

CRANFIELD UNIVERSITY

HUGO MELLANDER

INTERIOR FRONTAL CRASH PROTECTION FOR PASSENGER CARS
AT HIGH DELTA-V - POSSIBILITIES AND LIMITATIONS

SCHOOL OF INDUSTRIAL AND MANUFACTURING SCIENCE

PhD THESIS

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HUGO MELLANDER

Interior frontal crash protection for passenger cars at high delta-v
– Possibilities and limitations

Supervisor: P Irving

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the Degree of Doctor of Philosophy

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1 Abstract

The purpose of this study was to analyse the possibilities to design an effective interior restraint system for the driver of a passenger car subjected to fully distributed frontal crashes in the speed range of 56 to 80 km/h (35 to 50 mph). In order to limit the research area the issue of structural integrity of the occupant compartment will not been addressed in this study. In other words it has been assumed that the frontal crush zone is large enough to absorb the kinetic energy and that the occupant compartment is not heavily deformed.

A computer model of a driver restraint system including an airbag, a seat belt, knee padding, seat and a steering wheel with column has been developed with a 50%-ile crash test dummy as the driver. The computer model results have been validated by means of mechanical sled tests.

A decelerating sled has been used for all the mechanical testing. The sled has been equipped with a mock-up of the frontal section of the occupant compartment of a passenger car including the steering wheel, steering column, seat and the driver restraint system consisting of an airbag, a knee restraint and a three-point seat belt.

The crash pulse at ~~50~~ 56 km/h, used in simulation and experimentation, has been selected to be representative for a mid size car from the nineties. To assess a realistic crash pulse for a high velocity fully distributed frontal crash with a mid size car from that period a crash test was performed at 80 km/h.

A number of input parameters describing the restraint system have been selected for a two level variation analysis using design of experiment technique (fractional factorial design at two levels). The restraint configurations defined in the matrix have been run through the computer model at ~~50~~ 56 and 80 km/h impact velocities.

The variables with the greatest effect on the dummy response have been identified. Some of the restraint system configurations have also been tested on the mechanical sled.

The results show that, for a given crash pulse, it is possible to design an interior restraint system with a low risk of injury at 80 km/h impact given that no significant intrusions into the occupant compartment occur.

The importance of tuning the characteristics of the restraint systems to the condition at hands i.e. the crash severity to achieve improvements in driver protection is also demonstrated.

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The crash pulse at 50 km/h, used in simulation and experimentation, has been selected to be representative for a mid size car from the nineties. To assess a realistic crash pulse for a high velocity fully distributed frontal crash with a mid size car from that period a crash test was performed at 80 km/h.

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5 Notations

5.1 Abbreviations and acronyms

AAAM= the Association for the Advancement of Automotive Medicine

AIS=Abbreviated Injury Scale

EURONCAP= European New car Assessment Reference Program

ESV= Experimental Safety Conference, renamed lately to International Conference on Enhanced Safety Vehicles

ECE= Economic Commission of Europe

HIC₃₆= Head Injury Criterion according to the expression below and as defined in Federal Motor Vehicle safety Standards (FMVSS) 208. Time interval maximum 36 ms

$$\left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a dt \right]^{2.5} (t_2 - t_1)$$

IARV= Injury Assessment Reference Value

IRCOBI= International Council on the Biomechanics of Impact

MAIS= Maximum AIS

NA= Not Available

NHTSA= National Highway Traffic Safety Administration

NIJ= Neck injury Criterion (FMVSS 208)

Ride down= The way the occupant is being brought to a stop (decelerated) in a collision

USNCAP= United States New Car Assessment Program

5.2 Units and sign conventions

All injury criteria values of forces, moments, and accelerations given in the tables are maximum values.

Inertia injury criteria and head and chest resultant accelerations are given as positive acceleration values as this is the conventional method used in all biomechanical research. A calculated resultant acceleration, being a vector, will by nature always be positive.

In diagrams showing head, chest and pelvic accelerations in x,y and z directions the sign convention will be according to SAEJ 211, mars 1995. As an example horizontal chest acceleration will appear as negative acceleration (deceleration) in the diagrams.

Compression forces in the femur and neck are given as negative values and tension forces in the femur and neck are given as positive values.

In this work a “stopping sled” sled has been used to simulate a colliding car. Vehicle/sled acceleration will therefore be reported as negative as the vehicle is brought to a stop in its forward one dimensional linear motion relative earth (in Hy-Ge testing, not used in this study, the sled will be accelerated backwards, hence, the sled acceleration in such a test is positive).

g= earth gravity 9,81 m/s²

h= hour

km= kilometer

km/h= kilometer per hour

m= meter

mm= millimeter

mile= 1,609 m

mph= miles per hour

N= Newton

Pa=Pascal =N/m²

mPa= 10⁶ xPa

kPa= 10³ xPa

s=second

ms=millisecond

6 Introduction

6.1 The problem

It has been known to mankind for thousands of years that the release of energy could inflict harm on the human body. Falls, fire and the use of weapons are examples of energy release that can be harmful under certain conditions. It has, for instance, been argued that the majority of people have an instinctive scare of heights developed through evolution. Nevertheless the lesson has not been learned for another type of energy release; namely, automotive transportation. It has killed millions of people during the hundred years it has existed. It is an epidemic of enormous proportion (Trinca, 1988).

It is estimated that worldwide the annual number of road fatalities is about 1,2 million and the number of injured are in the order of 20-50 million (Mackay, 2004). If motorization is spread to the third world without proper countermeasures being taken a prognosis has been made that the global death will continue to grow rapidly.

Today traffic systems and vehicle technology in different parts of the world are quite different. However, in most industrialized countries a systematic approach to the engineering and building of vehicles, traffic systems and roads is taken. The efforts to prevent an increase in and in some cases to reduce road casualty numbers, in spite of an ever-increasing number of vehicles and miles driven, have been rather successful.

Large reductions in the risk of being killed or seriously injured per driven kilometre have been made in the last decades. In many cases this can be attributed to improvements in road infrastructure, traffic control and management, speeds limits and to the increased crash safety of modern cars (European Transport Safety Council, 1997).

The total population of road vehicles are today about 700 millions of which 500 millions are cars and about 200 millions are buses and trucks. 30% of them can be found in Europe, 30% in the USA, 10% in Japan and 30% in the rest of the world. The percentage of car ownership is between 50-60 % of the population in most industrialised countries in the world like the USA and others. Some experts claim that the saturation rate could be as high as 80 % (Holmberg, 1996). Considering that the global population today is above six billion the challenges are enormous if one wants to create a sustainable global road transportation system with a minimum of casualties.

An ultimate goal for mankind must be to develop a homogenous sustainable road transportation system that yields a minimum of conflicts resulting in a minimum of injury producing crashes. A first step in this process could be to assess the technological feasibility for the development of car bodies and restraint systems, which could prevent serious and fatal injuries in the range of

crash speeds experienced on the roads. It must be a reasonable approach that “unavoidable” car crashes should be survivable for most occupants. This is indeed one of the objectives in Sweden’s long-term governmental program called Vision Zero Road Fatalities (Nollvisonen, 1997).

6.2 The technology - the origin and evolution of the automobile

The first cars got their design influence from horse carriages and bicycles in the 19th century (Stein 1964) (Scharchburg, 1993). They were soon developed to carry at least two passengers in the front seat and two or three passengers in the back seat. The width and length of the car was determined by the width of the existing roads. The demand for carrying passengers and goods and to have the necessary stability to prevent the car from rolling over also played a role.

Evolution continued mainly along two paths. One in America with an infrastructure build for automotive transportation and one in Europe where the car had to be driven on roads and streets in an already existing infrastructure with its roots back in ancient times. This led to design of relative large American cars produced until the energy crisis in 1973, when the US manufacturers were forced to downsize their cars to get better fuel economy.

In Europe the crowded cities, narrow roads and perhaps also another approach to engineering led to the development of many small and mid-sized cars. The very first cars designed in the 19th century were capable of speeds up to about 30 km/h but soon the power race started and cars became increasingly faster and faster. Most current cars are capable of reaching speeds between 150- 200 km/h and some even faster. There are cars and motorcycles in use on the roads today with a top speed of 300 km/h and above.

It has, however, been understood for some time that if society wants to reduce the number of road casualties and at the same time limit fuel consumption, speed limits have to be introduced and enforced. Today there are few places in the world where there is no restriction to the speed you can drive. On roads with oncoming traffic the speed limit usually is in the order of 80-90 km/h. For instance on Swedish roads the oncoming traffic has a speed limit of 90 km/h. If the road is narrow, curved and there are road crossings the speed limit is usually set to 70 km/h. On motorways with no oncoming traffic speeds up to 110 km/h are allowed. In the city the speed limit is usually 50 km/h, but in some places like near schools etc. it is reduced to 30 km/h.

In general 90 km/h seems to be a reasonable speed for drivers of cars on larger roads. It is not too fast and not too slow. An ordinary driver has the reaction time to cope with most of the situations and the stability and road holding of a modern car is very good at this speed. Fuel economy and air resistance are acceptable and it seems a reasonable hypothesis that 90 km/h is the speed that will be accepted on most larger rural roads with oncoming traffic also in the future.

However, looking at accident statistics and the crash performance of modern cars it is clear that frontal collisions between cars with a closing speed of 180 km/h, or car collisions with fixed object at 90 km/h are rare, but usually result in severe to fatal injuries (Mackay, 1998).

The design of a modern car is based on the fact that most crashes occur at a delta-v of 50-60 km/h and this speed range has been the basis for existing safety regulation, consumer testing and product development (Almquist, 1982) (Mellander, 2002). This implies that in many crashes some kinetic energy is lost by braking, or skidding, before the crash and/or the crash results in only partial reduction of the velocity due to rotation etc.

All existing crash safety regulations for frontal crash protection in Europe, the USA, Canada, Australia and Japan require tests at a speed lower than, or equal to, 57 km/h. All consumer-rating tests for frontal crash performance are being performed at speeds of 64 km/h or lower. The consequence is that a certain amount of high-speed frontal crashes (high delta v) still occurs every year which results in fatalities even with belted occupants travelling in airbag equipped cars.

The traditional countermeasure has been the improvement of the crash safety of cars. Considerable advancements have been made both in the structural "crashworthiness" of the car body and in the developments of efficient interior crash safety systems like seat belts and airbags. There are many different types of frontal crashes: angled, fully distributed, offset, under ride, etc.

In a frontal car crash the inertia forces acting on the body of the occupant to decelerate him should optimally be transmitted through the restraint system. The inertia forces acting on the occupant in such cases are mainly influenced by the deceleration pattern of the car body and the characteristics of the restraint system. However, in severe crashes certain parts of the car body may intrude into the occupant compartment and directly load the occupant. In such cases sustained injuries could be a combination of "inertia" related injuries and localized "intrusion" related injuries.

All modern cars have a frontal crash zone, which can absorb the kinetic energy in full frontal and off set crashes up to 60-65 km/h. In such collisions the crush performance of the structural system, buckling behaviour of beams, etc., is reasonably robust. Similarly, the interior restraint system of modern cars are designed and tested at crash speeds of up to 65 km/h.

6.3 What can be done

Recent visions, as described above, to further reduce the fatalities in road crashes have included the ultimate goal of reducing the death toll to zero. Therefore it is must be a matter of interest to find out if frontal crash protection systems can, from a technological point of view, be designed to efficiently

protect the occupant in frontal crashes with high impact severity (high Δv) (Mackay, 1998).

One solution to further improve the crashworthiness of current cars could be to make the car front longer and thereby creating a longer stopping distance in a crash. However, it is generally considered that making cars larger and thereby heavier is unrealistic due to a number of reasons such as fuel economy, use of raw materials and the effect on the infrastructure.

Another solution could be to make the front end stiffer, which would lead to structural incompatibility problems and also to a sub optimisation in terms of the crash protection that is offered to the occupant in the most common crash speed. However, there are emerging advanced technologies that in the future could make it possible to let the deformation characteristics be a function of the impact velocity.

The most realistic approach for the time being seems to be to investigate the possibilities to further increase the protection offered by the interior restraint systems. Taking into account new technologies that will enable the systems to be adaptive, or "smart" as it is sometimes called; it is now possible to make the protection characteristics of the restraint system a function of the crash speed. The purpose of this study is to demonstrate what could be achieved by applying new approaches in the design of restraint systems.

7 Objective

The objective is to demonstrate the theoretical and technological feasibility of an interior frontal crash protection restraint system, for a 50th %-ile male driver of a mid-size car, for impact velocities between 56 to 80 km/h.

A computer model and a mechanical model are to be created. Mathematical analysis, using a computer program, and factorial analysis technique will be used to find the parameters with the greatest effect. Crash sled testing will be performed to validate the computer model and to evaluate some of the identified configurations. Crash pulses from a state-of-the art mid size car will be used.

The study will focus on the analysis of the inertia forces acting on the driver occupant with the goal to keep accepted dummy injury criteria levels below recommended injury risk values.

With the recent advances in sensor and microelectronic technology new possibilities exist to design restraint systems that will adapt to the situation at hand (i.e. the violence in the coming crash). In the past most crash protection systems have been set to perform optimally at a certain crash speed. If the system was set to perform at a too high crash velocity the issue of sub-optimisation (too stiff systems that would give insufficient protection at the majority of crashes at low and moderate crash velocities) has always been focussed. With adaptive systems this can be avoided.

The hypothesis is that with the new technology and an increase in the ride down distance by e.g. moving the seat backwards before the crash interior crash protection can be achieved at 80 km/h impact velocity.

It will be assumed that the occupant compartment can be kept intact even at 80 km/h. Consequently the consequence of structural deformation of the occupant compartment and the following intrusion in high velocity crashes will not be studied, but should be addressed in future studies.

8 Literature study

8.1 History and development of seat belts

Restraint systems like seat belts are not a new invention. Leather straps of different kinds have been used to hold the occupants in place in horse drawn carriages and also in some of the very early automobiles and airplanes.

There exist quite a few early patents of seat belt designs. Gustav Desiré de Leveau patented an arrangement of straps to hold the occupants in place in an open car in 1903. A Mr Radtke from Germany was granted a patent in 1908 in England for a device to prevent occupants from tumbling around in the car in the case of a sudden shock to the car. In 1922 a racing driver in the USA, named Barry Oldfield, used a lap belt in racing cars (Andréason, 2000).

It took some time before more advanced types of seat belts were used in cars and airplanes to protect the occupants from being injured in a crash. In the late forties and fifties the automotive industry began to experiment with different types of seat belts. There were mainly two places in the world where most of the early development was done, in Sweden and in the USA. In Sweden the research came to be concentrated on chest bands of different kinds and in the USA a so-called lap belt consisting of a strap around the pelvis was initially favoured.

8.1.1 Evolution in the USA.

Pioneering work on early seat belt development was done in the American Air force (Chandler, 1993). The first restraint used in aircrafts was a lap strap but other types were, however, soon to be developed.

In the forties and early fifties the design principle of what is believed to be the very first version of a so-called three-point seat belt for aircraft emerged. These early belt systems had a lap belt and a diagonal belt, which had to be put on separately. Many pilots never used the diagonal chest strap since they thought it restricted their possibility to move. By combining the lap and chest band into one single continuous loop the inventors, Griswold and DeHaven, developed what they called a "must be worn" seat belt. If the pilot wanted to wear his lap belt he had to wear his chest strap too. There was even a three-point belt with a retractor, very much like the seat belts we use today, suggested by the inventors Griswold and DeHaven (U S Pat. Office Pat. No. 2,710,649).

In America it was concluded that a shoulder harness would restrict car drivers' and car occupants' freedom to move too much and consequently would not be accepted by the car occupants. It was considered that a lap belt would be sufficient to protect car occupants since the distance between the occupant and the dashboard was large enough to allow upper body motion in a crash without interference with the dash board (Fredricks, 1962).

Several attempts were made to introduce lap belts in cars, for instance by Nash, Kaiser and Ford in the early fifties. The public acceptance was however low and no American manufacturer decided to install lap belts as standard permanently. On the other hand shoulder harnesses were recommended and sometimes used in racing cars (States, 1962).

At this point in time there were discussions about trying to convince the American manufacturers to change from lap belts to diagonal belts. Many European researchers had now started to recommend a three-point belt consisting of a lap and shoulder belt as the best solution.

8.1.2 Seat belt research in Sweden

The first four-point harness, that was tried in some cars in Sweden, was designed by Raymond Sjöqvist (Andréason, 2000). This work was a result of an enthusiastic racing driver and layman and the belt was only installed in a limited number of cars.

An early development of seat belts took place within Vattenfall (the Swedish National Power Board) during the fifties by Odelgard and Weman. The management was the driving force behind the work as a measure to mitigate work related injuries and deaths. The first prototype was a horizontal harness that was routed under the arms. After many crash tests with a specially designed crash test dummy and after many discussions with physicians and other researchers the design was changed to the so-called diagonal belt (Andréason, 2000).

The Swedish manufacturers, Volvo and Saab, installed this type of belt for some years in the fifties. A Swedish physician performed an accident follow up study on the performance of these belts, mainly in SAAB cars and concluded that they were worn quite often and had an injury reducing effect (Bäckström, 1963).

During the work to develop and test the diagonal belt it was evident that in some tests of belts with poor geometry something called "submarining" could occur. This meant that the dummy could slip out of the belt with its hip and, in extreme cases, end up on the floor. As the concept of knee restraints was not yet thought of many improvements were thought out with different types of belt arrangements.

However, a lap and shoulder belt, a so-called three-point belt, was considered to be the best design. Volvo installed manual three-point seat belts as standard equipment in their cars in 1959 (Bohlin, 1981). In 1967 Volvo reported on the significant injury reducing effects of seat belts in a study of 28 000 cases (Bohlin, 1967). This report is considered to be an important step towards the installation and use of seat belts in cars.

8.2 Research on high velocity impacts and airbags

8.2.1 Experimental Safety Vehicles – structural research

In order to find a remedy for the increasing number of road casualties in the sixties the National Highway Traffic Administration in the USA initiated and sponsored a global research program called Experimental Safety Vehicles (ESV, 1970, 1971, 1972). The primary objective of the ESV program was to develop cars with good “crashworthiness” in all impact modes and with good road handling characteristics (Scott, 1973). There were very strict specifications set up for weight, crash performance, etc., in order to guide the work. In some of the experimental cars good crash performance was demonstrated in laboratory crash tests in frontal impacts (90° flat rigid barrier) up to 80 km/h. These cars were built with advanced frontal structures and had prototype airbags in combination with collapsible steering columns, experimental seat belts with load limiters and pre-loading devices (Dressler, 1979) (Baczynski, 1977, 1981).

The crash test dummies that were used in those days were less biofidelic than current test dummies and the biomechanical tolerance data were rather limited. The issue of compatibility, weight and cost of cars was heavily discussed at this time and recommendations were given for the force-deflection characteristics of the frontal part of the car taking frontal crash characteristics and compatibility aspects into account (Scott, 1973) (Rosti-Rossini, 1974).

However, many ESV cars were considered to be large and bulky and in many ways they were perhaps unsuited for mass production due to reasons like cost, styling, driving characteristics, etc. The real world crash performance of the ESV cars could never be established, as none of them was ever mass-produced.

The majority of frontal crash tests in the program were made at 56-64 km/h. This is the test speed range that is used today and many lessons were learned and would influence the development of crashworthy production cars of the seventies (Saxmark, 1973) (Asberg, 1976). Volvo integrated many features from their VESC (Volvo Experimental Safety Car) into the production model 240 see Figure 1 and 2 below.

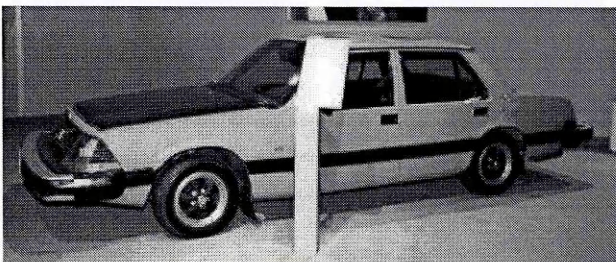


Figure 1. Volvo Experimental Safety Car.

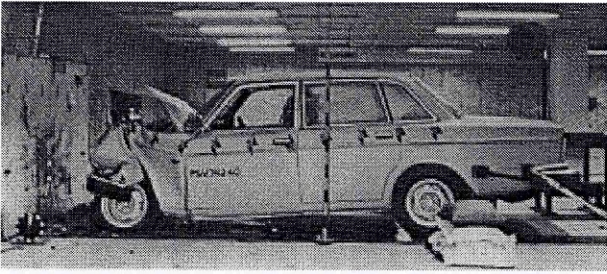


Figure 2. Volvo 244 production car after a crash test at 40 mph.

In another ESV-paper by the Department of Transportation in the USA (Carter, 1972) the feasibility of passive protection (no action required of the occupant to buckle up etc.,) at 80 km/h was investigated.

In a diagram, depicted in Figure 3, the required stopping distance using a square wave deceleration pulse and different levels of decelerations is shown. From the diagram it is evident that if a hypothetical value of 30 g is chosen as an average for a mid size car one would need a stopping distance at 90 km/h of 1,06 meter. If a less efficient pulse shape is chosen like a sine pulse, see Figure 4 with a peak value of 40 g the stopping distance increases to about 1,45 meters at 96 km/h. The less efficient a crash pulse is in the beginning of the crash the larger the stopping distance.

The objective in the report was to study both full frontal as well as pole impact conditions. Compatibility issues are also considered matching the deceleration response between colliding cars by tailoring the force characteristics of the frontal structure.

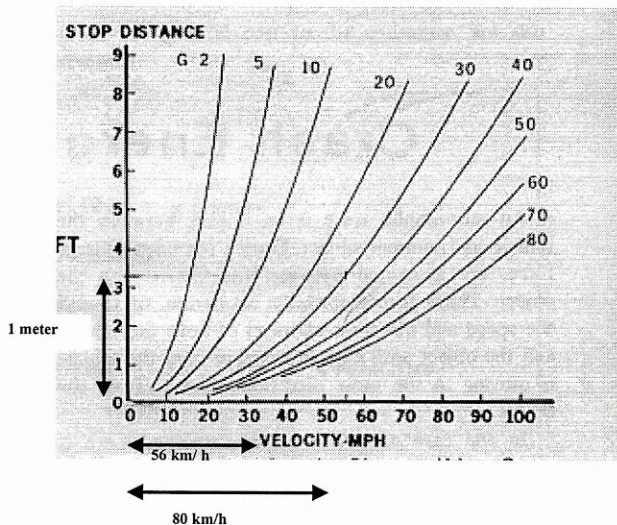


Figure 3. Required stopping distance as a function of crash speed for different levels of deceleration assuming a square wave (constant g) deceleration crash pulse (Carter, 1972).

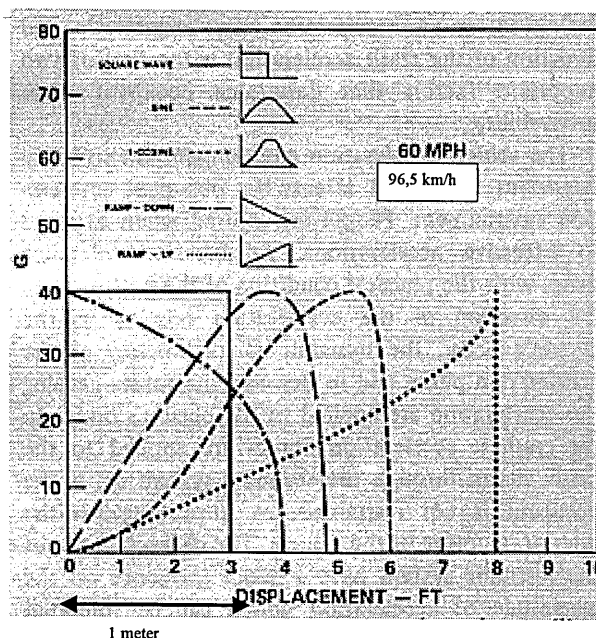


Figure 4. Effects on deviation from square wave deceleration pulse on required stopping distance 96,5 km/h impacts (Carter, 1972).

Test vehicles were designed, built and crash tested. The results demonstrated the feasibility of structural crashworthiness at high speeds. One of the guidelines was that independent of size and weight all cars should have the same crush force characteristics. Concepts with fixed force structures and velocity sensitive structures were tried and evaluated in mathematical models. The restraint systems used in this study was limited to airbags only and is consequently not directly related to the research in this project, other than that the basic reasoning for the design of restraint systems is the same. Although the crash test results in the study did not meet all of the objectives the conclusion was that (80 km/h) crash performance is possible for cars of different sizes and weight while maintaining compatibility. Quote "Although optimal solutions are not yet at hand, the feasibility of acceptable structural response in 50 mph (80 km/h) barrier equivalent crashes is clear" end of quote. It is estimated in the report that the benefits for installing such systems outweigh the cost by 1,4.

The methodology used in this study is good and could be used for a modern attempt to solve the same problem. The tools such as the mathematical models, the test methods, test dummy, injury criteria, etc., are by now out dated. Vastly improved tools are available today. Furthermore, the car at the focus in the study was a body on frame design, which is by now replaced by the uni-body design in almost all passenger cars. The restraint technology has gone through tremendous advances in the last three decades and would probably change the findings if a contemporary study was done.

In another ESV-paper the design of a lightweight 1393 kg car, crashworthy at impacts speeds up to 72 km/h, is described (Dressler, 1979). The base vehicle was a Simca 1308. The design principle was to divide the frontal structure into different zones to achieve pedestrian protection and crash compatibility with other cars. The deceleration pulse peaked at about 40 g with a sinus shape in a 72,4 km/h full frontal crash tests of the first prototype. The maximum dynamic crush was about 0.97m. In the full frontal crash test of the final prototype at 64,3 km/h the crash pulse peaks at about 50 g and the dynamic crush depth is 0.9 m. Offset crashes were also performed to evaluate the frontal structure and its ability to absorb energy in different crash modes.

There were no dummies installed in the tested cars. Peak acceleration and crush depth have been the major parameters to determine the offered occupant protection. Mathematical modelling and static crushing have been used as engineering tools. In the conclusions it is stated that the final prototype was crashworthy at speeds up to 72,4 km/h. The frontal structure was made up of HSLA (High Strength Low Alloy) steel. In terms of manufacturing feasibility the project was considered to be less successful due to complexity of the welding process.

In another recent study a coarse mathematical model of a restraint system was used to analyse occupant protection (Buzeman Jewkes, 1998). The influence of varying the car structure and mass was analysed. The accident spectrum from Volvo accident research was used. This work did not look at the effect of improving the crashworthiness of cars to give protection at high speed like 80 km/h. The conclusion was that improving the compatibility between cars in terms of geometry, stiffness and mass would yield large reduction in injuries.

In a recent study the body design principle and its influence of the shape of the crash pulse was studied. A mathematical model was used to analyse occupant response. High velocity impacts are not studied because of their infrequency (Witteman, 1999).

8.2.2 Restraint Systems research - airbags and seat belts

Airbags were invented in the fifties but were physically realized in the sixties as a means of protecting occupants in car crashes (Clark, 1966,1995). Numerous papers are available about the development and design of modern seats, seat belts and airbags. It is beyond the purpose of this work to list and discuss all of them. Some of the most important and interesting publications related to achieving protection at high delta-v will, however, be discussed below.

In the early years of the seventies airbags, energy absorbing steering columns and preloading belts were tested in experimental cars (Strother, 1976, 1977) (Volkswagen, 1969).

