restrain a driver at an 80 km/h crash (Figure 9).

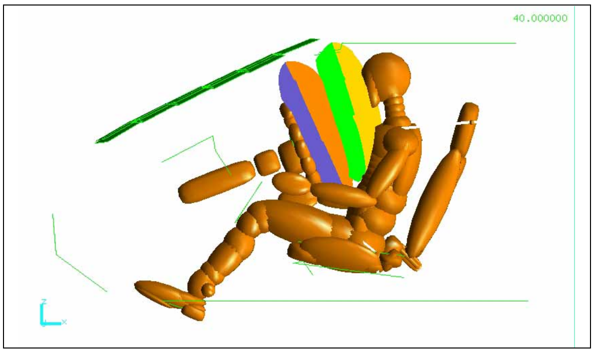

Figure 9. Mathematical model occupant kinematics at 40 ms

In the simulation with a restraint system designed to protect an occupant at 80 km/h (50 mph) the injury readings predicted from the model were all below the FMVSS 208 injury criteria levels (Figure 10). HIC_{15}, chest acceleration, chest deflection, femur right force and femur left force were all significantly lower than the FMVSS 208 injury criteria levels. In addition, steering column yield distance was 195 mm.

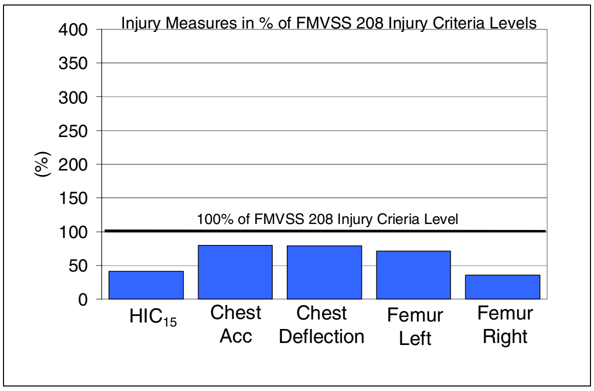

Figure 10. Injury readings in mathematical sled model

The restraint system in the mechanical sled test mock-up was also modified in the same way as was done in the mathematical model (Figure 11).

Figure 11. Mechanical sled test occupant kinematics at 40 ms

In the results from the corresponding mechanical sled tests that was mimicing the mathematical model not all injury measures were below the FMVSS 208 injury criteria levels (Figure 12). HIC_{15} and chest acceleration were somewhat above the injury criteria levels while neck tension-compression, NIJ, chest deflection, femur left force and femur right force were significantly lower than the injury criteria levels. In addition, steering column yield distance was 156 mm.

One of the reasons for the differences between the mathematical model predictions and sled test results can be that the kinematics of the airbag differed between the mathematical analysis and the mechanical test (Figure 9 and 11).

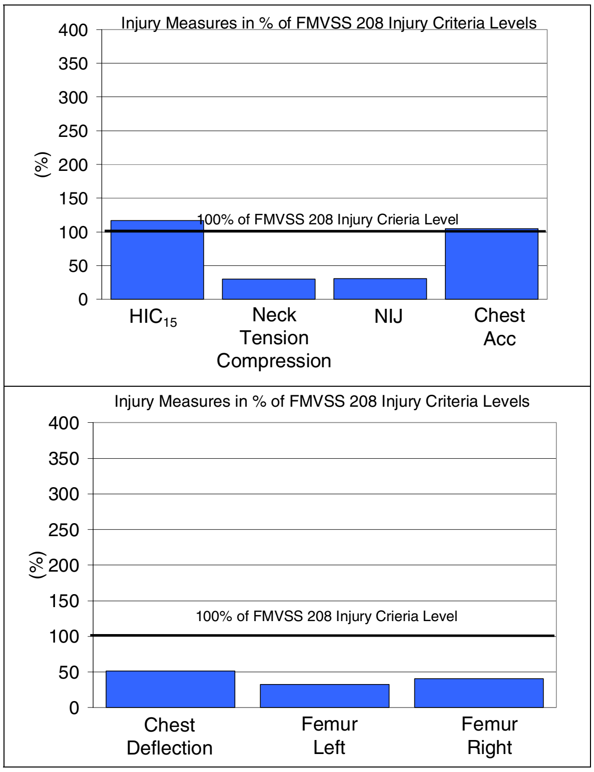

Figure 12. Injury readings in mechanical sled test

DISCUSSION

In the 80 km/h full vehicle full front crash test most occupant injury readings were above the FMVSS 208 injury criteria levels. Therefore the chance for survival of an occupant in such a crash is minimal. There were extremely high occupant injury values measured for the head, neck and chest of the occupant. The intrusion of the firewall and the intrusion of the steering wheel were likely to contribute to the high injury measures. The high neck forces were likely to be caused by the steering wheel being trapped under the chin of the occupant and the inflating bag pushing the chin upwards.