A key paper about possible ways to improve the three-point retractor belt was published in 1978 (Svensson, 1978). A manual seat belt adjusted correctly without any slack will give the occupant a good coupling with the car and consequently a good “ride down” in a crash. With the invention of the retractor belt the phenomenon of “spool out” of webbing from the retractor was discovered to be a problem. When significant forces are introduced in the belt during a crash the webbing tends to be compressed on the retractor reel hence causing webbing to be drawn out of the retractor. This will result in a delayed coupling of the occupant to the car during the crash and a poor ride down with large forward displacements. In this study results from tests using a webbing locking device in the D-ring (webbing guide) in the B-pillar and a belt pre-loading device that significantly increased the efficiency of the seat belt were presented.

New methods to evaluate the quality of protection and the importance of tuning the restraint characteristics such as stiffening the seat cushion to improve ride down was also demonstrated in other studies (Adomheit, 1975, 1977) (Nilsson, 1995).

In another study the importance of incorporating anti sub-marining devices in the seat cushion was also demonstrated (Lundell, 1981).

Daimler-Benz understood early the importance of combining seat belts with airbags to give “supplementary” protection in high speed crashes. The concept with the driver supplemental airbag system with preloading belts installed in some Mercedes Benz models in 1980 is described in a paper (Scholz, 1980). A comprehensive description of the European evolution of airbags is given in a recent paper (Nilsson, 2003).

The concept of installing a small airbag to protect the head and neck of an belted driver was presented in another paper (Johansson, 1989). This concept was nicknamed the Euro bag and showed considerable improvements in protection of a belted driver although the system was never tested at crash speeds above 56 km/h.

With the concept of preloading and force limiting of seat belts in combination with airbags the development took a major step forward. In a recent study it was shown that tuning of the different restraint systems must be done in order to avoid excessive thoracic loading. The primary finding being that the shoulder belt force must stay below 6 kN by introducing a force limiting device in order to avoid too many rib fractures (Bendjellal, 1997).

With the introduction of airbag technology many new parameters were introduced into the development process of restraint systems. With the newly developed mathematical models and new computer software an “optimisation” procedure became possible. In several publications it was shown that it was important to tune the system properly in order to avoid excessive bag slap to

occupant in out-of-position and to protect a variety of different occupant sizes in a good way (Biss, 1980) (Skötte, 1985).

Since the majority of frontal crashes occur at about 40-50 km/h it has been recognized that during the development process special care has to be taken in order to avoid “sub-optimisation”. In other words, designing a system that would give good protection at a relative high crash velocity could imply that the system would be too stiff at a more frequent lower crash speed. This phenomenon has been extensively reported on but builds on the hypothesis that a system's characteristics could not be adapted to the crash speed (Horsch, 1987) (Norin 1991). Such possibilities do exist today.

The modern systematic way of developing a passenger car by setting up the design targets that define the performance in terms of crash protection of the car was described in detail in 1987. This study shows the complexity of the modern engineering process (Almquist, 1982).

8.2.3 Optimisation studies

An important step in restraint system development was taken in a study “Safety System Optimisation Model” (Versace, 1976). Using rather coarse models in order to find out which vehicle characteristics would result in the lowest possible injury measures an analysis was performed. This work was probably the first study in this area of research. Looking at the approximation one was forced to do in order to limit computer time and effort it seems like a reasonable conclusion that the methodology could be largely improved by using modern modelling and computer technology. This study also included a cost benefit analysis which was and still is one of the most important aspects of a study with the objective to recommend possible improvement of overall crash safety to be implemented.

In another paper called “Restraint Force Optimisation for a Smart Restraint System” (Miller, 1996) the benefits of using adaptive restraint system technology was studied. In an adaptive system you could vary the characteristics of the system according to the conditions at hand. Madymo software and a computer model were used to test a set of possible combinations of restraint parameters. The most efficient solution seemed to be to adjust the level of the force in the load limiter according to the occupant sizes and to use a constant force characteristic for the load limiter. Airbag venting was also varied which largely affected the dummy responses. The highest test speed was 56 km/h in this study.

In the study “Restraint System Optimisation for Minimum Societal Harm” (Spark 1998) possible improvements to the restraint system of an existing car were analysed. The objectives were to look at the possible improvements that could be made to an existing car in terms of changing the restraint system characteristics and evaluate the benefits by estimating the reduction in societal harm (Malliaris, 1982). The spectrum of crashes occurring on the Australian

roads was used as input and by varying the restraint configuration the minimum societal harm was searched for. It is not obvious from reading of the paper if the crash pulse was varied. Societal Harm is a measure of the total injury cost for the society for road trauma. It is concluded that an optimising technique has been developed which could be used for the design of restraint systems.

In a recent study mathematical models were used to analyse the effect of changing the characteristics of the restraint systems in state of the art cars using a unique regression model developed by Volvo (Norin, 1995). The regression model related dummy readings to actual injury outcome in crashes. The method was used in order to evaluate hypothetical changes of the car in terms of estimated injury reduction. This study did not discuss increased crashworthiness at higher collision speeds or the possibility to use adaptive restraint technology.

In a report presented in 2001 possible improvements in restraint technology was researched into by varying the most important characteristics of the airbag and the belt system (Yang, 2001). Mathematical modelling was performed using Madymo software and significant findings were validated through sled testing. The conclusion was that seat belts with pre-loaders and force limiters in combination with airbags with variable vent holes would give sufficient occupant protection for different sizes of occupants at different crash speeds. However, there were no tests performed at speeds higher than 64 km/h.

An important aspect of analysing the level of crash protection in a car is to grade the effect of the individual dummy readings, head, thorax, etc., by using a Combined Index. There are several studies that have attempted this. The most important is probably "Assessing the safety performance occupant restraint system" (Viano, 1990). Through analyses of the injury spectrum in real world crashes in the USA a factor is assessed that will be multiplied to each injury criteria. The terms are then summed up and for each set of restraint configuration a value for a so-called Combined Index is calculated. The methodology is interesting but could probably be improved in a statistical sense.

8.3 Biomechanics of impact

8.3.1 Background

The science of impact biomechanics is a rather young science with its origin in the work done by Hugh DeHaven at Cornell University in the USA and by Colonel John. P. Stapp in the US air force and many others (DeHaven, 1952, 1953) (Aldman, 1962, 1988).

Hugh De Haven studied free falls in which people had survived or died. He drew a diagram depicted below of the combined effect of "effective acceleration" and the duration of the exposure when people impacted the ground or objects on the ground (DeHaven, 1942), see Figure 5. He defined an area in the diagram where the violence was "Probably survivable" and another area for "Not survivable trauma". His data came from simple calculations based on the height

of the fall to assess the impacts velocity and the depth of the imprint in flowerbeds etc. to roughly assess average deceleration. Looking at the diagram it can be seen that the human body can withstand high forces for a short time (fractions of a second) if the forces are well distributed but as the duration of the impact increases the tolerable force is decreasing. This is a pattern well recognised in most subsequent biomechanical research findings.

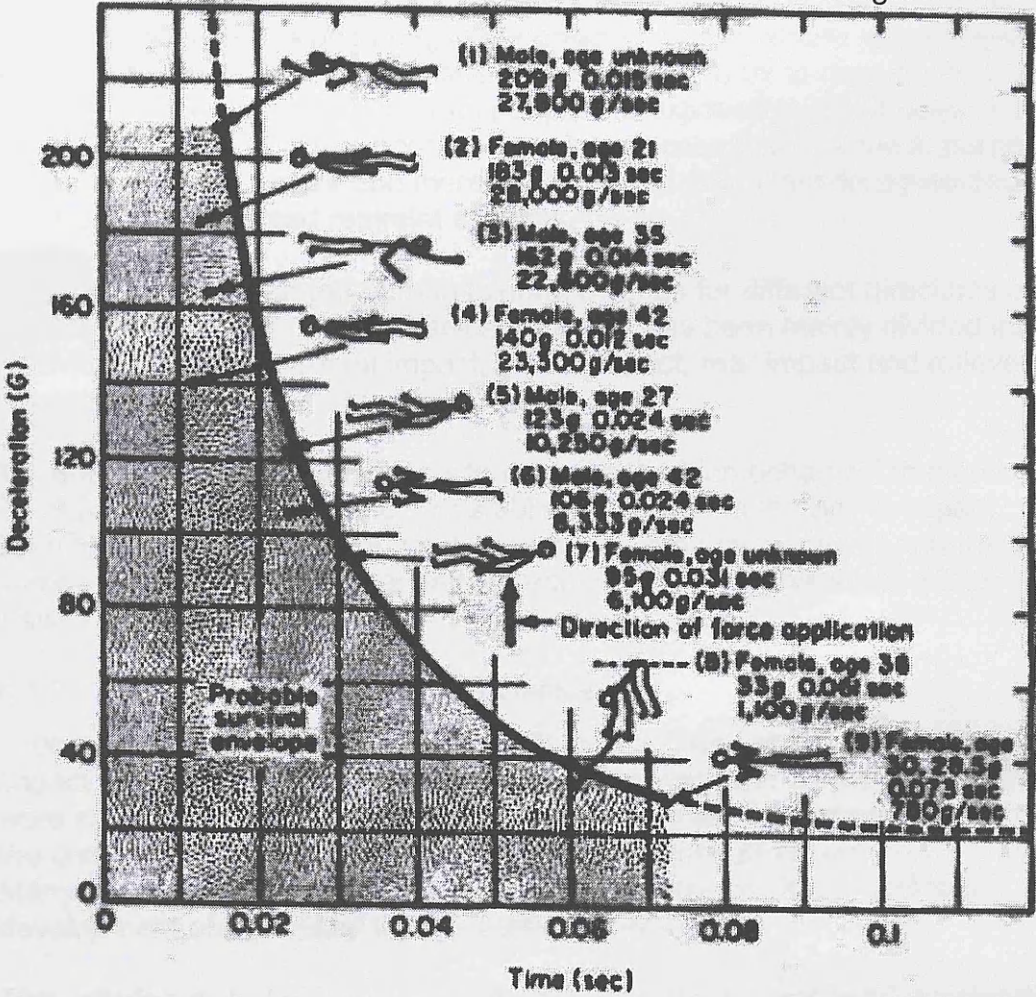


Figure 5. DeHaven’s famous diagram showing the effect of “effective” deceleration and the duration of impact on the likelihood of surviving free falls (Dehaven, 1942)

In an attempt to find out if pilots could be safely ejected from supersonic air planes Colonel Stapp subjected himself to about 40 g when he was decelerated from 965 km/h (600 mp/h) to zero in the famous sled tests in the Alamogordo desert in New Mexico in the fifties. A rocket-propelled sled running on tracks was accelerated almost to the speed of sound and then abruptly decelerated with a special braking system. The forward facing occupant was restrained with a special seat belt harness. Colonel Stapp did suffer minor injuries in the tests but they were clearly survivable as demonstrated. He lived to be an old man. Further research by Martin Eiband and others added more valuable information for the whole body human tolerance to rapid acceleration in different directions

(Eiband, 1959). In these early studies it was again found that the human body could withstand very high accelerations for a short time if the forces were well distributed over the body and that the tolerance decreased as the exposure time increased.

Pioneering researchers and engineers who tried to design safer cars used this information. However, there was a need of more specific human tolerance data related to the violence occurring in car crashes. Considerable efforts were therefore made in America, Canada and in Europe to try to map the human tolerance to the type of trauma that people are exposed to in car collisions (Newman, 1980). This has been an ongoing process that has run in parallel with the development of more and more sophisticated crash test dummies and more and more sophisticated restraint systems.

It has been found that the human tolerance varies for different directions of impact. Therefore the biomechanical research has been mainly divided into the following categories: frontal impact, lateral impact, rear impact and rollover exposure.

It is not the purpose of this thesis to describe the biomechanical research and its findings in detail but rather to establish the "state of the art" in impact biomechanics for frontal impact. However, the protection criteria and the test dummy used in the analytical and experimental work in this study will be justified and defined below.

8.3.2 The head - Injury and biomechanics

In early cars the interior was very hostile with stiff and sharp objects in the head impact zone. Without the use of seatbelts and even with lap belts head impacts were common and often resulted in cranial fractures. For a long time fracture of the cranium was considered to be the primary cause of severe head injury. Many years of experiments with instrumented cadaver heads lead to the development of the "Head Injury Criterion" (HIC) (Mellander, 1986).

This criterion is, today, calculated using the resultant linear head acceleration measured in three orthogonal directions at the centre of gravity inside the metallic head of a crash test dummy. The origin of this criterion is the so-called Wayne State curve, which has similarities with the diagram made by DeHaven mentioned earlier. Charles Gadd later interpreted the Wayne-State curve by making a graphical regression of the results (Gadd, 1969). He then formulated the Severity Index that was later transformed in to the HIC-criterion by other researchers (Mellander, 1986). The quality of the instruments used in the early experiments was poor and therefore the foundation for this research is rather weak.

The interpretation of the censored biomechanical data has also been widely discussed and elaborated upon for decades (Ran, 1986) (Koch, 1988).

Despite all the criticism the HIC-criterion is the criterion used in the crash safety development within the car industry today. It is referred to in almost all crash safety regulations and also used in all consumer-rating tests.

In an empirical way the criterion has led to the development of restraint systems that prevents head impacts or reduces the violence of the head impacts to a non-injurious level. The current use of airbags in cars with distributed forces acting on the head in a crash has led to certain changes in the HIC formula (FMVSS 208, 2001),

As more biomechanical data have been added to the early Wayne State University data set it has been possible to compute risk curves and relate a certain HIC value to a certain risk of injury for the population at risk (Mertz, 1997).

However, the human brain is sensitive to both linear and rotational acceleration and in spite of the improvements of current restraint systems brain injuries still occur in car crashes. Cranial fractures are today in most cases judged as less severe injuries. The types of injuries range from focal injuries to diffuse axonal injuries of the brain (Mellander, 1988) (Viano, 1997) (Lövsund, 2000). Brain injury is a severe injury, which needs immediate care and is quite costly to treat. Even if modern head trauma treatment is able to save many patients lives there are many cases resulting in permanent dysfunctions of different degrees. The so-called diffuse axonal injury, in which the nerve axons have been stretched but not torn, but have lost their ability to transmit nerve signals, is one of the most severe injuries. It is difficult to diagnose and difficult to treat. It has been attributed to the effect of angular acceleration but the injury mechanism is still not fully understood.

Ongoing research will hopefully lead to a better understanding of the injury mechanisms in the brain matter and the blood vessels in the brain. Even if there is some basic understanding of the injury mechanism of the nerve axons there seems to be no consensus on what a proper global injury criterion and injury criterion level should be. There are however suggested tolerance levels for angular accelerations for the different modes of motion (Mellander, 1987). It has also lately been suggested (Newman, 2000) that a "Power Criterion" would be a better way to estimate a tolerable energy transfer to the head.

It was decided that in this study the HIC criterion based on the resultant head acceleration would be used to assess the risk of head and brain injury. For tolerance see chapter Dummies - Injury criteria.

8.3.3 The neck - Injury and biomechanics

Severe neck injuries leading to different degrees of paralysis or even death are rarely seen in belt-restrained occupants in frontal collisions with modern cars. By staging real world crashes with known outcomes in terms of neck injuries in laboratories using test dummies with neck load cells Mertz (Mertz, 1971) was able to establish tolerance levels for flexion and extension.

There are however recent findings that show that minor neck injuries (soft injuries) are a problem even in frontal crashes (Jakobsson, 2004).

The introduction of airbags has diminished the forces acting on the neck of occupants in most frontal crashes. There are however cases where airbags may introduce injurious forces to the neck. This has been shown especially for small occupants, or children, who are said to 'be "out-of-position" at the time of airbag deployment. A criterion called NIJ has been developed to assess the injury risk of combined loading to the neck such as when an airbag transmits bending moment as well as axial loading to the neck (Kleinberger, 1998) (Eppinger, 1999, 2000).

However, since the primary focus of this work is to study occupants in position the conventional threshold values developed by Mertz, as described above, will be used in conjunction with Nij to assess the risk for neck injury in the sled tests. For tolerance values see chapter Dummies - Injury criteria.

8.3.4 The chest - Injury and biomechanics

The skeleton in the human thorax is the main load bearing structure in the chest on which the restraint system normally applies the ride down forces in a crash. The ribs act as a protective ring around the internal organs such as the heart, the lungs and the liver. If fractures of a rib or ribs occur due to excessive deformation of the rib cage damage to the underlying tissues and organs may occur. The ends of a fractured and displaced rib may penetrate into the chest cavity and injure the lungs. This may cause a so-called pneumo-thorax in which the pleural sack is punctured allowing air to enter into the pleural cavity. The pleural cavity normally has a pressure below atmospheric pressure in order to expand the lung. In the absence of this vacuum due to air leakage the lung will collapse. This is a severe condition and should be avoided.

A large number of rib fractures may also cause instability of the thoracic cage (so called flail chest), which also may prevent effective breathing. Patients suffering from these types of injuries must be treated with artificial breathing within a short time to survive. In some severe exposures even the heart may be affected causing bruising of the heart muscle and pericardial bleeding (a bleeding inside the heart sack) which is a life threatening injury.

If the thoracic cage is severely deformed local stress, leading to an aorta rupture, may also occur at the so-called aortic branch. An aorta rupture is very difficult to diagnose and will, if not treated immediately by surgery, be fatal. Local deformation and/or rib fractures may also injure the blood filled organs in the chest cavity such as the liver/ spleen and the kidneys (Mulligan, 1994).

Valuable information was achieved analysing stunt dives in which volunteers subjected themselves to blunt trauma to the thorax and whole body (Mertz, 1975) (Viano, 1975).

In sled tests with human cadavers the pattern of rib fractures was compared with the pattern of rib fractures seen in occupant involved real world crashes of similar type and violence. Dummy kinematics was also compared to that of the cadaver. The restraint system, a three point belt, and the seat was the same in the experiments as in the field crashes. It was concluded that the fracture patterns were similar, but the Hybrid II test dummy had a stiffer thorax and had somewhat different kinematics (Kallieris, 1982).

Through numerous testing of restraint systems with cadavers a risk curves for the compression of the chest in frontal exposure has been established (Mertz, 1997). A cumulative frequency curve for receiving several rib fractures as a function of normalized chest deflection is today the most recognized method for assessing the risk for chest injury.

However, analysing the resultant chest acceleration and other combined criteria is also an established method to properly assess the function of the restraint system (FMVSS 208, 2001) (Kuppa, 1998). Consequently as a basis for the analysis in this work chest deflection and also chest resultant acceleration have been chosen as the parameters to be studied. For tolerance values and risk curves see section Dummies - Injury criteria.

8.3.5 The lower extremities - Injury and biomechanics

Leg injuries in belted occupants are often the result of intrusion into the occupant compartment in the foot well area, or interaction with an intruding dashboard. The femur bone is a strong bone and will endure quite high forces before it will fracture. A femur fracture is a moderately severe injury and if the fracture is not complicated it can be treated effectively.

In early biomechanical work it was established that the tolerance for a 50th %-ile male young male was in order of 10 kN (King, 1973) (Viano, 1977) (FMVSS 208, 2001). This then became the maximum allowable force to be measured in either of the upper legs of a crash dummy in a crash test in safety standards.

In European safety standards, however, a time dependency criterion has been applied called the "Femur Criterion" in which the highest acceptable force is 7,5 kN but only for a short time (milliseconds). Thereafter the force must be reduced below certain levels to avoid fractures (Directive 96/79/EC, 1996).

In a properly restrained occupant the femur forces, without the influence of intrusion, are normally quite low. If the occupant does not reach into the knee bar during the ride down non-injurious tensional forces will occur due to the mass of the leg. When an impact with the knee bar does occur with an unbelted occupant the forces may reach an injurious level.

Peak loads in the femurs will be used to analyse the results in this study. For tolerance values and risk curves see section Dummies - Injury criteria.

8.3.6 Crash test dummies

The very first crash test dummies developed in the fifties were made up of wooden blocks and were primarily intended to load the restraint system. Later on in the sixties more human like anthropometric and anthropomorphic dummies were developed like Sierra 1050 etc. Based on the knowledge from research with human cadavers and to some extent non-injurious exposure to volunteers the Hybrid II dummy was introduced and much used in product development testing and related to in safety standards.

It was decided that the 50th percentile male was to be standard for testing cars and this size of dummy became the most frequently used, even if there existed other sizes like the 5th and 95th percentile dummy. A crash test dummy had to be human like and at the same time be robust and strong enough to withstand and measure “overload” (forces that would damage the human body) conditions. It must be possible to calibrate the dummy in accordance to certain procedures and specifications before it is used in testing. This resulted in several design compromises and the dummies became rather simple mechanical devices in comparison to the sophistication and complexity of the human body.

The so-called Hybrid II dummy was the commonly used dummy and was even referred to in safety standards. The limitations and the non-biofidelity of the Hybrid II was discussed and analysed for years (Kallieris, 1982) and led to the design of a new dummy called Hybrid III introduced by General Motors in the seventies (Foster, 1988) (Backaitis, 1994). This new dummy had an improved seating posture and many other features including a much better chest design. It could be instrumented with a potentiometer for the measurement of chest deflection and a neck load cell and had an improved clavicle design etc. It has been thoroughly tested and analysed in hundreds of projects and has been found to be good enough to be incorporated in safety standards in the USA and in Europe.

In spite of this there was still a need to reach even further and to try to develop a more biofidelic dummy that would have most of the characteristics of the human body found in the most recent cadaver research. There was also a need for additional instrumentation. The National Highway Safety Administration decided to sponsor a project to develop an advanced frontal impact test dummy. The project group named the dummy the “Thor dummy” (Rangarajan, 1998) (Hoofman, 1998) (Xu, 2000) (Haffner, 2001) (Kent, 2002).

At the start of this thesis work it was decided to try to use the Thor dummy both in the computer studies and in the physical sled testing. Considerable efforts were made to acquire a reliable mathematical description of the dummy to be incorporated into the computer model (Martinez, 1999). Despite many months of work the model still yielded unrealistic results. The problem was located to the description of the characteristics of the spine among other things (see chapter Validation and computer model set up- Thor dummy). It was not realistic to try

to correct this as the model is very complex and the property of another company.

The physical Thor dummy was however initially tested in the sled tests but gave confusing and unreliable results for the so-called CRUX- measuring devices in the chest. The CRUX array of potentiometers is very complex and the output signals must be fed into a special computer program in order to achieve the actual deformation pattern of the chest. In spite of numerous investigations, analysis, calibration tests, debugging of the data output post-processing program and retesting with the dummy the problems were not solved.

Due to time and cost reasons the dummy had to be replaced with the Hybrid III dummy as defined above and the planned computer analysis and some of the testing had to be redone. However, since most of the automotive safety technology that has been developed up to now has been tested with the Hybrid III dummy it was considered to be a satisfactory device for this work.

8.3.7 Variation in human tolerance

The human tolerance to blunt trauma varies due to a number of factors such as age, sex, differences in anthropometry and fitness among others. In order to limit the complexity of the mapping of human tolerance, the population at risk for car occupants has to be defined. However, the population at risk defined as “the population that is likely to be exposed to the hazard of collision injury” is fairly large as we travel in cars almost from birth till death.

In order to give a structure to this problem, the population at risk is conventionally divided into different size categories like infant, 3-year, 6-year, 10-year-old children and 5th %-ile, 50th %-ile and 95th %-ile adults. Most of the biomechanical work and interest have so far been concentrated on the 50th %-ile male adult but there is now a growing interest in other occupant categories. However, even within the categories of 50th %-ile male car occupants there is a large scatter in resistance to blunt impacts (Mackay, 2000).

8.3.7.1 Impact biomechanics research and Injury criteria and Injury criteria tolerance levels

Human tolerance to blunt trauma has to a large degree been determined through cadaver and animal experiments. Knowledge has also been gained by subjecting volunteers to non-injurious violence. Injuries in real world crashes have been compared with crash test dummy readings in reconstructions of these crashes.

In the first efforts to give guidance in the design of safer cars, injury criteria and injury criteria levels were defined. These injury criteria were chosen as they correlated with “serious injury”. For frontal impacts, such an injury criterion was chest acceleration and the injury criterion level or human tolerance level was set to be 60 g as measured in a crash test dummy. A more scientifically correct

denomination is protection criterion and protection criteria level for crash test dummy results (Aldman, 1983).

Many regarded the 60 g level, and all other recommended levels, as a “go /no go” criterion. A value below the tolerance level was considered to be “safe” and a value above it was considered to be unsafe meaning serious chest injury would result from such an exposure. However, as the science of impact biomechanics evolved it became clear that such a simple model was not appropriate.

8.3.7.2 The concept of cumulative injury risk functions

Establishing a relationship between, for instance, experimentally applied loads and the actual bodily damage (injury as defined by an AIS score (AAAM. The Abbreviated Injury Scale, 1998)) such as fractured ribs has confronted the analyst with a challenging problem.

The experimental data are in most cases what is called “censored”. In other words, it is not known at exactly what level of violence an injury in an experiment will occur. What is known from an outcome of an experiment with no injury is that forces of lower magnitude will not produce an injury, but it is not known how much the loads could have been increased in a particular experiment before an injury would be produced. The opposite is true for experiments that produce injuries. It is not known how much the forces could have been decreased and still have produced an injury. In other words the exact force level at which an injury will occur is not known.

Censored data are data biased in one direction or another. The sign of the bias is known but not the magnitude making the application of conventional correlation methods using regression analysis complicated as these methods assume data free from bias. Figure 6 depicts the outcome from a typical biomechanical experiment.

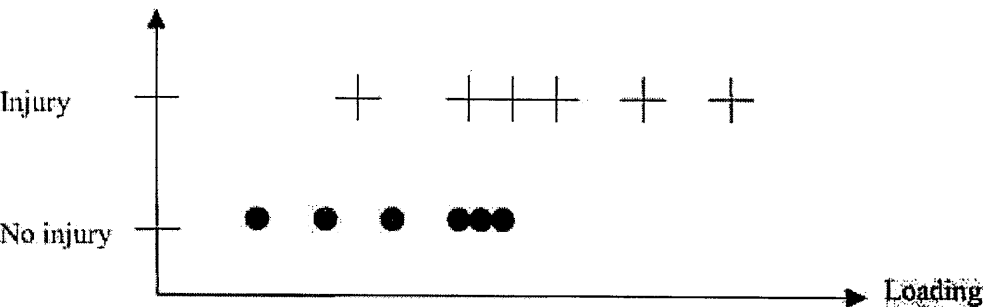


Figure 6. Outcome of a typical biomechanical experiment

The challenge now becomes to convert these censored data into a cumulative injury risk function as depicted in Figure 7.

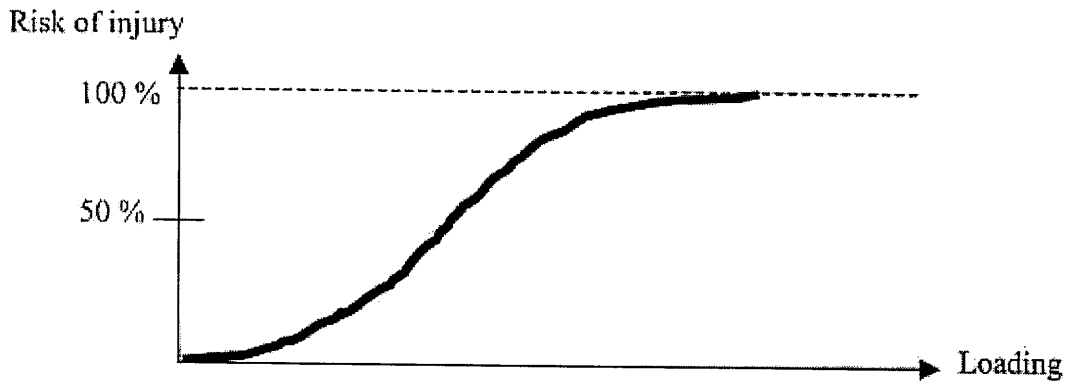


Figure 7. An example of a non-specific cumulative injury risk function.

The derivative of the cumulative function is the distribution function (or the frequency density distribution function). One of the decisions that have to be made is to choose a suitable distribution function to fit the data to. The biomechanical community has been discussing for some years what the “best” fitting method and injury distribution function is, but it is not the purpose of this presentation to elaborate on that issue.

However, as has been shown in previous work (Ran, 1986)(Koch, 1988) a good choice is the Weibull distribution and data can be fitted using the Maximum Likelihood method (Wonnacot, 1977). A number of cumulative injury risk curves have been published through the years where injury is defined by an AIS score. In some work it is argued that the “best” injury distribution function is a normal distribution. Assuming such a distribution, the injury risk function becomes a straight line if plotted on log-log paper.

The International Standards Organisation/TC22/SC12/Working Group 6 has released a set of recommended injury risk curves for the head, neck and chest, etc., for different occupant sizes (Mertz, 1997). These injury risk curves are used, for instance, to establish injury risk in the rating of crash safety of cars.

8.3.7.3 Assessing Injury risk in New Car Assessment Programs

The Euroncap system is using a “sliding scale system of scoring points”. In an effort to encompass the concept of cumulative injury risk curves, it defines two limits for each injury parameter. For instance, for the head protected by an airbag when there is a “hard contact”, a “higher performance limit”, giving the maximum score, is set to be a 5% risk of injury $\text{AIS} \geq 3$ and corresponds to $\text{HIC}_{36} \leq 650$ and a resultant acceleration of 72 g. The lower performance limit, giving no score, is set at 20% risk of an injury $\text{AIS} \geq 3$ and corresponds to $\text{HIC}_{36} \leq 1000$ and a resultant acceleration of 80 g (Euroncap, 2004).

In the US NCAP (<http://www.nhtsa.dot.gov/cars/testing/ncap/>, 2004) the test dummy readings in the crash are related to the injury risk curves that

“demonstrate the probability of an injury to a real person in that crash”. Such a risk curve for AIS≥4 chest injuries is shown in Figure 8.

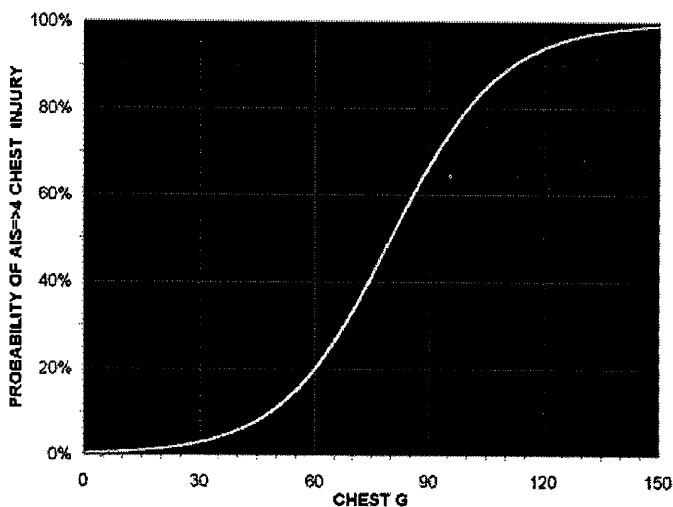


Figure 8. A cumulative injury risk curve for chest injuries AIS≥4 as defined in USNCAP.

The star rating is then done according to the scoring system as depicted in Figure 9.

★★★★★	= 10% or less chance of serious injury
★★★★	= 11% to 20% chance of serious injury
★★★	= 21% to 35% chance of serious injury
★★	= 36% to 45% chance of serious injury
★	= 46% or greater chance of serious injury

Figure 9.The star scoring system used in US NCAP.

8.3.7.4 Some words of caution

There are a number of things that can be said about the above-described methods leading to the assessment of injury risk curves. Firstly, it must be understood that the biomechanical data available for analysis from different sources are limited and many times the experimental technique varies making it difficult to lump available data into one set of data. If one introduces confidence intervals to the injury risk curves, they often become rather wide making prediction with high significance difficult (Koch, 1988).

Secondly, the transfer function of biomechanical data from experiments performed on a living or dead human body, to a mechanical substitute like a crash test dummy is complex and sometimes not fully understood. In that context a model that relates real world injuries, as defined by AIS scores, for a certain type of collision of varying violence to the actual dummy response in the reconstructions of said collisions is superior (Mellander, 1989) (Korner, 1990). Although being expensive and time consuming the approach has been tried in some research and proven to be very efficient. Especially when the effect of an upgrading of the crashworthiness of an existing car model has to be estimated. Figure 10 describes graphically the first step in this method.

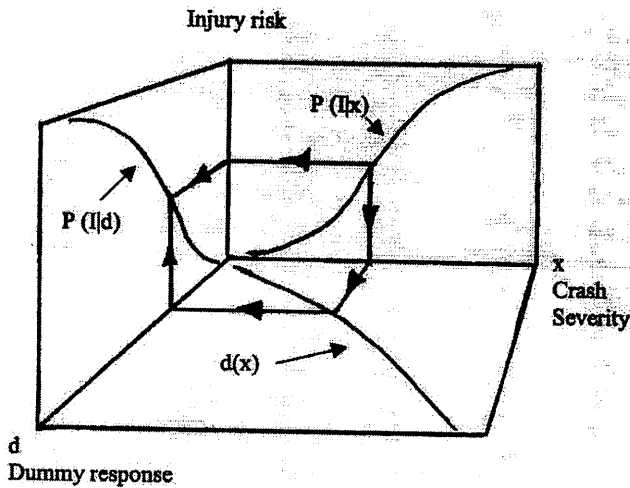
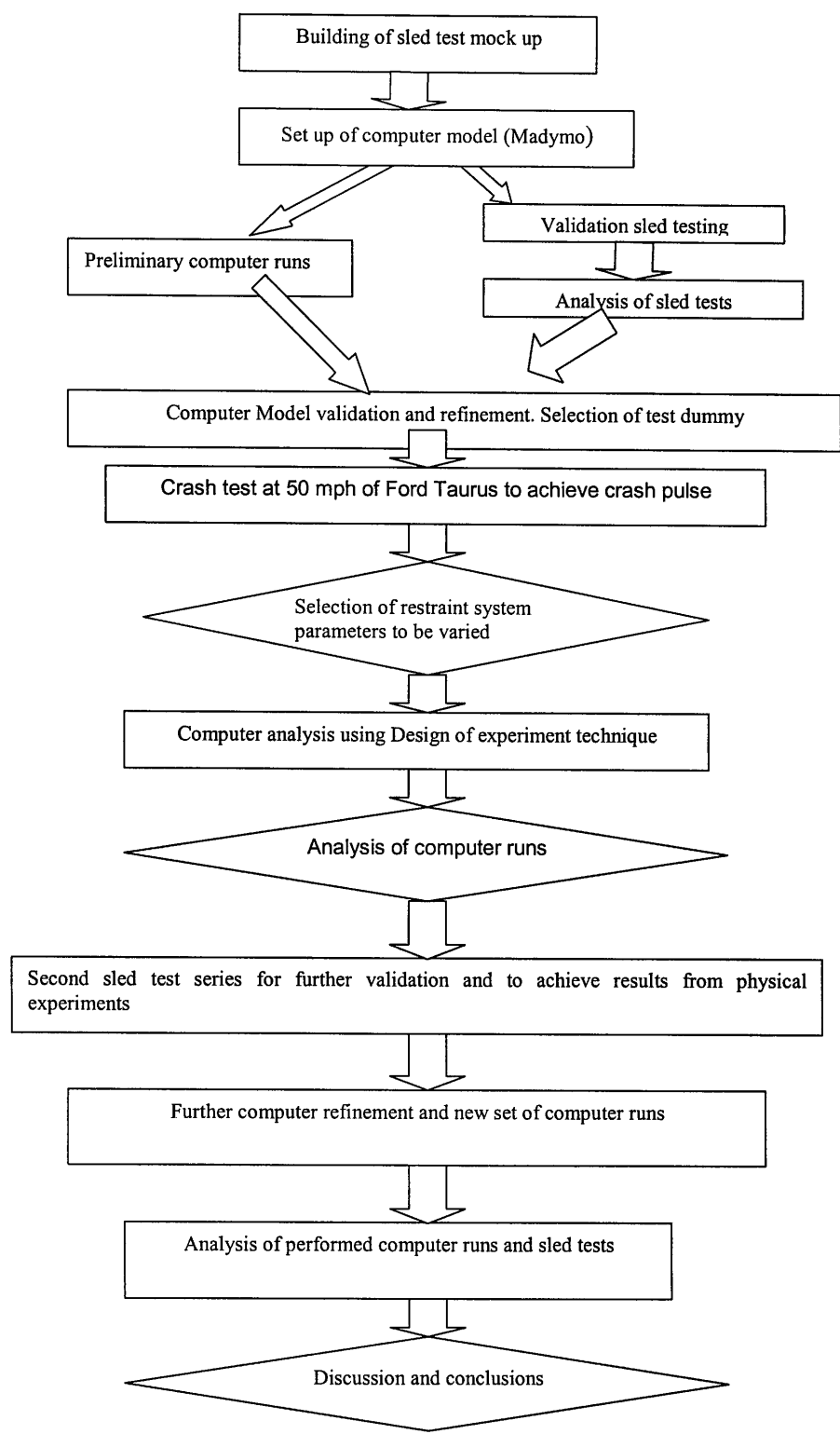


Figure 10. Converting injury risk vs crash severity $P(I|x)$ into injury risk vs dummy response $P(I|d)$, (Mellander, 1989).

Thirdly, most rating systems focus on injury risk curves for a 50th %-ile occupant. Care should be taken when the results are transferred to other sizes of occupants. Fourthly, in rating programs only one crash test for each crash configuration is performed. Considering the variations that occur in crash testing, care should be exercised in the interpretation of the results and their correlation to occupant injury risk.

9 Methodology – Flow chart

In order to organize the work to be done and to define all the sub tasks a flow chart of all the sub tasks was set up as below. A logical flow of activities was strived for where each activity was a prerequisite for the following activity.



10 Equipment and Experiments.

10.1 Sled testing apparatus

A decelerating sled equipment has been used as the physical testing device. This is a well established test methodology that has been used since the seventies and the correlation between complete vehicle barrier tests and sled tests are well known (Mellander, 1978) (Planath, 1994). However, the limitations being that the effect of compartment intrusion, steering wheel intrusion and vehicle pitching cannot easily be simulated in a sled test. These effects were not taken into account in this study. A one axial accelerometer was mounted to register sled deceleration.

The sled was brought up to the desired speed by being pulled by a wire running on the floor of the test hall. The wire was attached with a clamp to the sled and the clamp was released just before impact when the sled was running at a steady state. At the end of the track the sled was linearly decelerated with a specially designed stopping device. A “battering ram” mounted on the front of the sled makes contact with steel bars that are mounted in a rig attached to the concrete barrier. The steel bars are forced into bending by the ram. The steel bars can be varied in thickness, width and number in order to create the desired crash pulse see Figure 11 below.

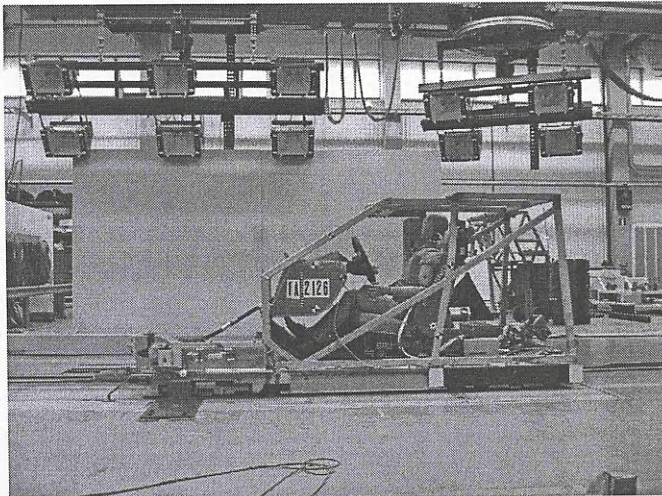


Figure 11. Sled with mounted mock up.

A mock-up of the driver environment of a mid size car (Ford Taurus) was built and mounted on the sled (see Figure 12 and 13 below) including seat, steering wheel with column, airbag, knee restraints and seat belt.

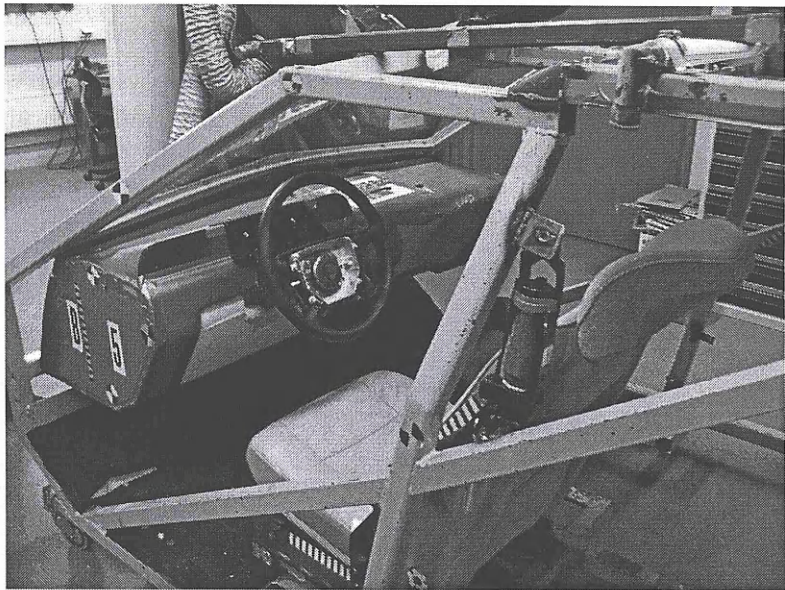


Figure 12. Sled test rig.



Figure 13. Close up view of knee restraint and dashboard.

10.2 The occupant belt restraint system

The driver restraint systems consisted of a three-point seat belt with an upper B-pillar mounted retractor. The seat belt had a load-limiting feature in the diagonal with a force level of 5,5 kN permitting one revolution of the retractor reel to spool out webbing in the validation tests. In the second test series there was no limitation to the spool out due to force limiting.

In all tests the seat belt had a pre-tensioning device, which was triggered at the same time as the airbag. The applied pre loading force, which is a function of the amount of webbing that can be pulled in, could reach 2 kN. The quasi-static elongation of the seat belt was 10% at 10 kN static loading. A steel plate was built in under the seat cushion in order to avoid seat chassis deformation.

10.3 The occupant airbag restraint system.

The airbag was of a production dual chamber type and had a volume of 60 litre in the sled testing. The airbag was mounted in a production type, state-of-the-art and steering wheel and initially in the project filled via a simulated gas generator.

Helium gas stored in a pressurized vessel was led via a hose and allowed to enter a diffuser located inside the airbag. The diffuser was put where the pyrotechnical gas generator normally is mounted. A mechanism mounted on the sled test track operated a valve and let the gas flow from the vessel into the hose and into the airbag. The position of this valve in relation to the sled was varied in order to time when the peak pressure in the bag, with the occupant loading it, occurred. The vessel had a volume of 2 litres and the initial pressure was varied before the different tests with the goal to achieve desirable bag pressure (see chapter Results validation tests). The hose had a length of 0,5 m and an internal diameter of 35mm.

The gas was distributed into the airbag via a diffuser. In order to try different gas flow profiles the sizes and numbers of the holes in the diffuser were varied to reach the desired pressure profile as used in the test. Conventional 50 grams pyrotechnical airbag “production” gas generators were used later in the project (see chapter Second round of sled tests and Retuning of Computer model). The steering wheel was rigidly mounted to the dashboard and did not move during the first validation sled test series.

This was later on changed when a collapse mechanism was installed in the steering wheel (see chapter Second round of sled tests and Retuning of Computer model). A reinforced standard seat has been used in all tests. The seat was positioned in the mid position with a 26° seat back angle in the sled tests. The knee bolsters consisting of energy absorbing polypropylene, see Appendix A.

All measurements of the test rig can be found in Appendix A.

10.4 Crash test dummy

An advanced 50th percentile adult male anthropomorphic crash test dummy named THOR Alpha (see Figure 14) according to the specification (Haffner, 2001) was used in the sled tests namely 2126-2132, 3260 and 3266. The dummy was instrumented to measure head, chest and pelvic acceleration in three orthogonal directions. Chest deflection was measured in four locations Upper Right, Upper Left, Lower Right and Lower Left. Femur forces were measured with axial load cells.

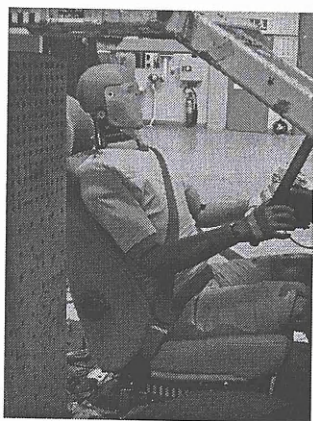


Figure 14. Thor dummy as used in the project.

A Hybrid III dummy as defined in US Code of Federal regulation 49 Part 572 was used in the tests 2133, 3250-3253 and 3261-3265. It is depicted below in Figure 15. The dummy was conventionally instrumented to measure head, chest and pelvic linear acceleration in three orthogonal directions. Chest deflection was measured at mid sternum. An upper neck load cell was mounted to measure forces and moments in three directions. Femur forces were measured with axial load cells in each leg.

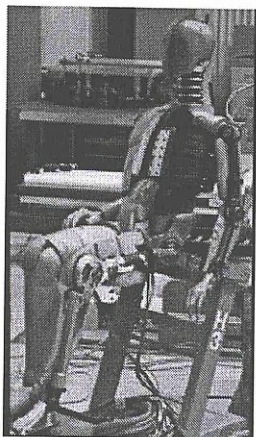


Figure 15 A hybrid III dummy as used in the sled tests.

The dummies were positioned in accordance with FMVSS 571.208 and measurements were taken as described in Appendix A. A deviation of ± 5 mm was allowed in relation to the first positioning. All the positioning measurements are available in the reference material.

10.4.1 Injury criteria (or Protection criteria)

To analyse the performance of the restraint system the following injury criteria were selected and measured. Conventional threshold values are indicated below

Head resultant acceleration	$\leq 80\text{ g}=785\text{ m/s}^2$
Head Injury Criterion 36 ms	$\leq 1000\text{ units}$
Neck forces	$NIJ\leq 1$
	Flexion moment 190 Nm
	Extension moment 57 Nm
	Axial Tension 3300 N
	Axial Compression 4000 N
	Shear force 3100 N
Chest resultant acceleration	$\leq 60\text{ g}= 589\text{ m/s}^2$
Chest deflection	$\leq 63\text{ mm}$
Viscous criterion	$\leq 1\text{ m/s}$
Femur force left and right	$\leq 7,5\text{ kN}$

The dummy results will also be analysed in relation to suggested injury risks levels as defined in Table 1 below.

Suggested IARV for 56 km/h testing corresponding to a 5% risk AIS 3+									
Head acc. (m/s ²)	HIC ₃₆	Nij	Neck shear (kN)	Neck tens. (kN)	Neck Ext. (Nm)	Chest acc. (m/s ²)	Chest defl (mm)	Chest (vc)	Femure (kN)
706 _{EUNCAP}	650 _{EUNCAP}	0,6 _{NHTSA}	1,9 _{EUNCAP}	2,7 _{EUNCAP}	42 _{EUNCAP}	392 _{USNCAP}	31 _{State of the art}	0,5 _{EUNCAP}	3,8 _{EUNCAP}

Suggested IARV for 80 km/h testing corresponding to a 20% risk AIS 3+

863 _{EUNCAP}	1000 _{EUNCAP}	1,3 _{NHTSA}	3,1 _{EUNCAP}	3,3 _{EUNCAP}	57 _{EUNCAP}	589 _{USNCAP}	50 _{EU Dir.}	1 _{EUNCAP}	7,56 _{EUNCAP}
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The indices on the values relate to the sources where the information was found
EUNCAP= EURONCAP; EU Directive 96/79/EEC, NHTSA see also Notations and Abbreviations

Table 1.Suggested Injury Assessment Reference Values to be used in the analysis. The source for the information is indicated as the lower index.

As can be seen in Table 1 a risk of 5% has been chosen as acceptable for 56 km/h crash velocity and a risk of 20 % has been chosen as acceptable for the crash at 80 km/h.

The level for chest deflection corresponding to a 5% risk of AIS 3+ injury is actually 22 mm (EURONCAP). This is, however, an extremely low chest deflection rarely seen in crash testing with some severity.

Since the most recently tested cars have received a yellow coloured rating for the chest of the driver in the EURONCAP program a method was assess what

the “state of the art” is in driver protection at the moment. A level of 31 mm chest deflection for the 56 km/h test have been arrived at after analysing the Euroncap rating process. The diagram in Figure 16 is drawn using information from the Euroncap website (<http://www.euroncap.com>) about the technique for assessing the scores in the rating process.

Four each body region in frontal impact the maximum score is four points and if a value falls between two limits the score is calculated by linear interpolation. A chest deflection below 22 mm would give the highest score (4) and a chest deflection above 50 mm would give no score. Between 22 and 50 a line can be drawn with the equation $y=-0,143X+4$. The upper segment gives when $Y=3,99$ an X of $0,07 +22=22,1$ mm chest deflection and $Y=2,67$ gives then $22+9,3=31,3$ mm. A chest deflection of 31 mm would then become the minimum level for the best cars in 40 mph off set crashes that have received a “yellow score” on the protection of the chest.

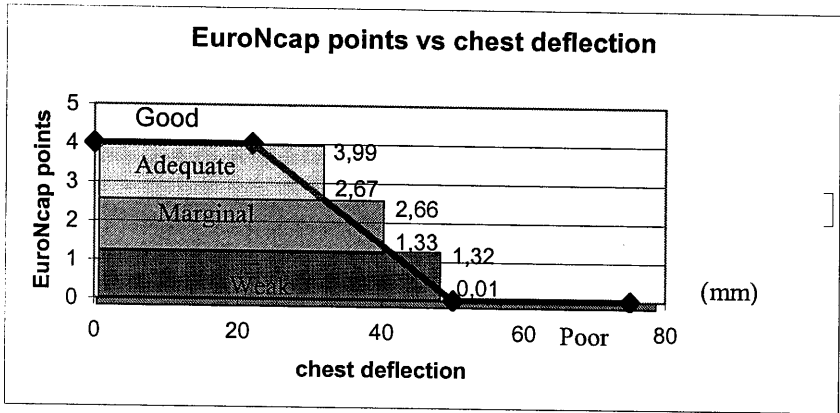


Figure 16. An interpretation of the scoring process in Euroncap for assessing the level of chest protection.

10.4.2 Measuring system and filtering

All instrumentation set up, filtering and measurement technique was done according to SAE J211/1 Mars 1995, in all practical aspects the same as ISO 6487.

10.5 Computer model

A real world car crash is always a unique event. It is extremely difficult, time consuming and costly to understand what has happened and explain the physics involved in a real world crash. Early crash safety research interested in laboratory experimentation solved this problem by dividing the crashes into different types of crashes like frontal impacts, side impacts, etc.

It was then possible to perform a specific crash test, like a fully distributed frontal crash, in the laboratory under very controlled circumstances. The researchers built a physical model of the specific crash that he or she was interested in. Such models could be a car that was crashed into a rigid barrier or a sled test. It was, however, also obvious that a crash could be described with a mathematical model of the specific crash of interest. With the introduction of computers it became possible to perform rather complex calculations in a fairly short time.

Specific computer software was developed in which models of a crash test dummy restrained by seat belts, or airbags, could be described and be subjected to the inertia forces in a car crash. Several software programs with so called "occupant models" with seat belts and airbags have been developed since the seventies. Most of them originate from "The Crash Victim Simulation Program" that describes the occupant as a system of bodies (a so called multi body system) with defined coupling between each other (Bowman, 1979). Examples of such models are BDRAC, BPAC, (Fitzpatrick, 1985), Cal-3D (Wang, 1988) and Madymo 2D and 3D (Nieboer, 1990).

The simulation of the airbag turned out to be a challenging problem. In most models the airbag was described as a non-deformable ellipsoid, or a deformable shape, based on line segments and circular arcs that led to unrealistic deformations of the bag. With the introduction of finite elements models it was possible to describe the airbag and its deployment and deformation in a much more realistic way (Nieboer, 1990), (Pipkorn, 1996).

In this project a Madymo 3D model version 5.4.1 has been used. It is a "Multiple Body System" model (Nieboer 1990, Madymo user's manual, 1996). Madymo is a computer program that can combine both multi body technique, for the simulation of the motion of bodies, or system of bodies, connected with joints, and finite element techniques for the simulation of structural behaviour such as the deployment of an airbag.

Initial conditions have to be set in terms of the state of the bodies before the integration is started. Joints can be added or removed and the joint characteristics can be described in terms of joint stiffness, damping and friction. A number of standard force models are defined for airbags, seat belts, etc., and for contacts between bodies and between bodies and adjacent objects. In the finite element model the continuum is divided into finite volumes, surfaces or line segments. The elements are connected through the nodes. Beams and membranes elements can be described.

The constitutive equations for materials such as metal, fabrics, foams, etc., are available in the program.

The multi body algorithm will yield second time derivatives of the degrees of freedom in explicit form.

The user first has to define his input file by selecting the number of multi body systems and the finite element structure to be analysed. All these systems have to be defined in terms of number of bodies, their configurations and joints.

Spring-damper elements that are mass less are available in different types such as a uni-axial element simulating a spring parallel to a damper and a uni-axial element simulating spring in series with a damper. Springs with non-linear characteristics as well as velocity dependant damping can be described.

A finite element mesh of the airbag with appropriate material characteristics can be defined.

Through conventional, so called tank tests, of the gas generator the mass flow rate is estimated. The mass flow rate of the gas generator is then described in the input data file and the pressure filling the airbag is calculated using the ideal gas equation.

The bodies can be described with planes, ellipsoids, cylinders and facet surfaces. Contacts between the bodies and/or the car interior are modelled based on these surfaces. The interacting forces between the bodies are a function of the depth of the penetration of the bodies. Elasticity (and plasticity); damping and friction forces can be defined.

The seat belt model can model belt slack, pre-tensioning and force limiting in the different portions of the seat belt such as between shoulder and upper D-ring etc. The different belt segments are connected to the body of the occupant and belt slippage from one segment to another over the body can be simulated. Belt friction forces due to body alignment cannot be described.

A homogenous acceleration field approach is used to apply forces to the centre of gravity of the bodies and to the finite elements.

The output parameters are typically accelerations, forces and kinematics' data. Calculation of HIC- values can also be made.

A number of pre- and post-processors are available for Madymo.

A MADYMO-model (Madymo 3D model version 5.4.1.) that incorporated a 50th percentile HIII-dummy (Backaitis, 1994) and a 50th percentile Thor dummy model was used for this work study. The Thor model was developed by INSIA-Politechnial University of Madrid (Martinez, 1999). The model also consisted of a seat, a knee bolster, a belt system and an airbag with steering column, see also chapter Validation and computer model set up and Appendix A.

The model was used to study the performance of the driver protection systems at different impacts velocities (Δv). The model was initially validated against sled tests described in chapter "Validation and Computer model set up" below but further refinements were done during the project. The model geometry was adjusted to create a good agreement between the model geometry and the physical sled test geometry shown in Appendix A. The overall model geometry can be seen in Figures 17 and 18 below. A detailed description of the model set up used in this study can be found in Appendix B. The model will produce dummy results such as head acceleration, chest acceleration, chest deflection, femur loads versus time, peak values of these parameters and HIC values. All curves were filtered with a 100 Hz Butterworth filter.