For an occupant protection system to protect the occupant at such high impact velocity the system has to be adapted to such high impact velocities. To evaluate the theoretical and mechanical potential to adapt an occupant restraint system for such high impact velocities mathematical modeling and mechanical sled testing were used. Both the compartment geometry of the mathematical occupant model and the mechanical sled mock-up were based on the compartment geometry of the vehicle tested. However intrusion of the firewall and steering wheel was not included in the study since it was assumed that the intrusion can be eliminated through design modifications of the vehicle structure.

A number of parameters which possibly influence the performance of an occupant restraint system in a crash test were studied. From the analysis of these results valuable insights were given that will be used in future work. However other parameters with possible influence on the occupant response should also be studied. The restriction on the occupant’s forward displacement due to the geometry of the occupant compartment especially the upper windshield frame was not addressed. However the test at 80 km/h showed “reasonable” occupant kinematics. It is, however, obvious that the forward displacement of the occupant must be controlled in order to avoid a head contact with the windshield frame. Such a contact can result in high HIC numbers and neck loads. There are three major load carrying systems directly controlling the ride down of the dummy’s thorax namely the load limiting belt, the airbag and the collapse mechanism in the steering column. The phasing-in of the functions of these systems is of importance, especially for the chest deflection, and should be further explored.

The results from the study show that with proper design of an adaptive restraint system efficient occupant protection can be achieved at both high and very high impact velocities. However, in the proposed protection system the ride down distance of the occupant was greater than what is available in the vehicles on the market today. In addition there was a very early coupling between the occupant and the vehicle through the airbag. The airbag was inflated from a tank with stored gas. A fast opening valve was controlling the flow from the tank to the airbag. Due to the slow evacuation of the tank the valve was opened prior to impact. Therefore inflation of the airbag was initiated before impact. However, it needs to be evaluated if the proposed airbag system in an 80 km/h crash can be fired after initial contact or if the airbag has to be fired prior to impact.

The goal was to define an occupant protection system that in crash testing in high velocity with an occupant would result in injury measures below the FMVSS 208 injury criteria levels. The results form the mathematical model indicated that such a system can be developed. However, in the mechanical test carried out not all results were below the FMVSS 208 injury criteria levels. One reason can be the difference in airbag kinematics between the simulation and the mechanical test. However, this need to be studied in more detail.

In addition a restraint system designed to protect the occupant at very high impact velocities can be too stiff for the occupant at low impact velocities. In addition it can be too stiff for the elderly population with lower tolerance limits. However, with proper tuning of an adaptive restraint system (belt and bag) good protection can be achieved in both high and low impact velocities.

The analysis was made with a specific crash pulse obtained from crash testing of a conventional mid-sized car. As it is well known that the crash pulse has an effect on the dummy response it is recommended to try different crash pulses and study their effect on the dummy response.

The basic configuration of the tested restraint system was advanced. However, belt force limiting devices with other characteristics and a more sophisticated energy absorbing seat structure should be tried.

CONCLUSION

- Efficient driver protection at frontal impacts up to 80 km/h appears to be reachable.

REFERENCES

[1] EEVC. 2003. “Report on Recent Activities. 2003.” European Enhanced Vehicle-Safety Committee.

[2] Swedish National Road Administration. 2003. “Statistics Road Casualties”.

[3] Department of Transportation . 2003, National Highway Traffic Safety Administration, 49 CFR Parts 571 Federal Motor Vehicle Standards (FMVSS 208) as amended to June 2003.

[4] Carter, Robert L. 1972 “Passive Protection at 50 miles per hour”. NHTSA. DOT HS 810, 1972

[5] Mellander, H; Pipkorn B and Håland, Y. 2004. “Driver protection potentials in high severity frontal impacts with up to 50 mph delta-v”. Conference Safety 2004, Institution of Mechanical Engineers, London 2004

APPENDIX A: FMVSS 208 INJURY CRITERIA LEVELS

HIC_{15}	700
NIJ	1
Chest Acceleration	60 g
Chest Deflection	63 mm
Femur Force	10000 N