Through past experience calculated neck forces and moments have been found to be unreliable. Consequently the computed neck forces were not reported.

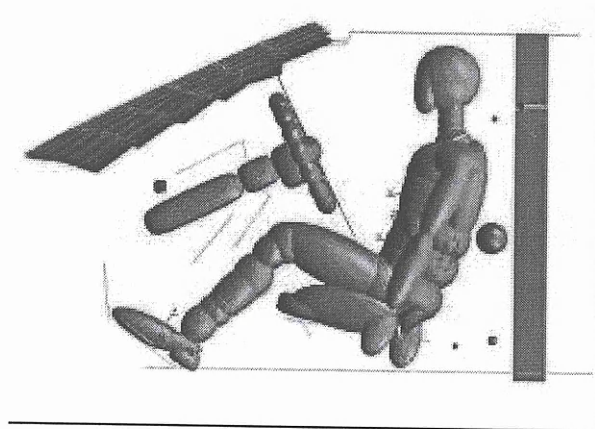


Figure 17. General lay out of computer model.

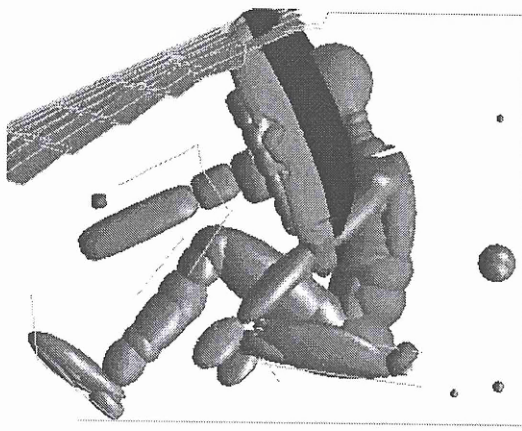


Figure 18. Animation from the computer model that shows a ride down sequence.

10.6 Crash Pulses

10.6.1 56 km/h

Crush distances for some old and current mid size cars from the crash testing in NHTSA rating programs are shown in Table 2. As can be seen there is quite a large difference. The average stopping distance for cars with 1300 - 1800 kg gross weight is 0,52 m compared to 0,54 m used in this project.

(All the information from NHTSA rating program can be found on the Internet <http://www.nhtsa.dot.gov/cars/testing/ncap/>).

USA NCAP Testno.	Car	Year	Weight (kg)	Speed (km/h)	Barrier	Crush.dist. (m)	File no.
4206	Audi A8	98	2058	56	Flat	0,675	42060030
2911	A8	98	2058	56	Flat	0,538	29110030
4776	Taurus	04	1785	56	Flat	0,482	47760087
4871	Toyota Camry	04	1699	56	Flat	0,565	48710096
3239	VW Passat	00	1695	56	Flat	0,495	32390089
4312	Saab 95	02	1826	56	Flat	0,454	43120089
477	Chevr Citat.	82	1361	56	Flat	0,605	4770034
5092	Volvo S40	04	1698	56	Flat	0,339	5092098
3461	Volvo S80	01	1820	56	Flat	0,517	3461085
1689	Volvo 240	92	1590	56	Flat	0,724	16890024
1166	Volvo 740	88	1610	56	Flat	0,584	11660023

Table 2 Data about crash pulses from NHTSA rating programs

The 56 km/h crash pulse with 0,54 m crush distance used in the model and in the sled testing is shown in Figure 19.

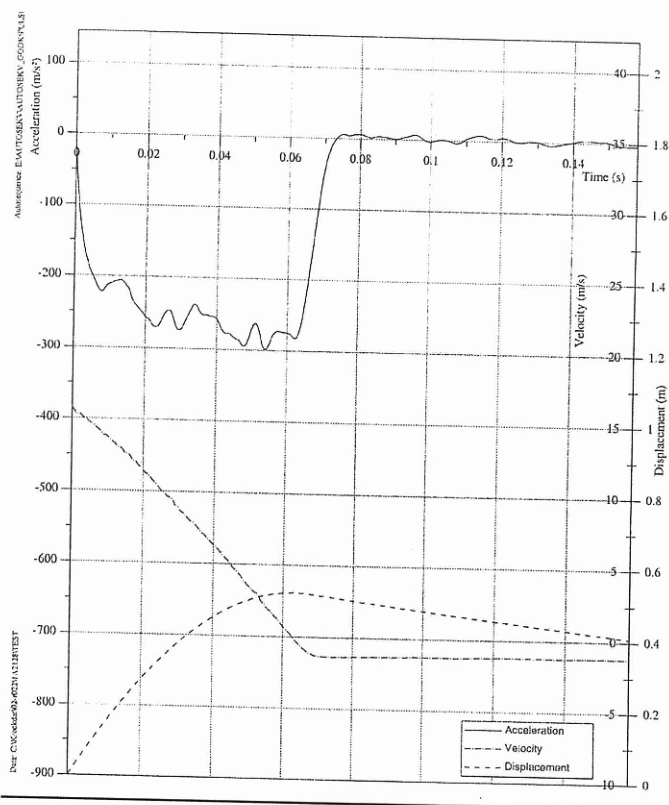


Figure 19. Crash pulse for the 56 km/h deceleration profile used in the model in the validation runs and in the sled tests.

A comparison of different crash pulses from contemporary mid-sized cars is shown in Figure 20.

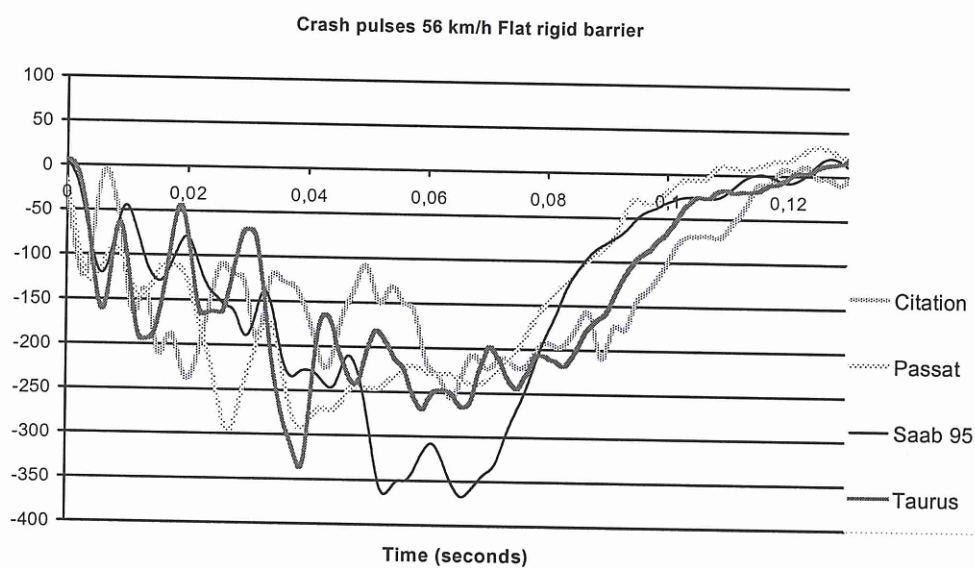


Figure 20. A comparison of crash pulses from US NCAP rating tests. 56 km/h flat barrier 90° impact.

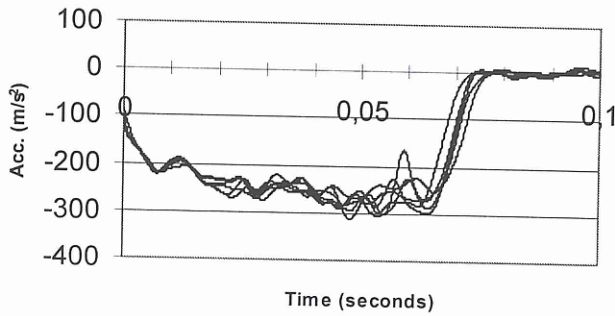


Figure 21. A comparison of all sled test pulses in the validation tests showing good repeatability is shown in this figure.

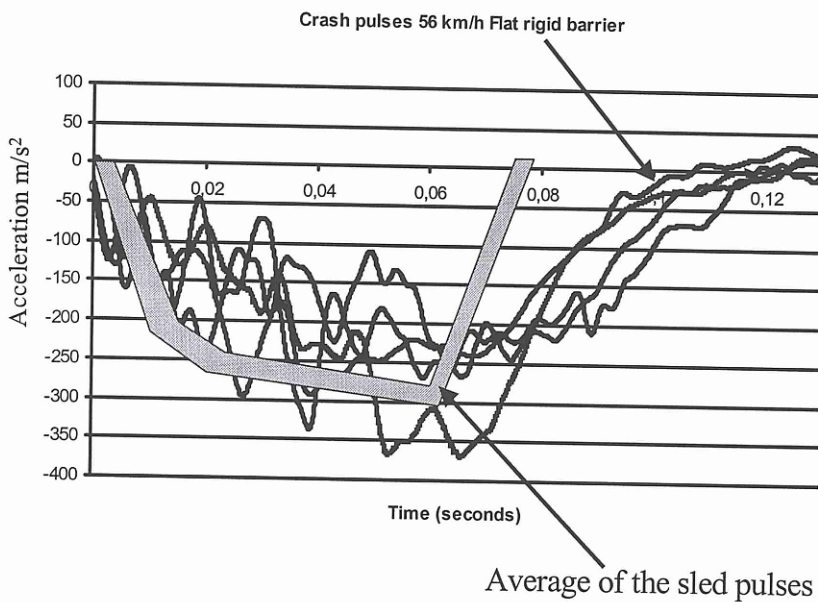


Figure 22. A comparison of crash pulses from contemporary midsize cars and an average of the sled pulses in the validation sled tests.

The variation in pulses between the different sled tests is quite small as can be seen in Figure 21. The used sled test pulse has a shorter duration due to the fact that it is more efficient in the early phase of the crash as can be seen in Figure 22. This pulse has been chosen as earlier experience has shown that trapezoidal shaped crash pulses are very effective in yielding low dummy readings. On the other hand it is always a challenge to design a car that will have a crash pulse like this. However, the recent trend seems to be that cars are getting stiffer and stiffer.

10.6.2 Barrier impact test of mid size car at 80 km/h

In order to achieve a crash pulse for a current mid-size car a Ford Taurus was crash tested into a flat 90° barrier at 80 km/h. The car was equipped with accelerometers in the conventional locations at the prop shaft tunnel and at the B-pillars.

A 50th percentile HIII dummy was positioned in the driver seat. The seat was in the mid position with a 27° seat back angel. The car was equipped with a standard US airbag and a three-point seat belt system without pre tensioning or load limiting device. All test procedures followed state-of the art test procedures for CFR 49; Part 571,FMVSS 208 and Part 572 except for the test speed which was raised to 80 km/h and the fact that only one dummy was used in the driver’s position. Photos of the car before and after the crash are shown in Appendix C. The dummy readings were as follows (see Table 3).

	HIC ₃₆	Chest defl. (mm)	Chest acc. (m/s ²)	Femur force L (kN)	Femur force R (kN)
Ford Taurus	2610	43	918	- 10,8	- 8,3

Table 3.Dummy reading from 80 km/h full frontal crash test of a Ford Taurus.

The crash pulse was measured with accelerometers at four locations namely the tunnel, trunk and left and right B-pillar. The recorded deceleration for the B-pillar is shown in Figure 23.

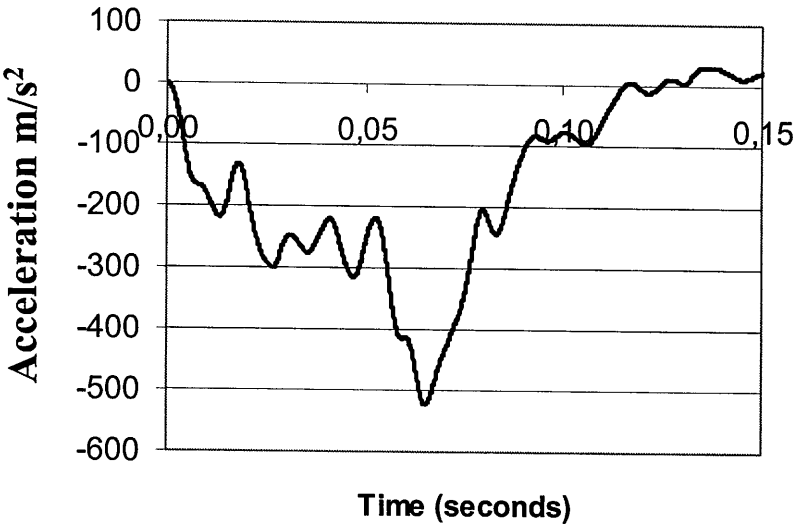


Figure 23. Accelerometer trace (B-pillar) from an 80 km/h full frontal crash test of a Ford Taurus.

The body stood up quite well to the crash forces but there was significant intrusion in the foot well area. As can be expected the violence experienced by the dummy was extreme and all the dummy readings were above conventional threshold values except for the chest deflection and the left femur. Due to the intrusion and change in steering wheel angle during the crash the loading of the dummy chest appeared rather high up and probably the potentiometer in the chest did not properly record the actual chest deflection. The very high chest acceleration (918 m/s^2) suggested that the chest deflection must have been considerably larger. It is a known fact that the chest deflection potentiometer in the Hybrid III dummy can give erroneous results in odd loading conditions. The pulse at the B-pillar was chosen as being most representative for the crash pulse experienced by the occupant. The dynamic stopping distance was 1.04 m.

The crash pulse developed for the sled testing at 80 km/h is depicted in Figure 24. The stopping (crush) distance was 0,99 m.

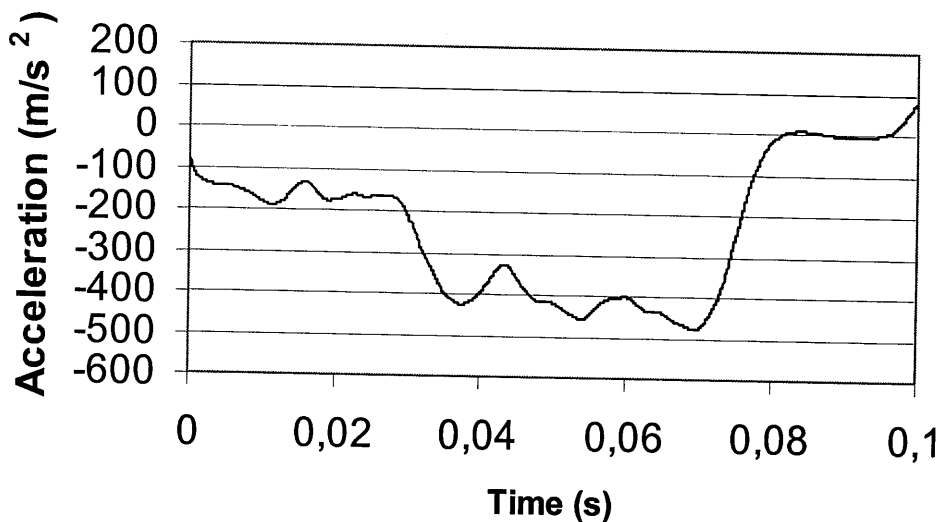


Figure 24. Sled deceleration profile developed for the 80 km/h sled tests.

10.7 Design of Experiment technique

In all crash safety research and product development a model of what happens in a real world crash has to be created. Such models are mechanical crash tests with the entire car, mechanical sled tests and mathematical analysis with computer models. Each of them has advantages and shortcomings but none of them can exactly describe a real world crash with its uniqueness and complexity.

A restraint system is very complex and consists of many parts with specific characteristics. One of the challenges in designing effective protection systems is therefore to find the “best” combination of restraint systems characteristics. It is not practical to test every possible combination. To find the influence of one specific variable a conventional method has been to vary the variable of interest while holding all the other parameters at their mid value. This technique, however, does not analyse the whole spectrum of possibilities.

With the introduction of design of experiment technique and factorial analysis the possibility has been given for a much more rational approach. With a limited number of experiments the influence of each identified parameter (factor) can be studied as well as the interactions (if any) between the variables. The technique is very useful when conducting physical experiments where the underlying process is not fully known or understood. The factorial analysis establishes a linear relationship between the variables and can also quantify interactions between variables.

In this work a computer program and a computer model have been used in order to “simulate” the outcome of different crash tests with different combinations of restraint characteristics. In order to facilitate the work to find the influence of the different restraint system parameters (variables or factors) design of experiments with factorial analysis has been used. The factorial analysis will calculate the effect of each parameter (variable or factor) and the experimenter can use this information to judge whether the parameter has a great influence (effect) on the outcome he is studying or not.

A design of experiments technique has been used to set up a matrix for the computer simulations (Box, 1978). A two levels fractional factorial design technique has been used in order to find trends and to make an intelligent selection of experimental set-ups for physical testing possible.

A re...
namely a 2^{7-4}_{III} design that will result in 7 different combinations of the
namely a 2^{7-4}_{III} design that will result in 7 different combinations of the
variables to be tested in 8 computer runs (or experiments).

The chosen test matrix had the following layout see Table 4.

Variation	1	2	3	4	5	6	7	Result
Run								
1	-	-	-	+	+	+	-	
2	+	-	-	-	-	+	+	
3	-	+	-	-	+	-	+	
4	+	+	-	+	-	-	-	
5	-	-	+	+	-	-	+	
6	+	-	+	-	+	-	-	
7	-	+	+	-	-	+	-	
8	+	+	+	+	+	+	+	
Design pattern				1,2	1,3	2,3	1,2,3	

Table 4. The matrix lay out used in the analysis

Based on earlier experience and on the study of other work (Biss, 1980) (Skötte, 1985) (Yang, 2001) the following parameters (variables or factors) were selected for variation at two levels, see Table 5.

Parameter/variable	-	+
Airbag	60 liter	80 liter
Gas generator	Baseline	Temp. + 50%
Vent hole area	9,2 cm ²	18,4 cm ²
Pre-tensioner	1,5 kN	3 kN
Load limiter	4 kN	7 kN
Seat position	Mid	200 mm rearwards
Force column stroke (100mm)	4 kN	8 kN

Table 5. The two levels of the parameters chosen for the analysis.

A reduced factorial design will always result in confounding patterns where interactions between two or several variables may result in responses that cannot be distinguished from the main effects. However, in this study the effect of interactions between two or several of the variables were studied in the early phase of the work and it was considered to be of minor significance. Furthermore it is not obvious that the computer analysis is set up to calculate the effect of interactions. Consequently it has not been further studied.

The main effect of each identified parameter (variable) on the dummy responses like HIC, chest acceleration, etc., has been calculated in accordance with conventional methods (Box, 1978). It has been studied using a diagram as depicted in Figure 25. The slope of the line in respective column visualizes the magnitude of the main effect of each parameter on a dummy response. The main effect for each parameter on a dummy response is found at the bottom of each column.

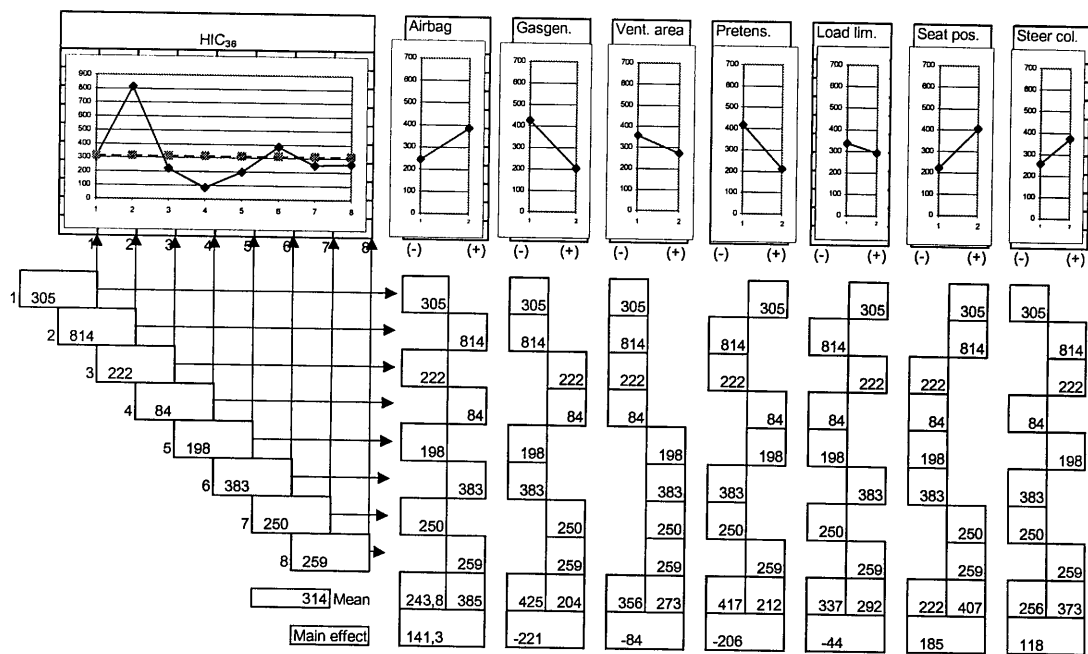


Figure 25. An example (HIC_{36}) of the type of diagram used for the analysis of the main effect on a dummy response from the results of the computer runs.

11 Results from validation sled tests

A number of tests were run in order to tune the test apparatus. In these tests the Thor dummy was used to get information about its performance and to make an assessment of its usability for the project. A specially designed gas simulator built on stored gas technology (see chapter Equipments and Experiments) was used to fill the airbag instead of using conventional pyrotechnical gas generators.

Six tests (2126-2131) were performed with the Thor dummy with varying results. The sled pulse used in these test is shown in Figure 19.

In the first four runs a European type of seat belt was used. A seat belt approved in Europe has to comply with European safety standards like R16 (ECE regulation number 16). The spool out due to force limiting has to be limited in order to comply with the requirement of maximum forward displacement of 300 mm for the chest of the dummy in a 50 km/h sled test. This means that the retractor will only allow a 100mm spool out due to force limiting. During these tests the gas generator simulator was also tried out. The opening of the valve allowing the gas to enter into the airbag is critical and a trial and error approach was used to tune the apparatus. The goal was to reach a maximum pressure inside the airbag of approximately 50 kPa during ride down which is deemed to be "state of the art".

The results from the tests can be found in the Table 6 below.

Test no	Head acc (m/s ²)	HIC ₃₆	Chest acc (m/s ²)	Chest defl. Crux (D) mean (mm)	Femur Force L (kN)	Femur Force R (kN)	Peak Bag pressure/ Time msec (kPa)
2126	1185	2204	595	42	- 4,4	- 3,7	63/75
2127	1131	1974	NA	44	- 3,2	- 3,0	59/77
2128	1158	2136	604	40	- 4,5	- 3,5	59/76
2129	1041	1742	576	42	- 3,8	- 3,9	57/76
2130	929	1381	555	43	- 5,0	- 3,3	58/80
2131	933	1529	554	42	- 4,5	- 2,8	51/75

Table 6. Results from validation tests with the Thor dummy.

The head acceleration in test 2126 was too high and consequently the HIC₃₆ number was too high (2204 compared to the conventional threshold value of 1000 units).

It was felt that the peak pressure in the bag appeared rather late (75ms) and was somewhat high 63 kPa (50 kPa is a normal value). The tank was filled to a pressure of 50 MPa. It was judged that a decrease in tank pressure and an increase in the diameter of the hole in the diffuser would remedy a problem. Consequently the holes in the diffuser in the steering wheel were drilled to a larger diameter (16 holes with 6 mm diameter) for test 2127 and the tank was filled to 40 MPa. However, there was very little effect on the dummy values as can be seen in Table 6 and the HIC (1974) value was still too high.

In test 2128 the trigger mechanism was moved to open the valve at zero time before impact in order to get peak pressure earlier in the event. The tank was filled to 40 Mpa. However, this change did not affect the time when peak pressure appeared as a peak pressure of 59 kPa was registered 76 ms after impact. Consequently there was little or no reduction in the dummy readings. In test 2129 test tank pressure was set at 45 Mpa and the trigger mechanism was moved to open up the valve 142 mm before the sled impacted the braking device. This resulted in a first small peak of airbag pressure 5 msec before impact indicating the deployment of the airbag. However, there was no change in the timing of the peak pressure, which appeared at 76 ms after impact with a magnitude of 57 kPa.

A possible explanation to this could be that the main pressure rise was created by the dummy interaction with the bag and that the timing of the filling of the bag from the tank was of subordinate importance. As shown in Figure 26 the upper portion of the dummy thorax is imbedded in the bag at 70 ms. The dummy readings were still too high in this test.

In test 2130 the sixteen holes in the diffuser were opened to a diameter 8 mm and the opening of the tank valve started 142 mm before impact. Tank pressure

was 45 Mpa. In this test a seat belt according to a US-specification was used that had no limit to belt spool out during force limiting. Peak pressure (58 kPa) appeared at 80 ms after impact. The change to another type of seat belt did not affect the results considerably but it did bring down the HIC number (1381) closer to the conventional threshold value 1000.

In test 2131 the tank pressure was 45 Mbar and the valve opened 292 mm before impact. The diffuser was the same as in test 2130. This resulted in a first peak of airbag pressure at 12 msec before impact but the main peak (51 kPa) was still rather late at 75 msec. The HIC number was still well above accepted threshold values. Chest accelerations were high in all of the tests but the chest deflection as measured by the crux- potentiometers meters was acceptable. However, the small variation in measured chest deflection opens up the question if the dummy was set up correctly and/or if registered signals were post processed in a proper way (the Thor dummy is supplied with a special computer program which converts the output from the potentiometers to 3D chest deflection measurements).

In order to get a reference with a well-known and specified dummy the last test in the series was run with a Hybrid III dummy. For results see Table 7.

In test 2133 the tank pressure was set at 45 Mbar and the valve opened 142 mm before impact. The diffuser was the same as in test 2130. This produced a first bag-opening peak at 5 msec before impact. The main peak (39 kPa) appeared at 67 msec.

Test no	Head acc. (m/s ²)	HIC ₃₆	Chest acc. (m/s ²)	Chest defl. (mm)	Femur Force L (kN)	Femur Force R (kN)	Peak Bag pressure (kPa)
2133	953	1373	507	39	- 3,1	- 2,3	39

Table 7. Results from the validation test with the Hybrid III dummy.

This main peak pressure was much lower then in all the other tests in which a Thor dummy was used. Looking at the pressure measured inside the diffuser it peaked at about 280 kPa in the test 2131 with the Thor dummy. It reached the same value (280 kPa) in this test. One explanation to the rather low main airbag peak value could then be inline with the reasoning above. It is the interaction between the bag and dummy that is the main component in the second main airbag pressure peak. The Hybrid III dummy could be slightly stiffer in the spine and chest and consequently will not load the airbag as much as the Thor dummy.

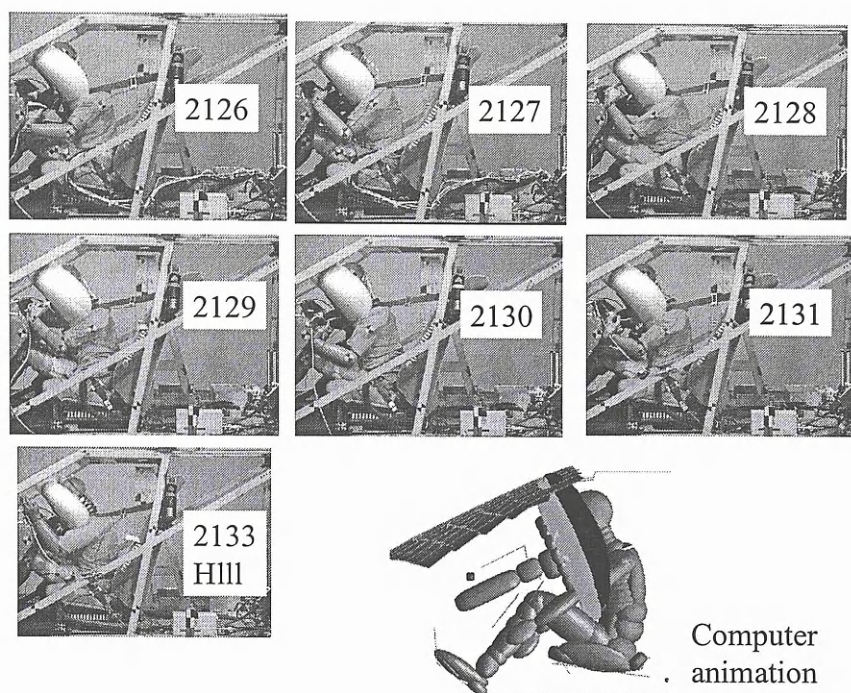


Figure 26. Film frames at 70 ms taken from the sled tests at 56 km/h in comparison with a 70 ms frame from a 56 km/h computer run animation.

12 Validation and computer model set up

12.1 THOR-dummy model

As mentioned earlier the intention was to use a new advanced dummy called Thor both in the computer analysis and in the mechanical sled testing throughout the project. The University in Spain had developed a computer model describing the Thor dummy. It was available for try out and after a request to the soft company that market the Madymo software it was made available for the project. After a considerable amount of work it was incorporated into the computer model of our restraint system to be analysed. This included the THOR-dummy, a seat, a knee bolster, a belt system and an airbag with a steering column. The upper body of the THOR-dummy model is divided into more parts than the corresponding HIII-dummy. This means that the belt cannot be attached to the body in the same way as for a HIII-dummy model. However, it was attached in such a way that they were similar. Both the THOR-dummy and the later on tried HIII-dummy were positioned in the mid seat position with a seat back angle of 27°.

However, looking at the animation of the first trial computer runs with the Thor dummy it was discovered that the dummy kinematics looked very odd. The THOR-dummy seemed to be much too stiff in the spine and in the thorax region. A comparison was made of the input data file of the THOR-dummy and the manual from the manufacturer describing the mechanical properties of the THOR-dummy. Several differences were discovered. For example, the lumbar joint showed to be much too stiff in the model compared to the dummy manual. This was also the case for the upper spine joint. Furthermore, the abdomen is connected to the pelvis with a translation joint. There is also a connection between the abdomen and the lower ribs, which causes very high forces to develop. Since the lower ribs are connected to the sternum, which in turn is connected to the spine this will result in abnormal kinematics of the upper body.

Several attempts were made to get instructions from the software company on how to correct the Thor model but with little success.

A simulation was performed to see how an acceleration field of 500 m/s² affected the HIII-dummy and the THOR-dummy. It was thought that the dummies should have about the same kinematics, or that the THOR-dummy, being more biofidelic, should be less stiff in the chest and spine. The pelvis segments of the dummies were attached to the inertial space with bracket joints. This means that the pelvis could not translate or rotate. The results of this simulation can be seen in Figure 27. It is evident from this figure that the dummies kinematics are quite different. This figure shows that the upper body and spine of the THOR-dummy is abnormally stiff. It was consequently concluded that the Thor dummy model should not be used for further computer analysis in this work project.

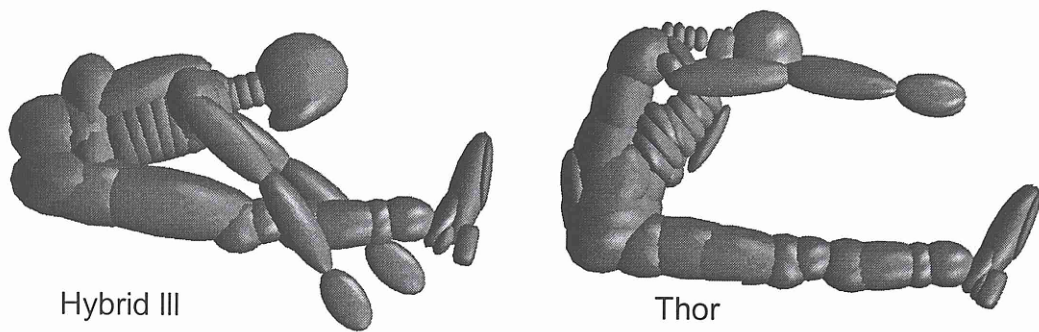


Figure 27. The HIII-dummy and the THOR-dummy affected by an acceleration field of 500 m/s². The acceleration field has been applied for 50 ms when these animations where printed.

12.2 Selection of crash test dummy for the primary analysis

Consequently at this point in time it was decided to concentrate on the Hybrid III dummy in the computer analysis. The validation process would focus on the Hybrid III dummy as the Thor dummy model for the Madymo program was not functioning well and there were doubts that the measured chest deflection in the sled tests was correct.

12.3 Selection of sled test for validation

A test was selected for the validation namely test 2133. The impact speed was 56,5 km/h and the crash pulse is depicted in Figure 19. Test results from the sled test used for the validation of the computer model at 56 km/h are summarized in the Tables 8 and 9 below.

Test no	Vel. (km/h)	Dummy	Trigg (ms) before impact	Diffuser pressure (kPa)	Bag pressure measured in the bag close to the diffuser		
					Max (kPa)	first peak (ms)	Max Time (ms)
2133	56,5	HIII	12	278	39	5 before	67

Table 8. Test parameters and results from validation sled test 2133 with a Hybrid III dummy.

Test no	Head acc.	HIC ₃₆	Chest acc.	Chest defl.	Belt force (kN)		Femur force R	Femur force L
	(m/s ²)		(m/s ²)	(mm)	Diag.	Lap	(kN)	(kN)
2133	971	1373	507	39	9	6,9	- 2,3	- 3,1

Table 9. Dummy readings from validation sled test 2133 with a Hybrid III dummy.

By comparing the test results with the conventional threshold values as described earlier it is quite clear that the chosen restraint system configuration was unsatisfactory as the HIC value was above 1000.

An analysis of dummy kinematics shows that the dummy is fairly well restrained, but the airbag is primarily supporting the head and the upper part of the chest. However, the absence of steering wheel column stroke seems to make the final ride down of the head into the airbag rather abrupt, see Figure 26.

In spite of the rather poor performance of the restraint system in terms of the HIC- value being above the threshold level the dummy results could be used to validate the computer model. Such a validation and also an analysis of the results have been made and are reported in a separate chapter see below.

13 Validation of computer model and analysis of results

13.1 Validation method

There are no standardized methods on how to validate an occupant crash simulation model. Each user has specific demands on quality and variation of the output variables. In this study major trends in the change of dummy response as a function of variation in restraint characteristics have been studied. At first the model was validated in detail for a crash (sled) test at 56 km/h and then later on also for a crash (sled) test at 80 km/h. In a validation process you usually focus on a specific crash velocity “window” and you have to be very careful once you start to increase the crash velocity and use the model outside your validated “window”.

Experiences from sled test series with a controlled environment have shown a coefficient of variation of about 10% to be normal (Mellander, 1978). A way of assessing the degree of achieved precision in a modelling effort could be to state that the maximum values of the most important computed dummy responses, like horizontal head acceleration, must be within plus or minus 10 % of the actual values in the validation test.

A comparison of the most important dummy criteria is summarized in Table 10 below.

	HIC ₃₆	Chest acc. (m/s ²)	Chest defl. (mm)	Femur force L (kN)	Femur force R (kN)
Computer model	1180	441	42	- 3,1	- 3,3
Sled test	1373	500	39	- 2,3	- 3,1

Table 10. A comparison of the dummy readings from the computer model and the validation sled test.

13.2 Head acceleration

The sled test HIC-value was 1373 and the computer model HIC-value was 1180. The measured horizontal acceleration was compared to the calculated acceleration from the computer model.

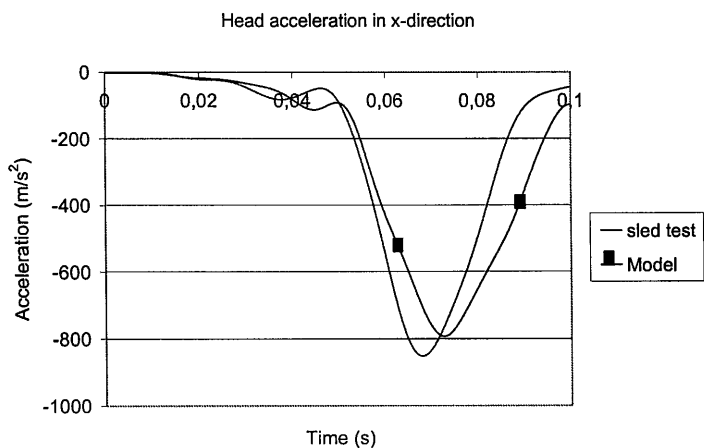


Figure 28. A comparison of the head acceleration in x-direction measured in the sled test and as calculated in the computer model.

The most important contribution comes from the accelerometer in the horizontal direction (x-direction) which is shown in Figure 28, (this is true also for the chest and consequently only accelerations in X-directions will be shown. The comparisons between the accelerations in y- and z-direction are available in the reference material). As can be seen in Figure 28 there is quite a good agreement between calculated and measured head x-acceleration.

The deviation is within the 10% found as an accepted coefficient of variation in state of the art experimental sled testing.

13.3 Chest acceleration

The maximum chest resultant acceleration was 45 g in the model and 51,7 g in the sled test. The chest acceleration in the x direction is depicted in Figure 29.

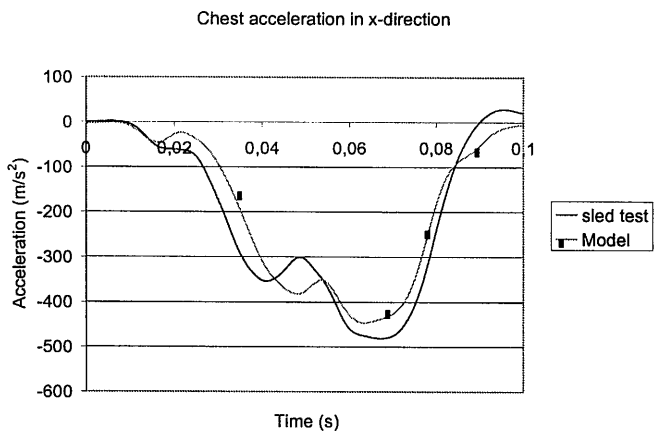


Figure 29. A comparison of the chest acceleration in x-direction measured in the sled test and as calculated in the computer model.

The comparison between the horizontal chest accelerations shows about the same trend as the head accelerations. The deviation is almost within the 10% found as an accepted coefficient of variation in state of the art experimental sled testing (Mellander, 1978).

The effect of the load limiter is evident in the x-direction acceleration. This is the decrease in acceleration after about 45 ms. The phenomenon can be seen in both the computer model data and the sled test data.

13.4 Pelvic acceleration

The pelvis acceleration in the x-direction computed in the model and from the sled test shows a good agreement see Figure 30. The deviation is within the 10% found as an accepted coefficient of variation in state of the art experimental sled testing (Mellander, 1978).

The peak z-accelerations however differs about 130 m/s² between the model and the sled test (see Figure 31). This is about 35 % of the maximum value. In other words, this is quite a large difference. However, it was decided that this difference could be accepted, as pelvic acceleration is not such an important injury response parameter. The reason for the difference could probably be attributed to the descriptions of the characteristics of the seat foam.

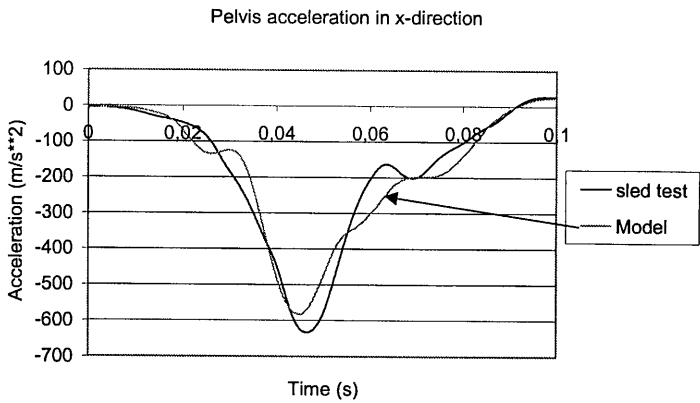


Figure 30. A comparison of the pelvis acceleration in x-direction measured in the sled test and as calculated in the computer model.

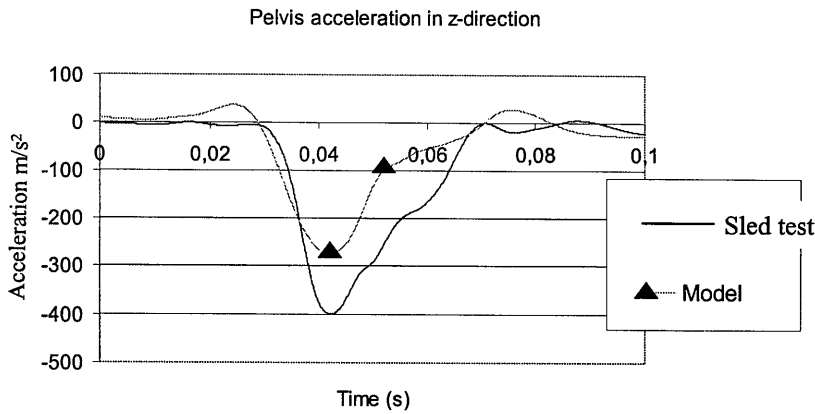


Figure 31 A comparison of the pelvis acceleration in z-direction measured in the sled test and as calculated in the computer model.

13.5 Femur forces

The contact between the knees and the knee bolster causes a force on the knees that is propagating into the femurs. The femur forces are shown in Figures 32 and 33. The femur forces model output are the z-components of the femur forces.

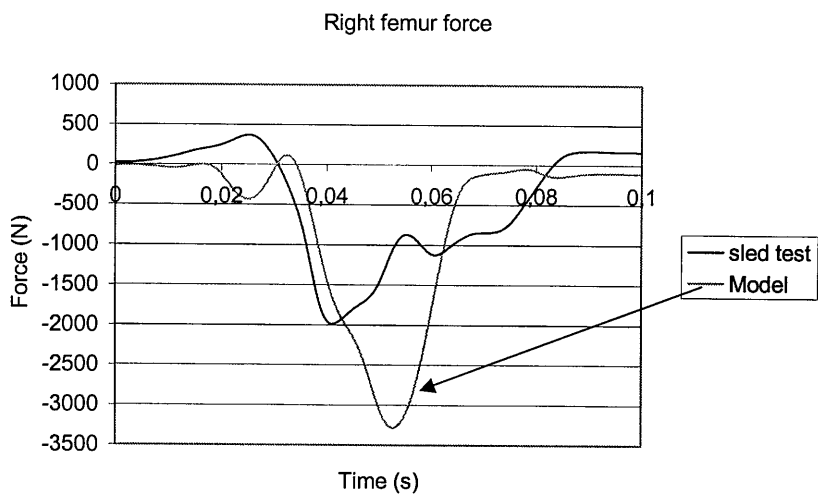


Figure 32. A comparison of the right femur force measured in the sled test and as calculated in the computer model.

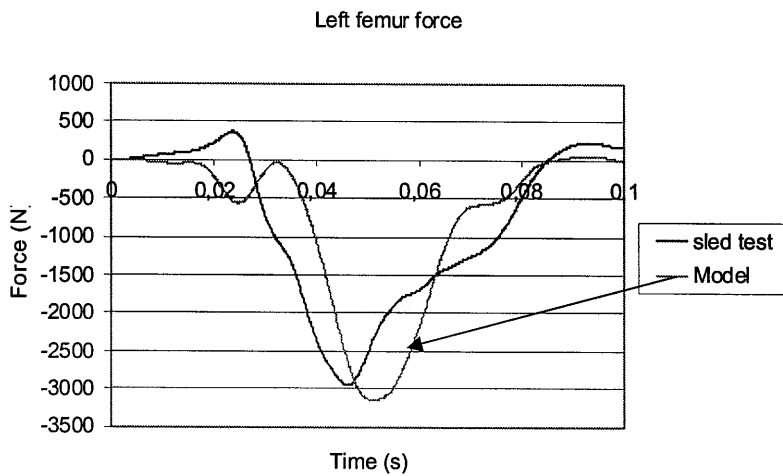


Figure 33. A comparison of the left femur force measured in the sled test and as calculated in the computer model.

The difference that occurs after about 20 ms is explained by the fact that the feet initially are in contact with the floor in the model, which was not the case in the sled test. This caused a force to propagate from the tibias to the femurs via the knees. The knees hit the knee bolster after about 30 ms.

The model gave a better prediction for the left femur than for the right femur. The model predicted about the same femur forces for both femurs. In physical experiments there are many factors, such as positioning of the dummy legs, which can influence the way the knees interact with the knee padding. This is probably the explanation for the difference between the measured femur forces in the sled test. Since the femur loads never reaches a critical level in any of computer runs or the sled tests in this study it was decided that the level of accuracy between the test and the model was acceptable.

13.6 Belt forces

The shoulder belt forces and the lap belt forces in the segment between the hip and the end bracket are shown in Figure 34 and 35 respectively.

The shoulder force was about the same in the model and in the sled test. The belt pre-tensioner was triggered after 7 ms, which can be seen in the curve. The effect of the load limiter is also evident in the curve as the shoulder belt force drops at about 40 ms. The force level at which this occurred was about 5.5 kN. It is also evident that the load limiter bottomed out as the spool out of the webbing was restricted to one revolution of the retractor reel.

The lap belt force showed a difference between the model and the sled test data after about 50 ms. Why the computed lap belt force decreases after this time is difficult to explain. It may, however, depend on the load limiter effect from the chest belt band. When the load limiter force is 5.5 kN, the retractor feeds the belt system with more belt. However, this extra belt length is supposed to be added only to the chest segment and no extra belt band is added to the pelvis segment. However, in the model a transportation of belt is possible at the buckle. Additional belt added to this segment will cause a belt force reduction.

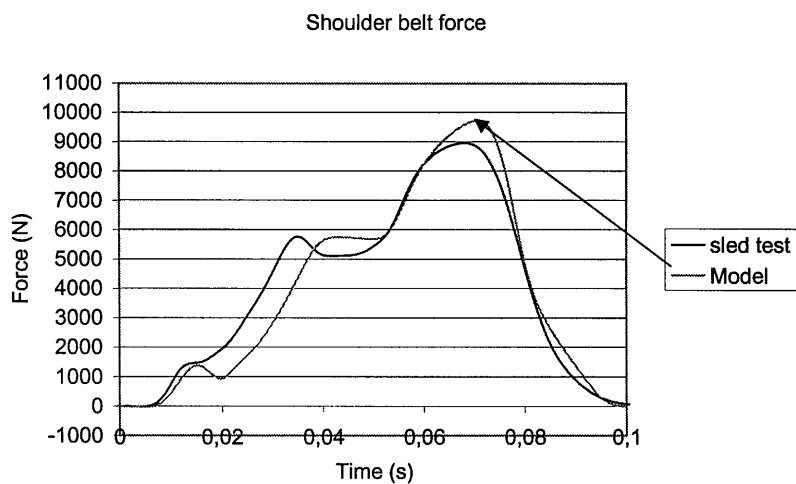


Figure 34. A comparison of the shoulder belt force measured in the sled test and as calculated in the computer model.

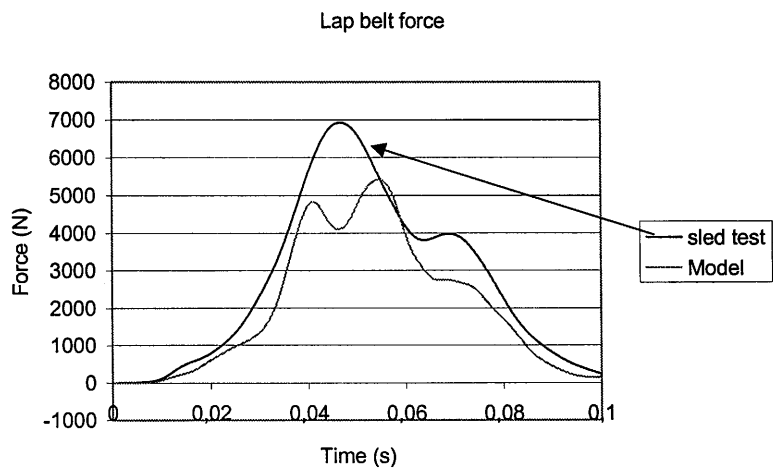


Figure 35. A comparison of the lap belt force measured in the sled test and as calculated in the computer model.

13.7 Chest deflection

The chest deflections from the sled test and the model are shown in Figure 36. There is a good agreement between the model and the sled test results.

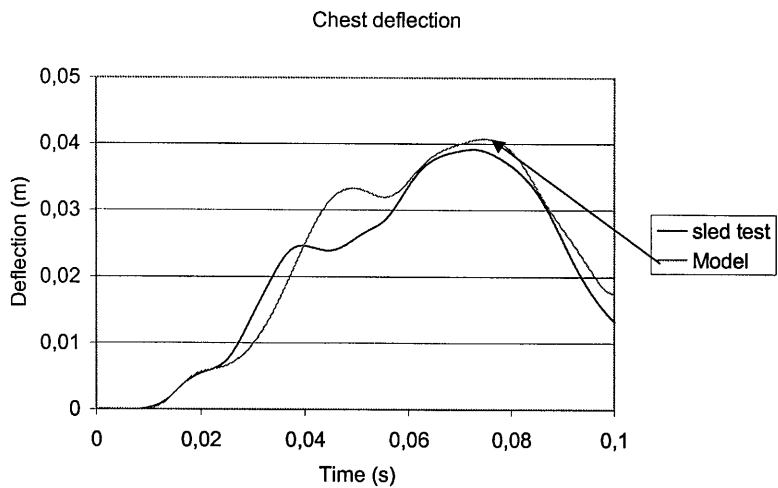


Figure 36. A comparison of the chest deflection measured in the sled test and as calculated in the computer model.

13.8 Airbag pressure

The gas pressure inside the bag close to the inflator outlet, as measured in the sled test and as calculated in the model, is shown in Figure 37. The pressure in the dual airbag chambers as described in the model was about the same. The plot shows the relative pressure, that is, the level above the normal atmospheric pressure.

Although there are some differences in peak pressure and duration, it was judged that the approach taken in describing the mass flow rate in the input file of the model was a reasonable one.

The airbag in the sled test was folded but the airbag is unfolded in the model. The inertia forces from the folded airbag, whilst being deployed, causes the large initial pressure in the sled test. This early peak has no effect on the dummy loading phase that occurs much later (~ 70 ms).

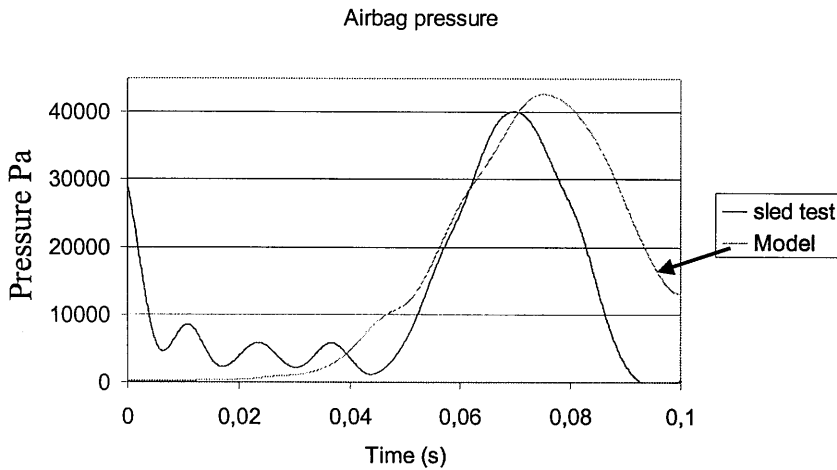


Figure 37. The airbag pressure as measured in the sled tests and as calculated in the model.

13.9 Validation analysis

The high HIC-value that was found in the sled test and computed in the model was assumed to be a result of how the gas was supplied to the airbag. Such gas generator data was also used as input to a tank test simulation. The volume of the tank was 63 liters. The calculations were made in the MADYMO software.

The result of this simulation can be seen in Figure 38. This figure shows that a real gas generator supplies much more gas in the beginning of the simulation. Therefore a computer simulation was made with data from a conventional production gas generator. This gas generator is referred to as Production in the figures.

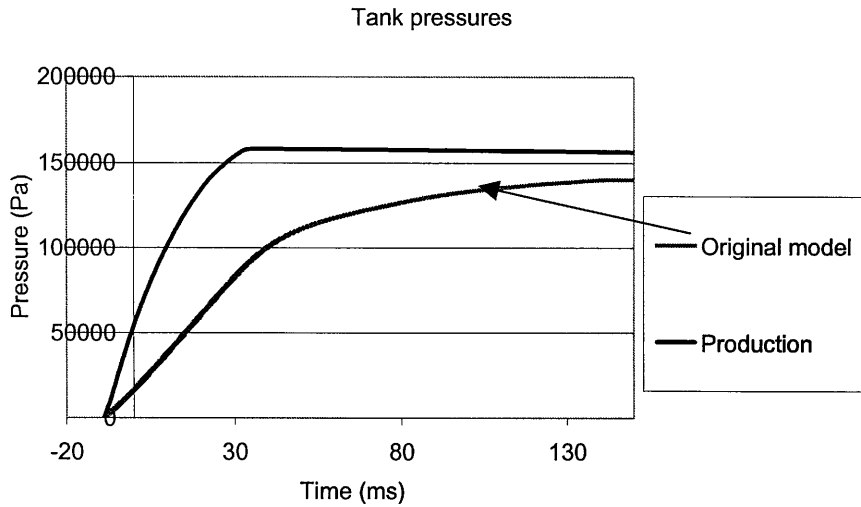


Figure 38. Tank pressures for the original gas generator and the production gas generator.

The airbag pressure from a production gas generator is shown in Figure 39. The airbag pressure in the mechanical sled test and the airbag pressure from the original computer model can be seen in this figure as well. The corresponding head acceleration in the x- direction is shown in Figure 40.

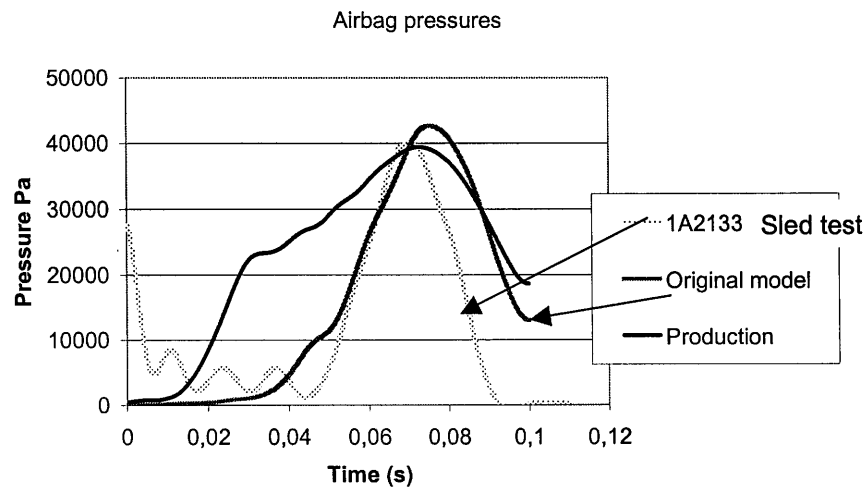


Figure 39. The airbag pressures from the sled test 2133 and as computed with the original gas generator and a production gas generator.

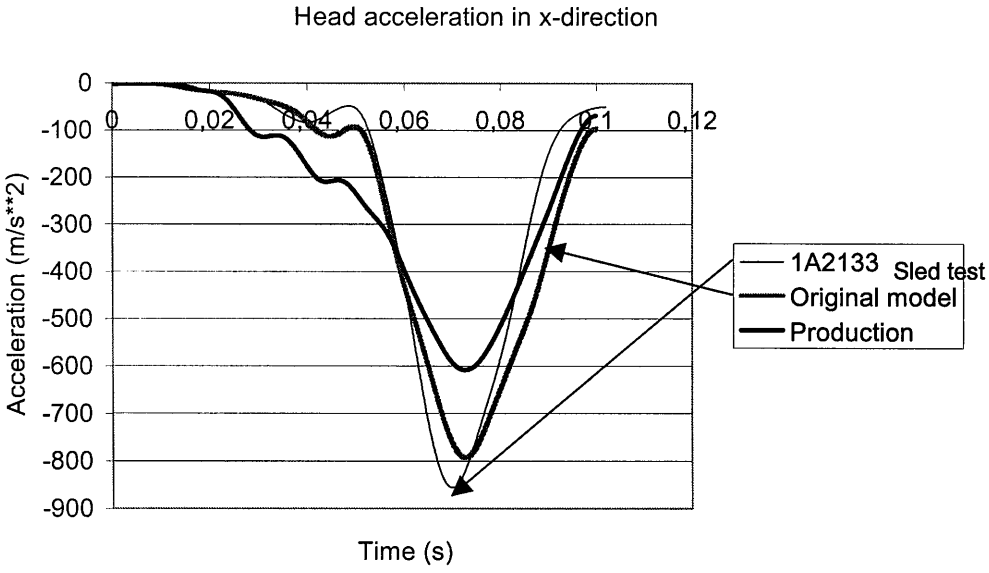


Figure 40. The head acceleration in sled test 2133 and as computed by the model with the original gas generator simulator and a production gas generator.

13.10 Primary analysis and suggestion for changes

The production gas generator gave a substantial head acceleration reduction, which is evident from Figure 40. The HIC-value for the production gas generator was 641, whilst it was 1373 in the sled test and 1180 in the computer model with the original gas generator. The airbag started to affect the head earlier and more efficiently when the production gas generator deployed the airbag. The peak values of acceleration will be reduced if the head is decelerated during a longer period of time.

13.10.1 Collapsible steering column

It was also decided to study another parameter using the validated model. Would a collapsible steering wheel column decrease the head accelerations? To answer this question the possibility to compress the steering wheel column 0,1 m was introduced into the model. This was made by giving the steering wheel column a constant force stroke of 4 kN. The steering wheel started to move forward when the force acting on the steering wheel exceeded 4 kN. A study was made with the production gas generator. The head acceleration in the x-direction can be observed in Figure 41.

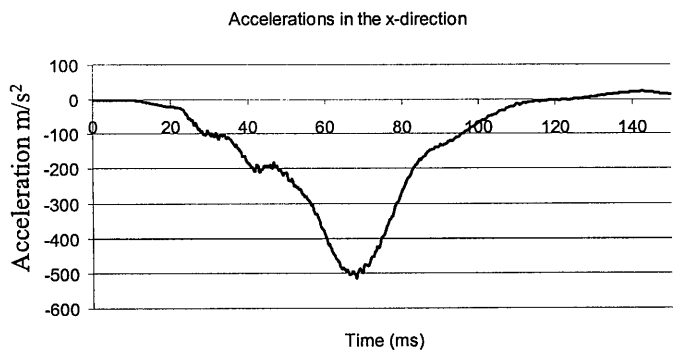


Figure 41. Computed head acceleration when deploying the airbag with a “production” gas generator and a collapsible steering column.

From this figure it is evident that a collapsible steering column will reduce the head acceleration. The reason why this is so beneficial is that the head has a longer distance to decelerate.

The HIC-values was 364 with the “production” type gas generator. This means that the high HIC-value can be decreased considerably by using a “Production” type gas generator and a retracting steering wheel column.

In summary the model with the HIII-dummy functioned in a reasonable way. There are some differences between the model data and the sled test data but

it was decided that they were acceptable. It has been shown that an improved gas generator can decrease the head accelerations in a substantial way. It has also been shown that a collapsible steering wheel column can have a beneficial effect. Introducing an improved gas generating profile and a collapsible steering wheel column will probably reduce the high HIC-value that occurred in the sled tests.

14 The selection of restraint system parameters to be varied

There are numerous parameters that govern the performance of the crash protection system in a passenger car. One of the most important car body related parameters is the front-end stiffness i.e. force deflection characteristics during dynamic deformation. In an impact with a stiff barrier this stiffness will govern the body deceleration (negative acceleration) time history that constitutes what is usually called the crash pulse. The crash pulse contains information about the magnitude and duration of the negative acceleration. The integral of the crash pulse is the velocity change during impact, or as it is usually called the delta-v. In a non-elastic (plastic) fully distributed impact with a 90° flat barrier the delta-v is the same as the impact velocity.

In order to constrain the scope of the research in this project it was decided to choose two delta-v levels to be used in the modelling and testing program namely 56 km/h and 80 km/h. The crash pulses are defined in the Chapter Equipment and Experiments – crash pulses. The effect of occupant compartment intrusion has not been included.

There is today quite a good understanding of which variables have the largest effect on the crash protection offered by airbag plus belt systems (Svensson, 1978) (Biss, 1980) (Skötte, 1985) (SAE PT-88) (Strother, 1977 and 1991,). The parameters of primary interest guiding the performance of the interior restraint system are the following

- Airbag size
- Gas generator performance
- Size of ventilation holes
- Trigger time
- Seat belt geometry
- Seat belt characteristics
- Seat belt Pre-tensioner characteristics
- Seat belt Load limiter characteristics
- Seat position
- Seat cushion stiffness
- Steering wheel/steering column energy absorbing function

In order to limit the work only the most important parameters were selcted for variation at two levels and the values were set as indicated in Table 11, see also chapter Equiment and Experiments.

Parameter/variable		-	+
A	Airbag volume	60 litre	80 litre
B	Gas gen. mass flow	Baseline	Temp + 50%
C	Vent hole area	9,2 cm ²	18,4 cm ²
D	Pre-tensioner	1,5 kN	3 kN
E	Load limiter	5,5 kN	7 kN
F	Seat position	Mid	200 backwards
G	Column force	4 kN	8 kN

Table 11. Selected parameters and definition of the two levels that were used in the factor analysis.

15 Results from computer runs

The first fractional factor analysis (as defined under chapter Equipment and Experiments - Design of Experiment technique) computed at 56 km/h gave the following results, see Table 12.

Run	A	B	C	D	E	F	G	Head Acc. (m/s ²)	HIC	Chest Defl. (mm)	Chest Acc. (m/s ²)	Pelvis Acc. (m/s ²)	Femur Force Left (kN)	Femur Force Right (kN)
1	-	-	-	+	+	+	-	515	370	40	370	532	+ 4,0	+ 4,1
2	+	-	-	-	-	+	+	580	452	38	357	591	+ 3,3	+ 4,1
3	-	+	-	-	+	-	+	493	309	40	483	640	- 3,1	- 3,2
4	+	+	-	+	-	-	-	502	265	33	382	602	- 2,3	- 2,8
5	-	-	+	+	-	-	+	483	266	35	399	597	- 2,4	- 2,8
6	+	-	+	-	+	-	-	512	367	37	448	643	- 3,1	- 3,2
7	-	+	+	-	-	+	-	568	408	38	357	591	+ 3,3	+ 4,1
8	+	+	+	+	+	+	+	475	349	40	370	532	+ 4,0	+ 4,1

Table 12. Results of factor analysis at 56 km/h.

The calculated effects for the different injury criteria are shown in Table 13.

	Airbag size	Gas Gen.	Vent hole area	Pre-tens.	Load limiter	Seat position	Steering Col. force
Head acc.	3	-13	-13	- 45	- 35	37	- 17
HIC	20	-31	-2	-72	1	93	-9
Chest defl.	-1,3	0,3	-0,3	-1,3	3,3	2,8	1,3
Chest acc.	-13	5	-5	-31	44	-65	13
Pelvis acc.	2	1	-1	-51	-9	-59	-2

Table 13. Effects calculated from the variation in results at 56 km/h as found in Table 12. The effects on femur forces are not shown as they change from compression to tension when the seat is moved backwards.

The first fractional factor analysis performed at 80 km/h using the computer model gave the following results, see Table 14 below.

Run	A	B	C	D	E	F	G	Head* Acc. (m/s ²)	HIC	Chest Defl. (mm)	Chest* Acc. (m/s ²)	Pelvis* Acc. (m/s ²)	Femur Force Left (kN)	Femur Force Right (kN)
1	-	-	-	+	+	+	-	726	916	44	385	738	+ 5,2	+ 4,6
2	+	-	-	-	-	+	+	1187	1612	41	488	787	+ 4,5	+ 4,2
3	-	+	-	-	+	-	+	550	480	42	518	731	- 3,6	- 4,0
4	+	+	-	+	-	-	-	587	432	34	422	710	- 3,3	- 3,5
5	-	-	+	+	-	-	+	558	520	36	446	712	- 3,3	-3,5
6	+	-	+	-	+	-	-	647	544	38	466	730	- 3,6	- 3,9
7	-	+	+	-	-	+	-	791	1064	41	462	784	+ 4,2	+ 4,5
8	+	+	+	+	+	+	+	802	1027	45	409	738	+ 5,2	+4,6

Table 14. Results of factor analysis at 80 km/h.

The calculated effects for the different injury criteria are shown in Table 15.

	Airbag size	Gas Gen.	Vent hole area	Pre- tens.	Load limiter	Seat position	Steering Col. force
Head acc.	150	-97	-63	- 126	- 100	291	87
HIC	159	-147	-71	-201	-165	661	171
Chest defl.	-1,3	0,8	-0,3	-0,8	4,3	5,3	1,8
Chest acc.	-7	7	-8	-68	-10	-27	32
Pelvis acc.	0	-1	-1	-34	-14	41	2

Table 15. Effects calculated from the variation in results at 80 km/h as found in Table 14. The effects on femur forces are not shown as they change from compression to tension when the seat is moved backwards.

At this point in time it was decided to perform a second test series to further validate the computer model and to test conventional gas generators and the energy absorbing mechanism in the steering column. Consequently, the results from the first factorial analysis were not further studied.

16 Second round of sled tests and retuning of computer model

16.1 Second round of sled tests

In order to further validate the computer model a second round of sled tests where performed at 56 and 80 km/h. The Hybrid III dummy was used in this test series. Since the gas generator simulator had not lived up to expectations and it had to be redesigned in order to be able to cut the gas flow after a certain time it was decided to use production type gas generators in this test series.

The seat belt that was used was of a US type with pre-tensioning in the diagonal belt (2kN) and no limitation to spool out due force limiting (5,5 kN). A special device was built in order to allow for a controlled forward displacement of the steering wheel. By changing the amount and characteristics of the honeycomb in the collapse mechanism different force levels could be achieved (see Figure 42).

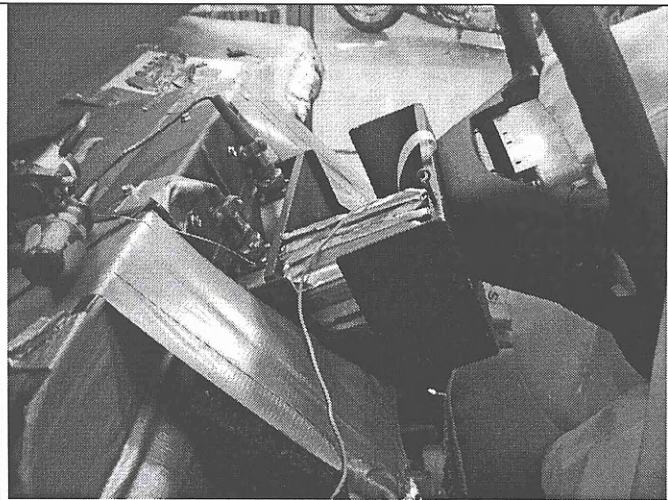


Figure 42. Force controlling collapse mechanism in the steering column.

The honeycomb used in the test was made by Hexcell Composites defined as ACG-3/4- 1.8 and had a crush strength of 6894,8 N/m if the cells were pre-deformed at one end before test. Using the area in the collapse device the forces could be varied from 5-15 kN. A number of sled tests were performed with varying column collapse force characteristics in order to find a configuration that functioned mechanically well.

Initially there was a problem with the steering column not being able to withstand the high bending moment created when the dummy loaded the airbag. The column bent and jammed in the bushing thereby restricting the compression of the steering column, see Table 19 and Figure 45. A number of changes were made to decrease the friction in the linear bushing and decrease the bending moment on the column.

A wire was attached to the part of the device attached to the steering wheel and to the floor between the legs of the dummy. The idea was that the wire would take away some of the bending moment on the steering column but would not restrict the sliding of the column, see Figure 46. The feature functioned well and allowed the column to slide in the bushing. However, once the collapse mechanism functioned properly it was found that the available stroke was not long enough as the device bottomed out when tested at 80 km/h. Since the effective column stroke in the first test rig was limited due to the compression of the cells to about 80-90 mm it was decided to increase the available stroke by moving the steering wheel backwards another 60 mm to allow for a thicker layer of honey comb. In test 3265 the available stroke was 170 mm.

It was also found that the dummy's head would strike the upper header and windscreen in tests 3253 and 3262, which can be seen in Figure 43. This impact created large compression forces in the neck as can be seen in Table 17. To alleviate this problem the header and the windscreen were removed.

This phenomenon points towards the problem of getting sufficient space for the forward motion of the occupant in a 80 km/h crash in a modern car with slanted windscreens. However, if the occupant is positioned 200 mm backwards as is tried in the computer analysis a head impact could probably be avoided.

The main dummy results in the sled tests are shown in Table 16, 17 and 18. Experiences from earlier sled test series with a controlled environment have shown a coefficient of variation of about 10% to be normal (Mellander, 1978).

In the final test 3265 a force level of 13 kN over a stroke of 91 mm produced dummy results that were below conventional injury criteria levels. As the computer model does not yield reliable neck forces the results from the second sled test series was the only way to analyse the neck forces in an 80 km/h test.

Before the upper header and windscreen were removed there were quite substantial forces on the neck, but after the removal the forces were decreased as indicated in Table 17. In the 35 mph test the NIJ was 0,4 and the neck extension force was 1,8 kN and in the last 80 km/h test NIJ was 0,35 and the extension force 1,5 kN. This is well below the threshold values as defined in chapter Crash test Dummies- Injury criteria.

It is important to point out that the tests in the second test series were not in any way optimisation tests, but rather tests to support the conclusions drawn from the analysis of the first results from the computer runs. They were also validation tests as they provided valuable data for the final fine-tuning of the model.

Test no.	Test vel. (km/h)	Head acc. (m/s ²)	HIC ₃₆	HIC ₁₅	Chest acc. (m/s ²)	Chest defl. (mm)	VC (m/s)
3250	56	600	565	385	432	38	0,5
3253	80	1109	1642	1417	687	47	0,7
3262	80	924	1685	1206	647	50	0,6
3263	80	927	1261	994	669	52	NA
3264	80	740	1104	665	610	54	NA
3265	80	613	700	395	548	52	NA

Table 16. Dummy results from the second sled test series.

Testno	Neck force + Tension - Compr. (kN)	Neck force Shear (kN)	Neck moment extension (Nm)	NIJ	Pelvic acc. (m/s ²)	Belt force (kN)	
						Diag.	Lap
3250	+1,8	0,9	71	0,4	639	5,9	4,2
3253	-4,3	2,1	138	1,1	878	5,5	7,5
3262	+1,5	1,8	85	0,6	NA	5,5	8
3263	+2,6	1,2	69	0,4	NA	5,7	7,6
3264	+2	NA	89	0,5	878	6,1	7,5
3265	+1,5	NA	68	0,4	880	5,8	8,7

Table 17. Dummy results from the second sled test series.

Test no.	Femur Force L (kN)	Femur Force R (kN)
3250	NA	NA
3253	- 5,1	- 3,9
3262	- 2,9	- 3,4
3263	- 3,2	- 4,7
3264	NA	NA
3265	- 2,6	- 3,4

Table 18. Dummy results from the second sled test series.

Test no.	Test vel. km/h	Force Level column (kN)	Displac. Column (mm)	Bag press. Peak vs time (kPa)/(s)	Misc.
3250	56	6,3	30	40/70	One cell block
3253	80	NA	NA	60/70	Col. bent jammed
3262	80	5	88	65/80	Bottomed out
3263	80	(21)	93	65/80	Bottomed out
3264	80	15	94	45/65	Additional blocks
3265	80	13	91	50/65	170 mm stroke

Table 19. Test results from the second sled test series.

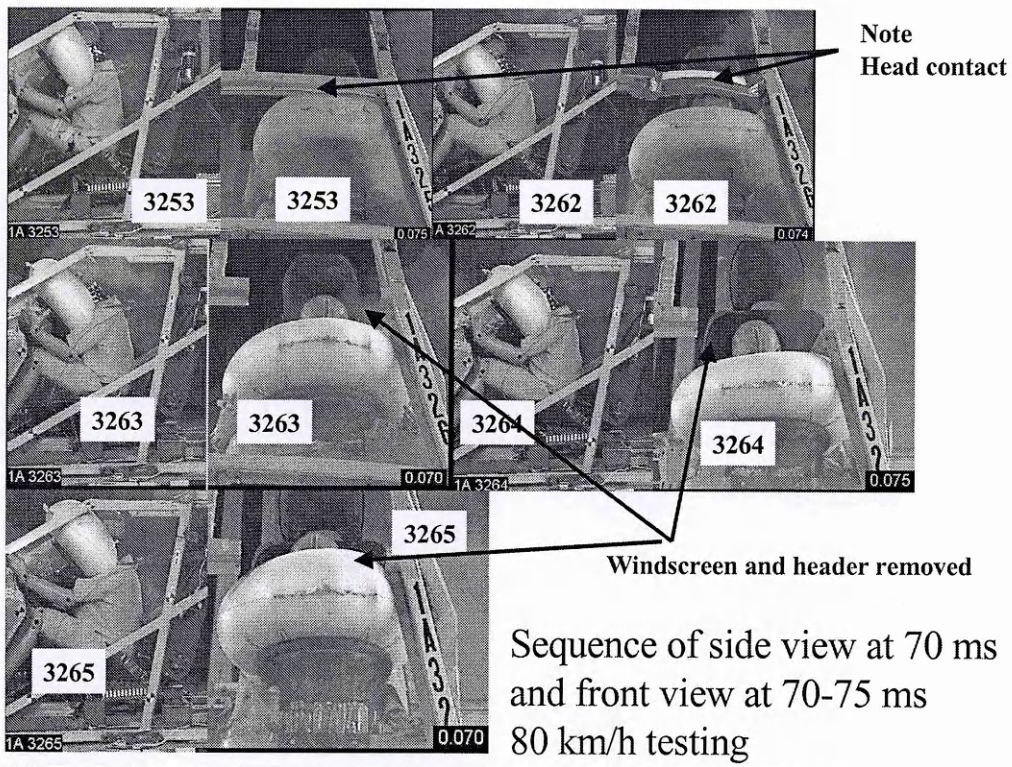


Figure 43. Sequences from high-speed film from second test series.

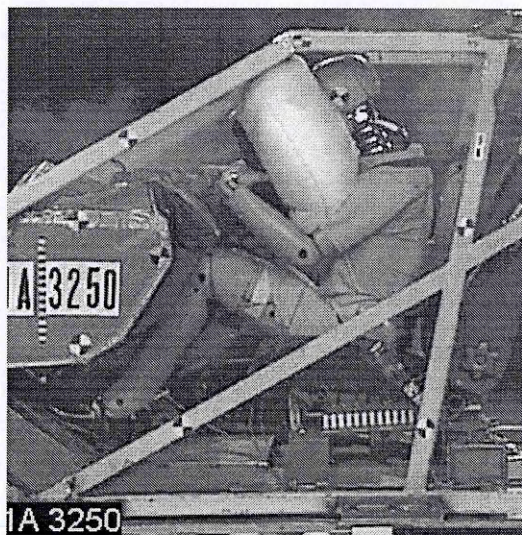


Figure 44. Sequence from high-speed film at 70 ms from test 3250 at 56 km/h.

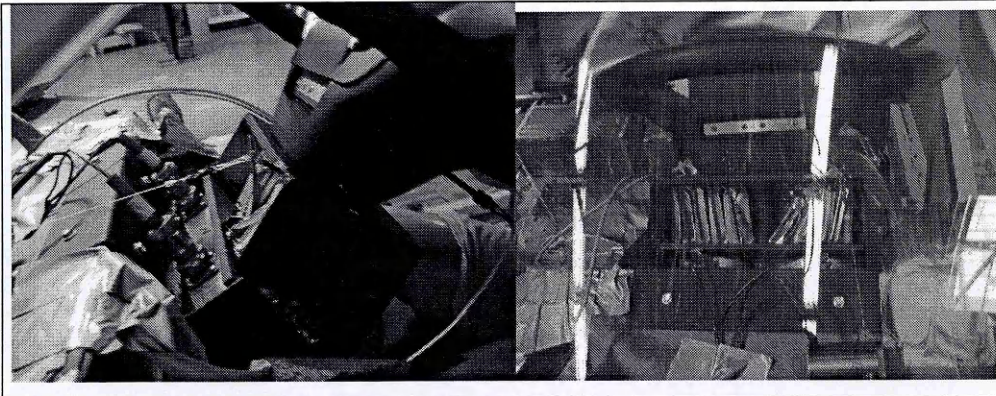


Figure 45. Photo of bent steering axle and partially deformed honeycomb blocks in test 3253.

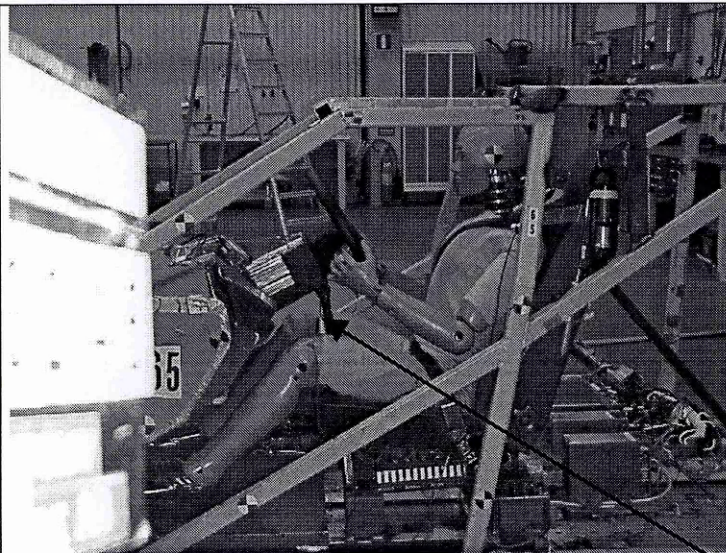


Figure 46. Photo of test set up showing the added wire to support the steering column.

16.2 Analysis of sled test results

It could be interesting to compare the dummy results from a 56 km/h sled test and an 80 km/h sled tests with the injury criteria levels suggested for a 5% and 20% IARV respectively (see chapter Crash test dummy- Injury criteria.) It was suggested that a reasonable approach would be to accept a 5% risk at 56 km/h and a 20% risk at 80 km/h. The results are depicted as percentage of the respective threshold level.

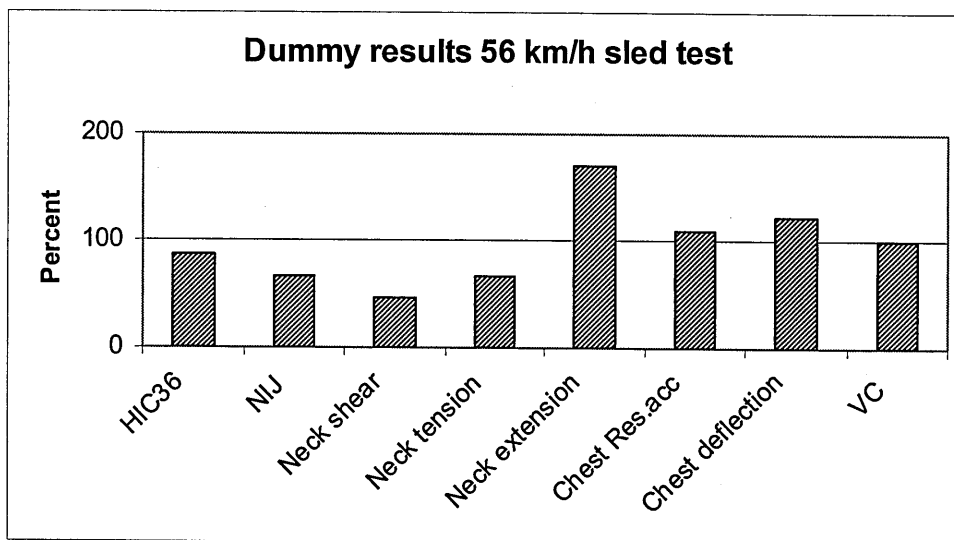


Figure 47. Dummy results from sled test 3250 at 56 km/h shown as percentage of 5% IARV threshold (see chapter Dummy- injury criteria).

As can be seen in Figure 47 depicting the results from tests 3250 at 50 km/h, most of the results are below the threshold but neck extension is rather high. However, looking at the kinematics of the dummy in Figure 44 it seems strange that the bending moment of the neck could be that high. One explanation for the high reading could be problems with the transducer. On the other hand the head and chin interaction with the airbag is very complex and it may very well be that there is a high bending moment occurring. A solution to this problem must then be found for instance by changing the air bag pressure. Chest acceleration and chest deflection are also above the threshold but it is marginal. Since this is not an optimisation study it was decided that the test results reflects a “state of the art” interior driver protection.

Test 3265 was selected as the “best” of the 80 km/h sled tests as the collapse mechanism in the steering column functioned well and the dummy results were the best. In Figure 46 the results are shown in relation to the threshold for a IARV of a 20% risk for AIS 3+ injury.

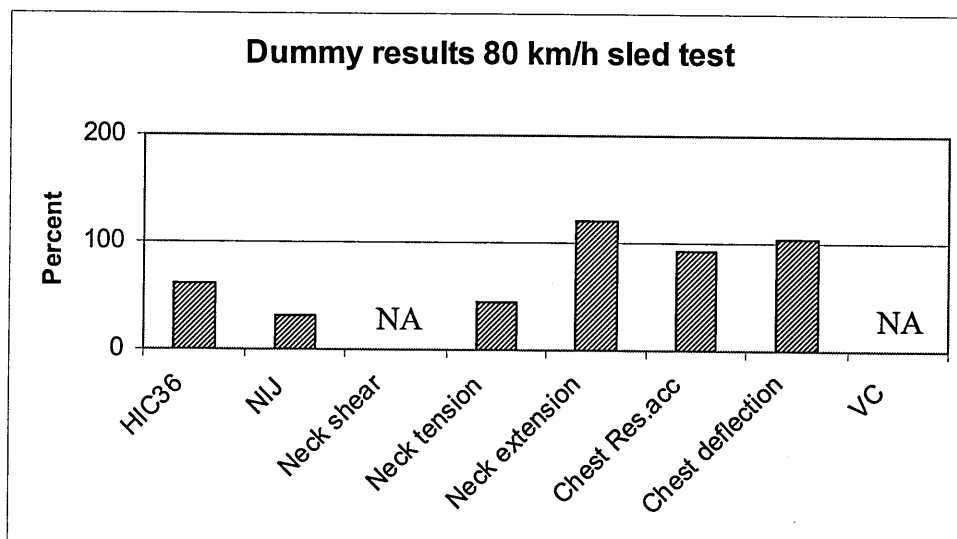


Figure 48. Dummy results from sled test 3265 at 80 km/h shown as percentage of 20% IARV threshold (see chapter Dummy- injury criteria).

As can be seen in Figure 48 all the results are below the threshold with the exception of neck extension. However, looking at the bending of the neck in test 3265 in Figure 43 it is very marginal and the dummy kinematics looks very reasonable. Two signals, neck shear and VC, are missing due to signal failure. In summary it could be said that this test showed a very good ride down sequence of the dummy and it gave evidence that effective interior driver protection at 80 km/h in sled testing without compartment intrusion is possible.

16.3 Retuning of computer model and preliminary computer runs

The computer model was validated using data from this test 3265. (The model was set up in such a way that the steering column stroke was not limited but a function of the collapse force and the energy being absorbed by the steering column. Consequently the stroke could exceed the 100 mm limit in the computer model. However, the force deflection characteristic was not defined after 100 mm and consequently the results were not reliable.

In order to eliminate this problem a new spring was defined which was extended when the steering column would stroke forwards. The force deflection curve of the spring was defined for 0,5 m. The mass flow of a production type gas generator was installed in the computer model and another set of computer runs were performed with the retuned model. For a comparison of a 70 ms sequence from a sled test at 80 km/h and an animation of a computer run with the same test condition see Figure 49.

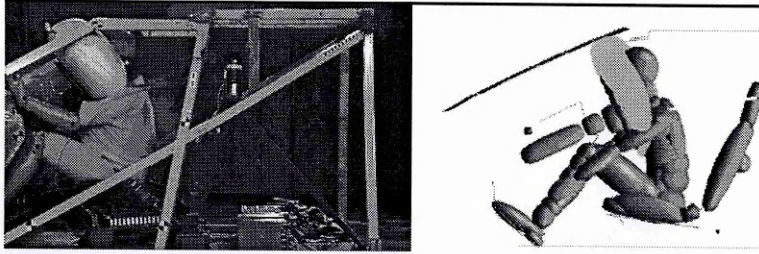


Figure 49. Film frame at 70 ms from sled test at 80 km/h compared with a computer animation from a computer run with the same test condition.

The results from the 80 km/h runs were specially looked into (the variation were done according to Table 11). The very high HIC number 12027 in run 2, in one of the 80 km/h runs, see Table 20, indicate that the dummy head is bottoming out through the airbag and is coming into contact with the steering wheel. Through the study of the animation it was found that the airbag was not sufficiently filled with gas and the dummies head had a hard contact with the steering wheel.

Run	Head Resulting Acc (m/s ²)	HIC ₃₆	Chest Deflection (mm)	Chest Resulting Acc (m/s ²)
1	651	655	35	406
2	3313	12027	47	861
3	538	401	43	574
4	446	310	39	403
5	700	614	33	439
6	1473	1678	38	491
7	707	829	57	525
8	1121	1256	35	414

Table 20. The results of computer runs at 80 km/h.

Since this will result in non-linearity in the output data it was decided to change the value for the variables for the 80 km/h factorial analysis according to Table 21. The mass flow for the “plus level” was changed by increasing the gas temperature with 150% (compared to the baseline generator output). The collapse force for the steering column for the “plus level” was also changed to 10 kN. A new set of runs was performed with the new variables.

Parameter	-	+
Airbag	60 liter	80 liter
Gas generator	Baseline	Temp. +150%
Vent area	9,2 cm ²	18,4 cm ²
Pretensioner	1,5 kN	3 kN
Load limiter	4 kN	7 kN
Seat position	Mid	200 mm rearwards*
Force column stroke	4 kN	10 kN

*Seat and seat belt anchorages were moved backwards 200mm

Table 21. The new variables chosen for the analysis at 80 km/h. The “minus” level will be referred to as baseline in the forthcoming text.

17 Results from second round of computer simulations

Since the forces in the femur in all the performed computer analysis and sled tests were well below the tolerance value they will be not be reported further on but are available in the reference data.

17.1 56 km/h crash speed

The matrix with results in the retuned model calculated for 56 km/h is shown in Table 22 below.

Run	Airbag	Gas gen.	Vent Area	Pre tens.	Load Lim.	Seat Pos.	Steering Column	HIC 36	Chest Deflection mm	Chest Res. Acc. m/s ²
1	-	-	-	+	+	+	-	305	32	326
2	+	-	-	-	-	+	+	814	24	297
3	-	+	-	-	+	-	+	222	37	443
4	+	+	-	+	-	-	-	84	31	322
5	-	-	+	+	-	-	+	198	27	309
6	+	-	+	-	+	-	-	383	34	400
7	-	+	+	-	-	+	-	250	24	303
8	+	+	+	+	+	+	+	259	32	330

Table 22. Results from computer simulations at 56 km/h.

The main effect of the variables on HIC₃₆, chest acceleration and chest deflection for the 56 km/h runs are shown in Figure 50, 51 and 52 respectively. In terms of having a large main effect on the HIC numbers gas generator mass flow came out with the highest effect of 221, with the higher mass flow showing a reduction.

The pre-tensioner with a high force level also had a slightly positive main effect as the HIC number was reduced with 206 units. Moving the seat backwards 200 mm had a negative main effect on the HIC-number, as it showed an increase with 185 units.

For chest deflection and chest acceleration the main effects of the different variables were small with the exception of load limiting where the high load limiting level gave a main effect of 67 m/s² higher chest acceleration and a 7 mm increase in chest deflection. Moving the seat backwards gave a main effect of a 54 m/s² reduction in chest acceleration and 4 mm reduction in chest deflection.

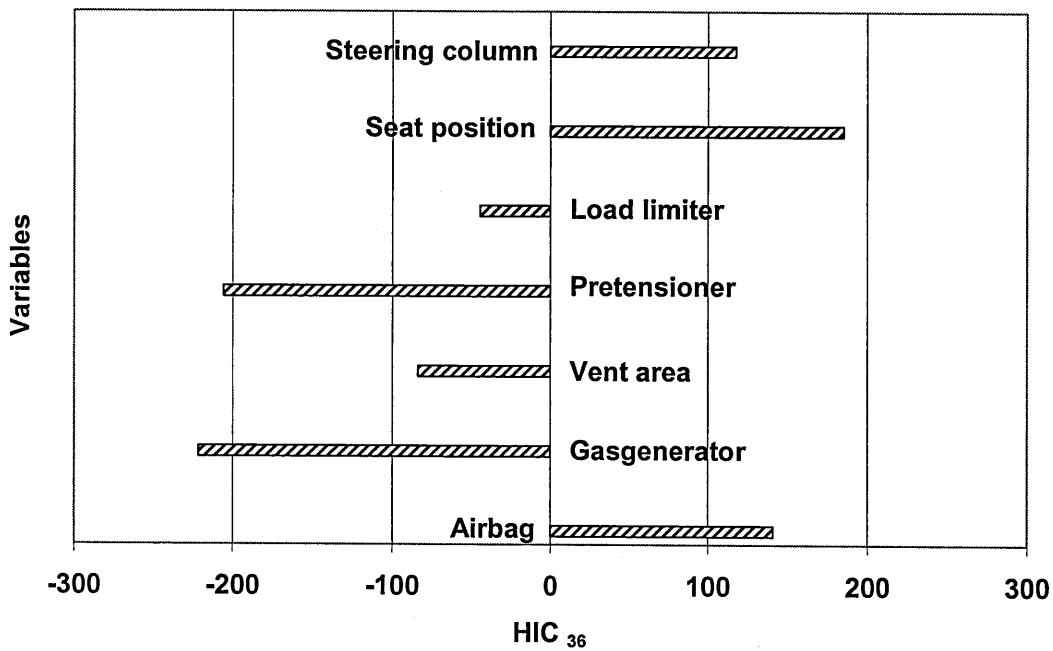


Figure 50. Main effects (going from minus (baseline) to plus (increment)) of the variables on HIC₃₆ values in 56 km/h impact speed computer runs.

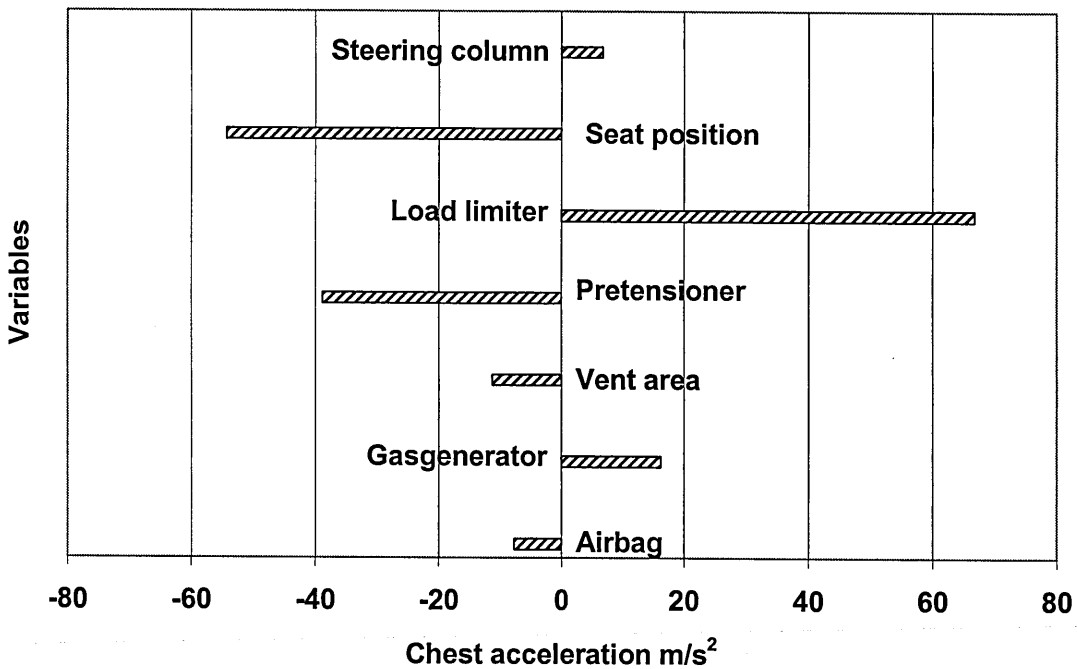


Figure 51. Main effects (going from minus (baseline) to plus (increment)) of the variables on chest acceleration values in 56 km/h impact speed computer runs.

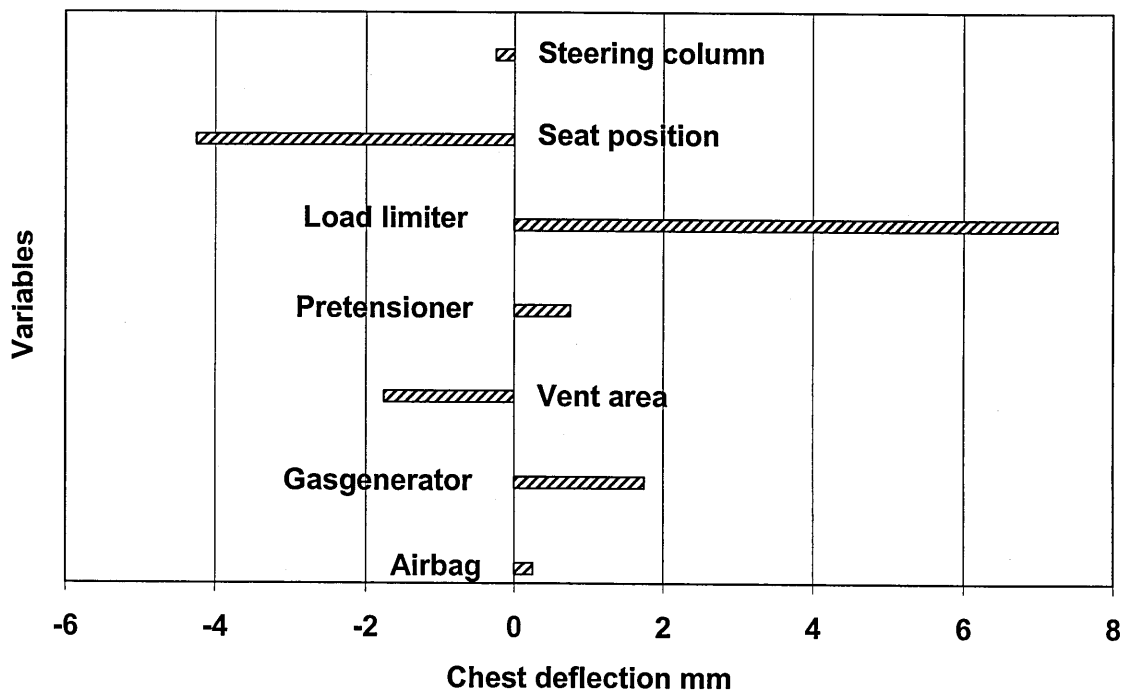


Figure 52. Main effects (going from minus (baseline) to plus (increment)) of the variables on chest deflection values in 56 km/h impact speed computer runs.

17.2 80 km/h

The main computer simulation results calculated for 80 km/h with the changed values for mass flow and steering column force, see Table 21, are shown in Table 23.

Run	Airbag	Gas gen.	Vent Area	Pre tens.	Load Limiter	Seat Pos.	Steering Column	HIC 36	Chest Deflection mm	Chest Res. Acc m/s ²
1	-	-	-	+	+	+	-	526	36	450
2	+	-	-	-	-	+	+	527	34	479
3	-	+	-	-	+	-	+	1617	38	597
4	+	+	-	+	-	-	-	822	36	469
5	-	-	+	+	-	-	+	525	37	507
6	+	-	+	-	+	-	-	193	42	552
7	-	+	+	-	-	+	-	275	40	436
8	+	+	+	+	+	+	+	324	39	484

Table 23. Results from computer simulations at 80 km/h.

The main effect of the variables on HIC₃₆, chest acceleration and chest deflection for the 80 km/h runs are shown in Figure 53, 54 and 55 respectively.

As can be seen most of the combinations produce dummy readings below the conventional injury criteria levels (femur loads are not shown as they were well below the injury tolerance level). The largest main effect on the HIC numbers had the airbag ventilation area with the larger holes decreasing HIC with 545 units.

Second largest main effect gave the seat position with a decrease of 376 HIC-units for moving the seat 200 mm backwards. Airbag size had an effect of 269 HIC-units with the larger airbag decreasing HIC. A more powerful gas generator and a higher steering column collapse force had a negative effect as HIC was increased with 317 HIC-units and 294 HIC-units respectively.

The chest resultant acceleration was mainly effected (positively) by moving the seat backwards (-69 m/s^2) and by applying the high pre-tensioning force (-39 m/s^2). Negative effect had high force load limiter ($+ 48\text{ m/s}^2$) and high steering column force ($+ 40\text{ m/s}^2$).

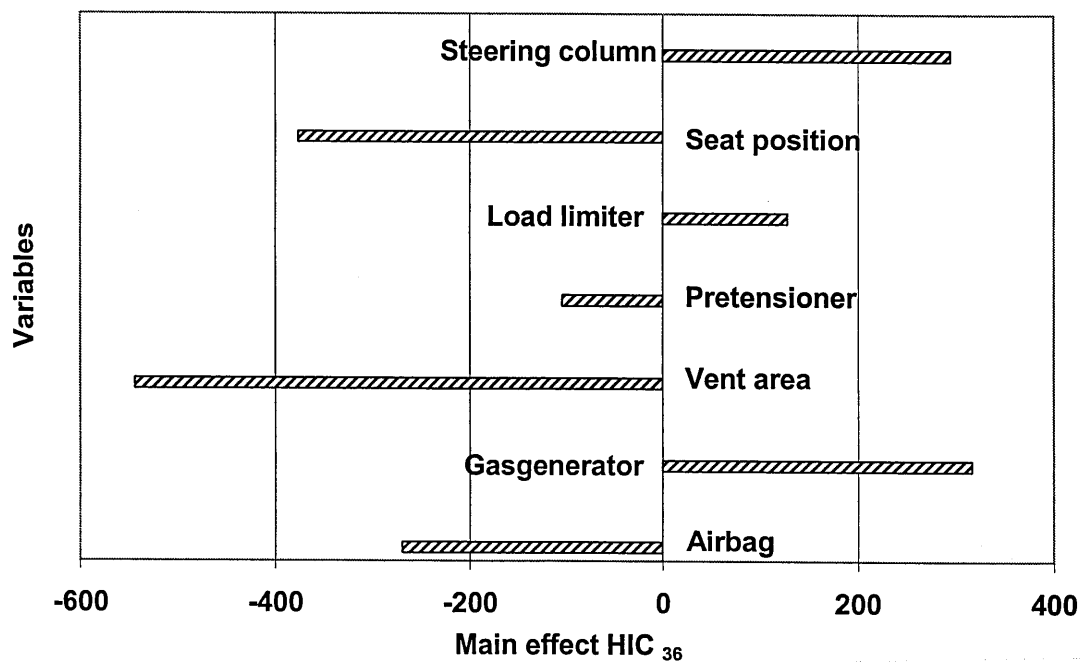


Figure 53. Main effects of (going from minus (baseline) to plus (increment)) of the variables for HIC₃₆ values in 80 km/h impact speed simulation runs.

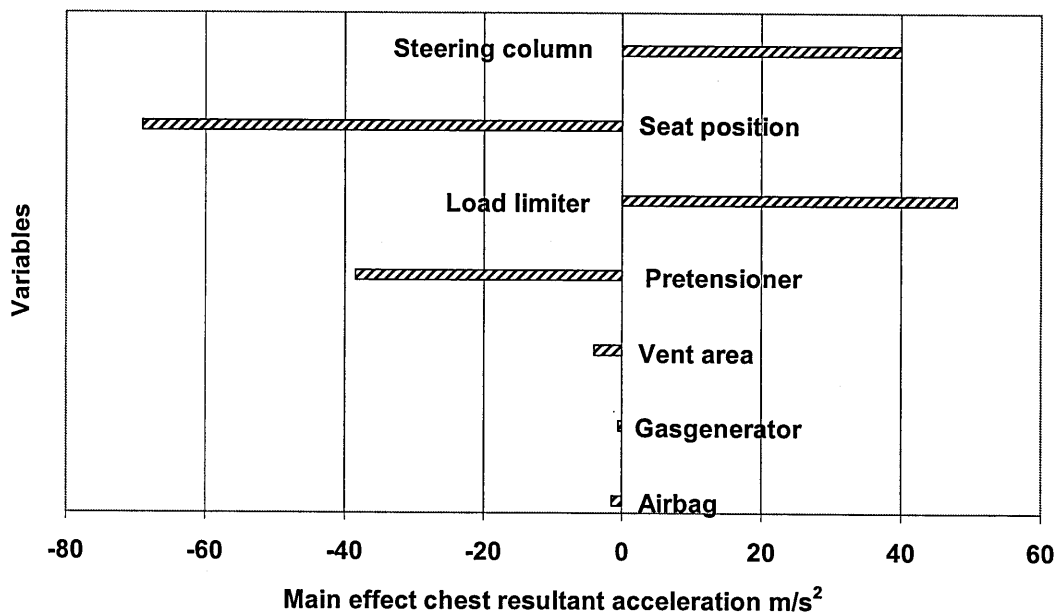


Figure 54. Main effects of (going from minus (baseline) to plus (increment)) of the variables for chest acceleration values in 80 km/h impact speed simulation runs

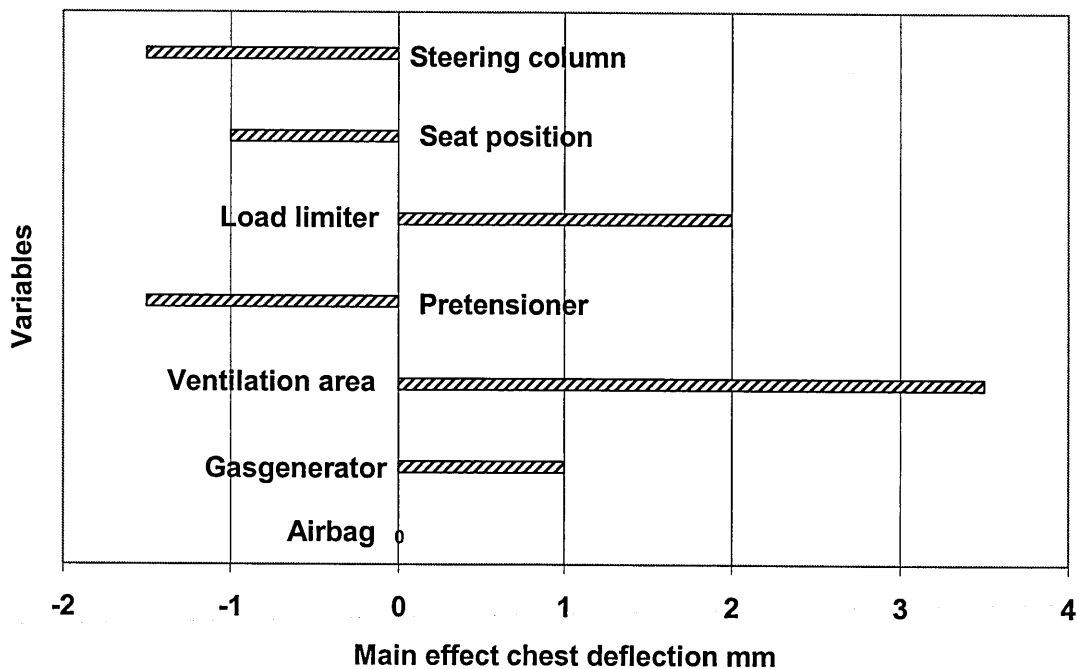


Figure 55. Main effects of (going from minus (baseline) to plus (increment)) of the variables for chest deflection values in 80 km/h impact speed simulation runs.

The chest deflection was not significantly effected by any of the variables other than ventilation area which had an effect of 3,5 mm and where larger vent holes increased the chest deflection.

Analysing the results it is obvious that moving the seat and seat belt anchorages backwards had a positive effect on most of the results and HIC and chest acceleration were reduced by discernable amounts in the 80 km/h runs. However, the reduction in chest deflection was surprisingly low at both crash speeds. A high pre-tensioning force always had a positive effect in reducing the dummy criteria with the exception of chest deflection at 56 km/h.

The results indicate that, given the set conditions in terms of the chosen crash pulse and no distortion of the occupant compartment due to intrusions, it is possible, through proper tuning of the characteristics of conventional restraint components, to design an effective restraint system for a driver at an impact velocity of 80 km/h.

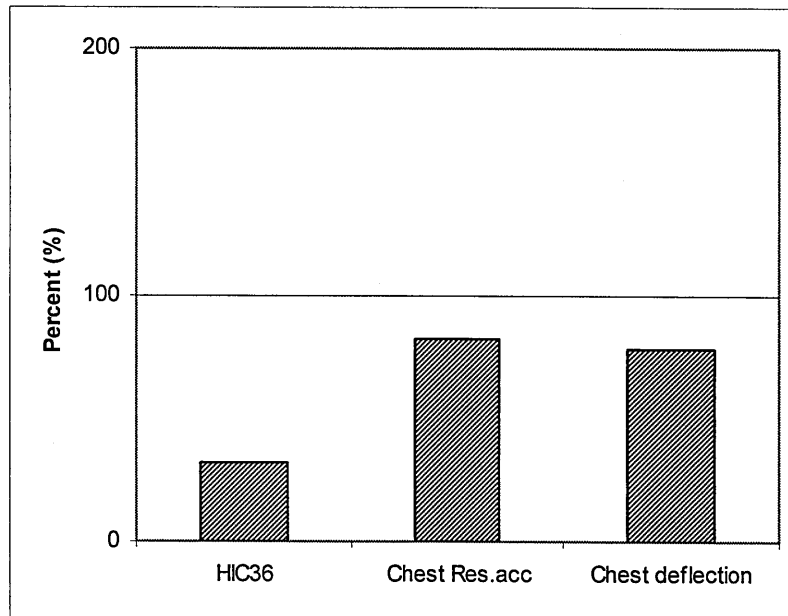


Figure 56. Results from computer run 8 at 80 km/h shown as percentage of 20% IARV (see chapter Crash test Dummy-Injury criteria).

The factorial analysis must not be regarded as optimisation study. However, it could be interesting to pick one of the computer simulations at 80 km/h and analyse it in relation to the IARV for 20% AIS 3+ injury risk as was done with the sled test 3265. Run 8 at 80 km/h has a combination of variables which consist of a large airbag, increased mass flow, large vent holes, powerful pre-tensioner, high level of force limiting, high level of collapse force in steering column and the seat and seat belt attachments moved 200mm backwards to increase ride down distance inside the compartment.

One of the hypotheses at the start of this work was that increasing the interior ride down distance would make it possible to design an effective interior protection system. The set up in Run 8 is a good example of what the model predicts. In Figure 56 it is seen that the most important dummy results are well below the 20% injury risk threshold.

During the process of trying to interpret the data from the computer runs the energy dissipation of the occupant was also analysed.

The energy was calculated through a one dimensional linear translation analysis. The dissipated air bag energy was calculated multiplying the airbag force acting on the chest with the distance travelled to stop. The force was calculated through multiplying the bag pressure with an estimation of the area of the chest in contact with the airbag (estimated to be 0,3 m²). The distance travelled to stop is calculated through integration of the chest acceleration. The chest energy dissipated through the diagonal belt was calculated taking the belt

force acting on the chest and multiplying it with the travelled distance during ride down. The lap belt energy dissipation was calculated using the lap belt force multiplying it with the ride down distance. The knee restraint energy dissipation was calculated multiplying the force in the femurs with the ride down distance during contact.

The total kinetic energy for the dummy (74,3 kg travelling at 22.22 m/s) is 18 342 Nm. Summarizing the energy dissipated through the dummy's contact with the bag, the diagonal belt, the lap belt and the knee restraint (knee contact occurs only with seat in the mid position) an estimation of the total energy can be made in a global reference system (for the sake of simplicity energy dissipation through contact with the seat has been assumed to be of minor importance and has not been estimated).

As can be seen in the Table 24 the total energy dissipation estimate is not exactly the same as the dummy's kinetic energy. This is explained by the approximations that were done in the calculation methodology. However, in most runs the total energy estimates are of the same order except for run 2 where the estimate is 50% of the dummy's kinetic energy. At the moment no explanation has been found for this error.

Run	Bag energy dissipation (Nm)	Diagonal belt energy diss. (Nm)	Lap belt energy dissipation (Nm)	Knee restraint energy diss. (Nm)	Total energy dissipation (Nm)
1	3033	10375	2224	No contact	15632
2	1754	6659	1252	No contact	9665
3	7850	6971	5627	2123	22 571
4	3693	8184	5887	1324	19088
5	4465	7391	5830	1581	19267
6	1416	9279	5414	1811	17920
7	8007	6895	1258	No contact	16160
8	2546	9596	2216	No contact	14358

Table 24. An estimate of the dummy's energy dissipation into the different parts of the restraint systems using a global reference system approach.

From the results in Table 24 it is quite obvious that the load paths vary depending on the restraint configuration and the seat position. In some of the runs most of the chest energy is dissipated through the diagonal seat belt and in some through the airbag. In some of the tests the lap belt dissipates a considerable amount of energy and in the tests with the seat in mid position the knee restraint dissipates some energy.

This is an important finding and must be taken into account when designing an advanced restraint system.

It must be pointed out that this reasoning does not tell us where the energy has been absorbed. In order to calculate the energy absorbed by the restraint system, energy calculations with the car as the reference system have to be made for each system that participate in the actual energy absorption; like the energy absorbing device in the steering column, the air bag vents, the force limiters in the diagonal belt and the lap belt, the knee restraint and the seat. The dummy's kinetic energy (global reference system) minus the energy absorbed by the restraint system and the energy absorbed (car reference system) through compression of the dummy's different body parts, mainly the chest, is the remaining kinetic energy of the dummy absorbed by the crush zone of the car.

In a crash with a conventional seat belt system with manual belts some belt stretching will occur but the occupant's kinetic energy will mainly be absorbed through the deformation of the crumple zone of the car. This situation has gradually changed through the years with the introduction of airbags, retractor belts, seat belt load limiters, etc.

In a system where the occupant develops a velocity relative the car during the crash more emphasis has to be put on the proper tuning of the restraint system. The last portion of the occupant's kinetic energy must be absorbed by the restraint system including the energy absorbing collapsible steering column. Furthermore the restraint system must be able to function well with different sizes of occupants. A heavier occupant will need more energy absorbing capacity in the restraint system than a lighter one etc.

18 Discussion

The literature search and the experience from discussion with other researchers have resulted in information from projects dealing with the subject of high velocity impacts dating back to the seventies. There are numerous current reports about possible ways of improving restraint systems and optimising the protection at 50, 56 and 64 km/h but nothing about crash protection at 80 km/h. As an example it can be mentioned that many crash test laboratories can just about reach 80 km/h with its test equipment and there is very little experience about testing at that velocity.

In the first wave of safety research it was reasoned that considering a sufficient crush zone, a reasonable crush distance and a good crash pulse the best occupant protection would be achieved if the occupants were tightly coupled to the car. This would result in what is called a good “ride down” where the occupant follows the deceleration of the car until it stops. With the introduction of pre-tensioning belts and load limiting belts it was suddenly possible to take use of the distance between the occupant and the interior of the car to further smooth out the deceleration of the occupant.

It is rare that the peak chest acceleration of the dummy in crash testing falls below the peak acceleration of the centre of gravity of the car. In our analysis there actually are configurations for the 56 and 80 km/h computer runs that result in peak chest response at the same level, or lower than, the peak vehicle deceleration. This is a sign of how well the available interior ride down distance is used and how well the dummy is coupled to the car. It has been accomplished by primarily changing the configuration of the airbag, steering column and the seat belt with technology that is known today.

However, for the feature of moving the seat and the belt attachments 200 mm backwards just before the crash there is no known technology that could accomplish this today. In order to be effective and not too abrupt, such a sudden motion of the occupant could potentially injure the occupant. If we assume an average rearwards acceleration of the seat and the occupant of 0,5 g (in relation to the car) it would require 0,2 seconds to move the occupant backwards. Accident research at Daimler Chrysler has found that there is about a second of time before most crashes when the occupant is aware of the coming crash and responds to the coming threat by evasive steering and braking. In their newly introduced system called Pre-crash they use information from such manoeuvres to start to reposition the seat to a mid-position and raise the seat back to a crash position and close the sun roof and tighten the belts. This shows that the possibility to retract the seat is there when a high velocity crash is anticipated. However, what the effect would be on the control of the car if the occupant moves away from the steering wheel and the pedals remains to be investigated.

It is probably true to state that in a high velocity frontal crash any amount of seat retraction is favourable as long as the belt attachments (like in a belt in seat design) follows the seat and the characteristics of the restraint system are adapted for the situation at hand.

It can be argued that the stopping distance used in the 80 km/h of 0,99 m will result in severe intrusion into the passenger compartment, which was indeed the case in the crash with tested Ford Taurus. In order to limit intrusion into the occupant compartment cell considerable reinforcements may have to be introduced into the car body. Assuming that the length of a mid size car should not increase too much due to the negative effect on weight, fuel consumption, etc., a strengthening of the occupant cell would lead to a stiffer front structure. This would lead to a crash pulse with higher decelerations levels, which in its turn would negatively affect the occupant protection. The offset collisions results in quite another type of deformation that is much more difficult to prevent than the distributed deformation dealt with in this project. A recommended continuation of this study would be to try different types of crash pulses for the 80 km/h impact velocity.

It could also be argued that the likelihood of sever crashes with a delta-v of 80 km/h (closing speed of 160 km/h between two similar vehicles or 80 km/h into a fixed object) is extremely rare and therefore cars should not be designed for such sever crashes. It could, however, also be argued that with the introduction of adaptive restraint systems the possibility to further upgrade the protection system should be looked into. This must on the other hand not influence the protection given at the " most common crash speeds in sever crashes" like 50-60 km/h. It might even be the case that current restraint systems should be further tuned to fit the aging part of the population and children to give a good crash protection. The methodology and findings from this study could most certainly be used for such purposes.

The work in this project has focussed on the 50th-ile occupant, but it is recommended that the protection given by any high velocity restraint systems should be tested with the 5th and 95th percentile dummy.

The test dummy used in this work has primarily been the Hybrid III. The new advanced Thor dummy was initially tested but due to problems both with the description in the computer model and in the physical testing the Thor dummy was replaced with the Hybrid III dummy. The experiences gained with the Thor dummy pointed towards the difficulties of introducing too complex dummies i.e. measuring devises into every day car crash testing. Perhaps a crash test dummy used in the development of new cars and in homologation testing must not be too complex. On the other hand the Thor dummy has the capability to measure the deformation pattern of the chest in much better way than the Hybrid III dummy and should, therefore, be used in any future work when a better model of the dummy and an improved chest deflection measuring device exists.

A slightly modified version of the Thor dummy, named FID (Frontal Impact Dummy), has been introduced in Europe. It will probably be available as a module to plug into the Madymo software program quite soon. It has been shown in some recent research that the deformation pattern of the chest might be an important factor to control in order to limit the number of rib fractures when the chest is being compressed (Kent, 2002).

A number of parameters with possible influence on the outcome of the crash tests have been studied. The analysis of these results has given valuable insights that could 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 has not been fully 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 could produce high HIC numbers and neck loads.

It may well be that a prerequisite for effective driver protection at 80 km/h, with no a head contact with the windscreen or upper header, in a modern car is that the occupant, seat and seat belt attachments are moved backwards before the crash.

There are three major load carrying systems directly controlling the ride down of the dummy's thorax and head; 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 analysis has been made with a specific crash pulse arrived at after the crash testing of a conventional mid-sized car. As it is well known fact in past research 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 with the systems tested in this study.

The basic configuration of the tested restraint system is conventional. Belt force limiting devices with other characteristics and a more sophisticated energy absorbing seat structure should be tried.

The effect of moving the seat and seat belt attachments backwards 200 mm reduced most of the dummy responses but a possible technical solution to achieve such a seat retraction prior to crash has yet to be demonstrated. In order to utilize the interior ride down distance efficiently a much larger airbag in combination with a more powerful gas generator should be tried for the 80 km/h test. Possible interactions between the chosen variables in the factorial analysis

should be analysed. Further sled testing of promising configurations should thereafter be performed.

It has been assumed that no major intrusion occurs during the crash and consequently the technical feasibility of achieving crashworthiness at 80 km/h for a mid-sized car should be explored using the latest advancement in material and body design technology.

Below is a picture (see Figure 57) of a car that has been involved in serious real world, head on, fully distributed crash, with another car of the same model. The delta-v is estimated to be around 89 km/h (Kirk, 2002). The 25-year-old female driver was fatally injured mainly to her head and neck. She was wearing her seat belt that was pre-tensioned. The car was equipped with a driver airbag. (The vehicle rolled after impact). This crash gives evidence that even if rare severe collisions with distributed deformation does occur in the real world. The female driver (age 26) in the other car (same model) was belted in a pre-tensioned seat belt without a load limiter and there was a driver airbag. The delta-v of the car was estimated to be 82 km/h. She received an MAIS 3.



Figure 57. A real world crash with a high delta-v and a fully distributed deformation (Kirk, 2002).

19 Conclusions

1. Using a computer model and Design of Experiment technique key restraint system parameters have been varied in order to find the parameters with the highest effect on the dummy response in sled tests at 56 km/h and 80 km/h. Key parameters that will reduce the dummy readings have been identified.
2. The results show that, through proper tuning of the restraint system, it is possible to design a restraint system that offers driver protection for inertia forces up to 80 km/h crash speed, especially if the seat with seat belt attachments, can be retracted approximately 200 mm before the crash.
3. The results also show that by tuning the characteristics of the restraint systems to the condition at hands i.e. the crash severity, considerable improvements in driver protection can be made.
4. The prerequisite to further improve the crash safety of cars up to a level of 80 km/h impact velocity for distributed frontal crashes and maybe even further have been assessed. The challenge, however, will be to find the correct balance between active safety (crash avoidance) technology and passive safety (crash safety) measures in the future.

20 Recommendations

1. It is recommended that more advanced restraint system configurations are modelled and tested as well as the influence of different crash pulses.
2. It is recommended that the robustness of an advanced restraint system be tested i.e. what would the effect be of moving the occupant to other pre-crash positions or having different sizes of occupant etc.
3. Technical solutions to up grade the car body with new material or adaptive structures in order to withstand high velocity impacts must be further looked into.
4. Perhaps the most important issue of all will be to assess the cost benefit of any further sophistication of a restraint system. The influence of increasing the crashworthiness of current car bodies must be analysed and put in relation to possible future development of the interior restraint systems.
5. Any further advancements in crash safety has also to be evaluated in relation to the influence on cost, environment, weight increase, fuel consumption, customer acceptance and effect on the infrastructure.

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22 Appendix A

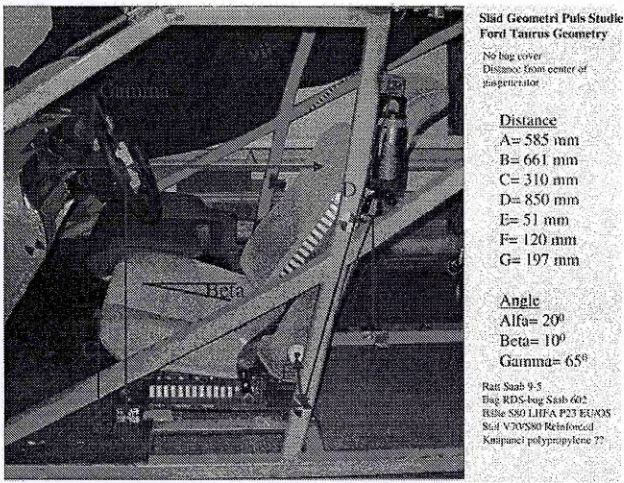


Figure1. Sled mock up geometry

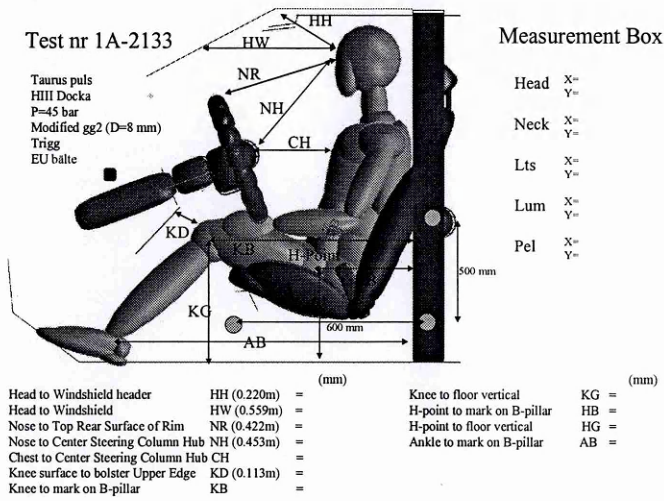


Figure 2. Instruction form for dummy positioning measurements

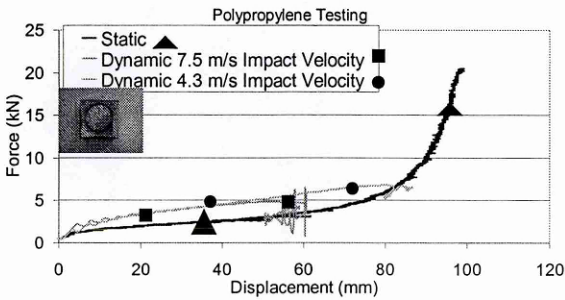


Figure 3. The static and dynamic load deflection characteristics of the padding used in the knee restraint.

23 Appendix B

23.1 Description of computer model set up

23.1.1 The seat

The physical seat cushion consisted of a steel plate underneath covered with comfort foam. The thickness of the foam was 10.5 cm at the side edges of the cushion and 7.5 cm at the center of it. The reason of using a steel plate and foam was that it could be used in several tests without having to be replaced. Conventional seats include springs, which may break during the tests. The model seat consisted of four planes and six ellipsoids. The ellipsoids did not affect the simulation results, but they did create a realistic geometry of the seat. The force-penetration characteristic of the seat cushion was divided into two planes. These planes corresponded to the seat foam and the steel plate respectively. The two remaining planes were placed in the front of the steel plate and they did not affect the results of the simulation. They were just remnants from the default model.

The force-penetration characteristic of the foam had not been measured, so it had to be generated using engineering judgment. The presented characteristics gave a reasonable penetration when compared to experience from other sled tests. The steel plate was considered to be rigid and the characteristics were defined as in Figure 1.

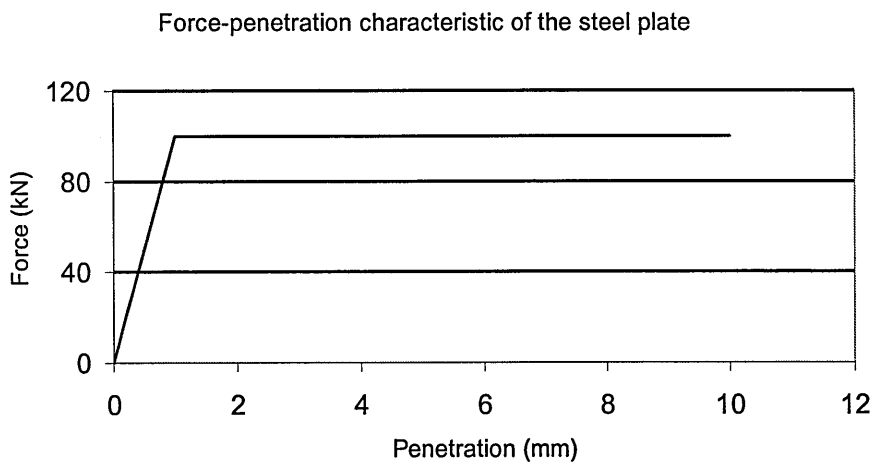


Figure 1. Force-penetration characteristic of the steel plate.

The distance between the two planes in the model was 9 cm. This is somewhere between 7.5 cm and 10.5 cm that was the measured distance. The uppermost part of the foam (40 mm) was considered to give zero force contribution. The reason for this was that the weight of the dummy was assumed to squeeze the foam about this distance. The more the dummy pelvic penetrated the foam, the larger force it experienced. The characteristics of the foam is shown in Figure 2.

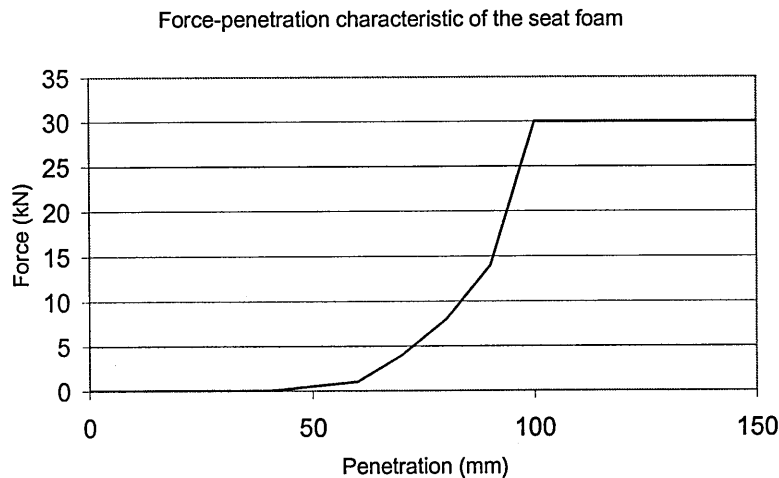


Figure 2. Force-penetration characteristic of the seat foam.

23.1.2 The knee bolster

The physical knee bolster was made of polypropylene foam. A component test was made in order to find the force-penetration characteristics of this foam. This test was made at two different impact velocities and a static test was made as well. The result of this test can be seen in Appendix A.

The characteristic of the knee bolster used in the model was the same characteristics as the one measured in the static test, see Appendix A.

23.1.3 The Toe pan and toe board

The floor in the physical model was made of a steel plate. This means that the floor was rigid and un-deformable and hence could not absorb any energy. The floor was shaped in order to imitate a real car floor. This means that the front most part of the floor was tilted to give a good support of the feet.

In the model the floor consisted of four planes. One part corresponded to the rear part of the floor and another to the front part of the floor. Two planes created the tilted part of the floor.

They were called the dash panel and toe panel respectively. The feet-floor contact was put into these two planes and they were assumed to be rigid.

23.1.4 The airbag

The physical airbag used in the validation tests was of the “Umbrella type”. This airbag deploys radially before it approaches the driver. The advantage with this airbag design is that it reduces the out of position (OOP) injuries. The airbag has two chambers. This means that the airbag has three layers of fabric. The midst layer has a number of holes that enables a gas flow between the airbag chambers. There are four vents in the layer opposite to the driver that enables airflow to the ambient air.

In most of the physical tests a gas generator simulator supplied the airbag gas. The gas generator simulator consisted of a tank with pressurized Helium gas and a hose that connected the tank with the airbag and a metal plate with holes at the airbag inlet. The initial tank pressure was set initially to 4 500 kPa. The reason of having a metal plate at the airbag entrance was to avoid an aggressive jet at the inlet.

Since the gas generator simulator is slower than pyrotechnic gas generators the airbag was trigged at 9 ms before the impact. The reason for this was that the airbag must be fully deployed when the head impacts the airbag. However, production gas generators were used in some sled test for reasons of comparison.

The model of the airbag was meshed with MEM3-elements with side lengths of about 3 cm. The total number of elements was 6151 and the number of nodes was 2965. An ALPHA damping coefficient of 10 s⁻¹ was used in the model. The material of the airbag fabric was modeled with the characteristics shown in Table 1.

Parameter	Value
Thickness	0.33 mm
Density	850 kg/m ³
Young’s Modulus	2*10 ⁸ Pa
Nu	0.28
Damping coefficient	0.05

Table 1. Airbag material characteristics.

Some parts of the airbag consisted of double fabric and these parts were modeled to have the same characteristics as in Table 1 but with a thickness of 0.66 mm. The parts of the airbag where the gas could flow between the chambers and into the ambient air were modeled with HOLE elements. The CDEX values were different for different holes in the airbag model.

In order to establish a way to define the mass flow of the gas, delivered by the gas generator simulator a specific study was made (not part of this project but available as part of the back ground data) that resulted in a method to calculate the mass flow rate. The calculated mass flow rate and the corresponding temperature at the airbag inlet are shown in Figure 3 and 4.

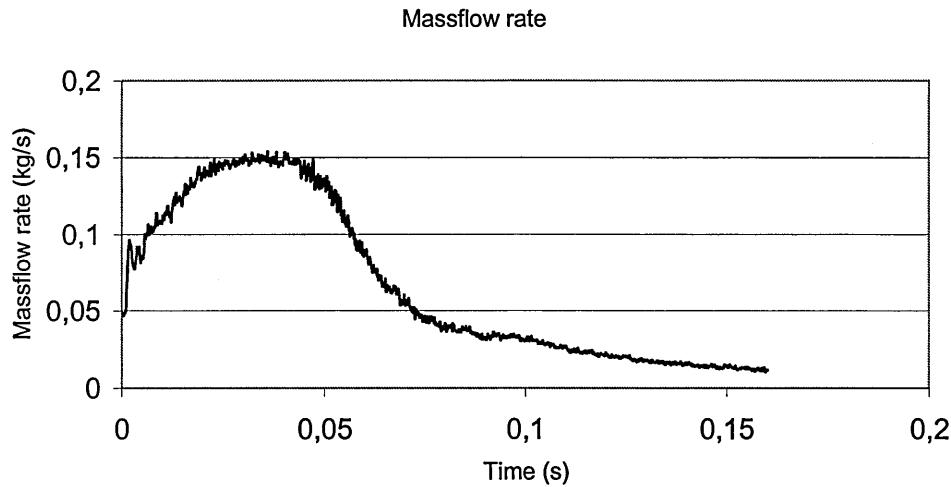


Figure 3. Calculated mass flow rate for the gas generator simulator.

The airbag was triggered 9 ms before impact in all simulations. This corresponded to the fact that the airbag was triggered at some distance before impact in all sled tests to achieve the correct phasing of the gas pressure curve.

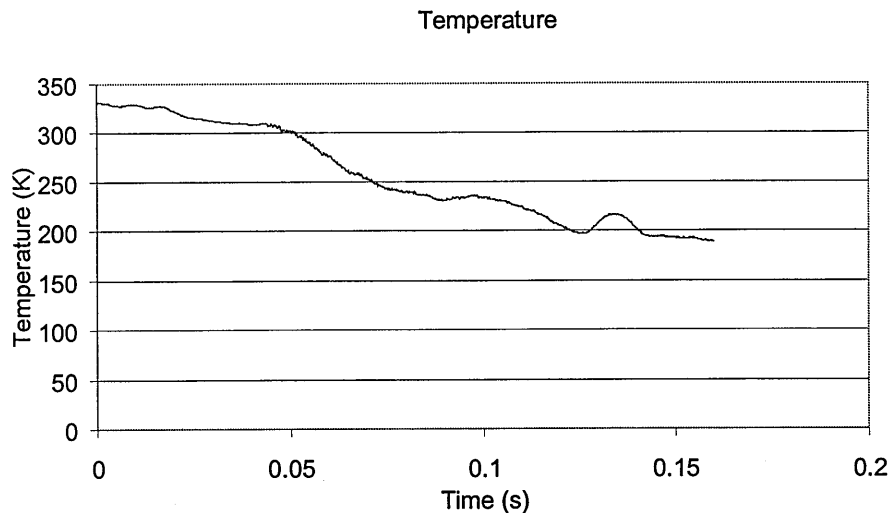


Figure 4. Calculated temperature as a function of time for the gas generator simulator

23.1.5 The belt system

The physical belt system incorporates a pre-tensioner and a load limiter. The effect of the pretension is that it retracts the belt and spools it back on the retractor reel. The pre-tensioner used in this study was a pyrotechnical device. The load limit function in the retractor will limit the force in the webbing when it reaches a defined level. The webbing will be paid out keeping the force constant. The retractor used in this study released the belt when the force level exceeded 5.5 kN. In the first set up the length of the released belt could not exceed about 10 cm to simulate a European type of retractor (belt spool out limited in order to comply with ECE Regulation 16). When the released belt length exceeds this 10 cm the belt force may increase again. This was later on changed to simulate a retractor that could spool out webbing indefinitely without an increase in force. The pre-tensioner was triggered 7 ms after the beginning of the impact. The pre-tensioner was modeled to affect the belt system with a constant force of 1,5 kN.

The characteristic of the belt webbing was modeled to vary on different parts of the body. Three different characteristics were used. One characteristic was used for the segment from the shoulder to the buckle. Another characteristic was used for the pelvis segment and a third characteristic was used for the folded belt next to the bracket. There are various amount of soft tissue at different parts of the body. Introducing varying characteristics for the different segments of the belt simulated this. The model itself does not account for the softness of the body tissue, since all bodies were assumed to be stiff bodies. This means that the belt webbing characteristics had to be a function of the belt

band itself and the amount of soft tissue at the body part that the belt affected. For example, the large amount of soft tissue at the pelvis gave a larger force reduction than the smaller amount of tissue at the chest did. The characteristic of the folded part of the lap belt on the outboard side was four times the characteristic of the unfolded belt band, since the belt band thickness was four times greater than for a single belt band. The belt band characteristics are shown in Figure 5 and 6.

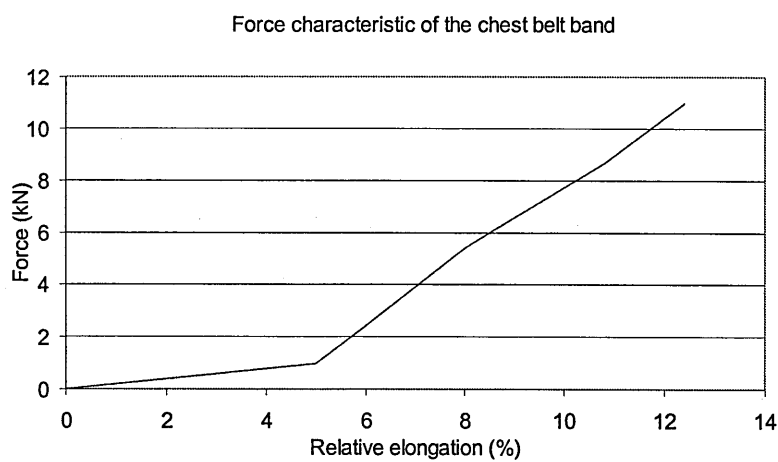


Figure 5. Webbing characteristics chest band.

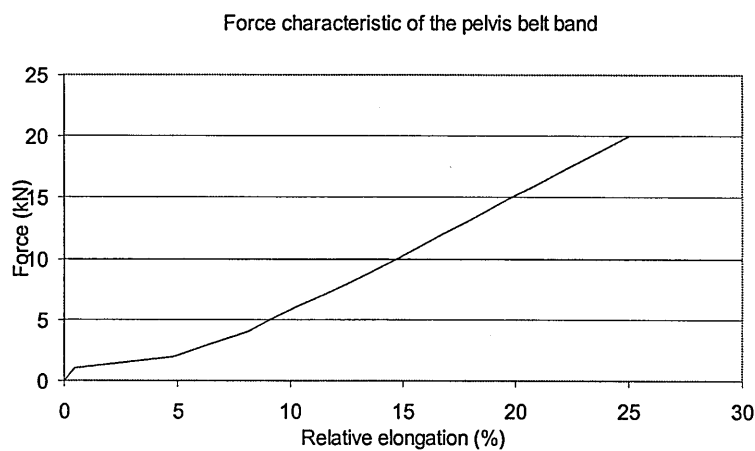


Figure 6. Webbing characteristics lap belt portion.

Interactions between car and dummy.

The dummy interacted with different parts of the car during the impact. Initially, the dummy was in contact with the seat and the knees were in contact with the knee bolster during the impact. The feet were in contact with the floor and the toe pan, which caused a force to propagate from the feet to the femurs via the knees.

The contact interactions between the car, the dummy and the airbag had to be specified in the model. The interactions between the dummy and the airbag were defined as an ellipsoid-node contact with a friction coefficient of 0.3.

23.1.6 Belt geometry

The segment between the hip and the end bracket was split into two parts. The different parts used different characteristics. The dummy with its belt attached can be seen in Figure 7.

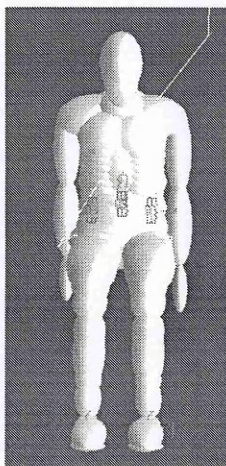
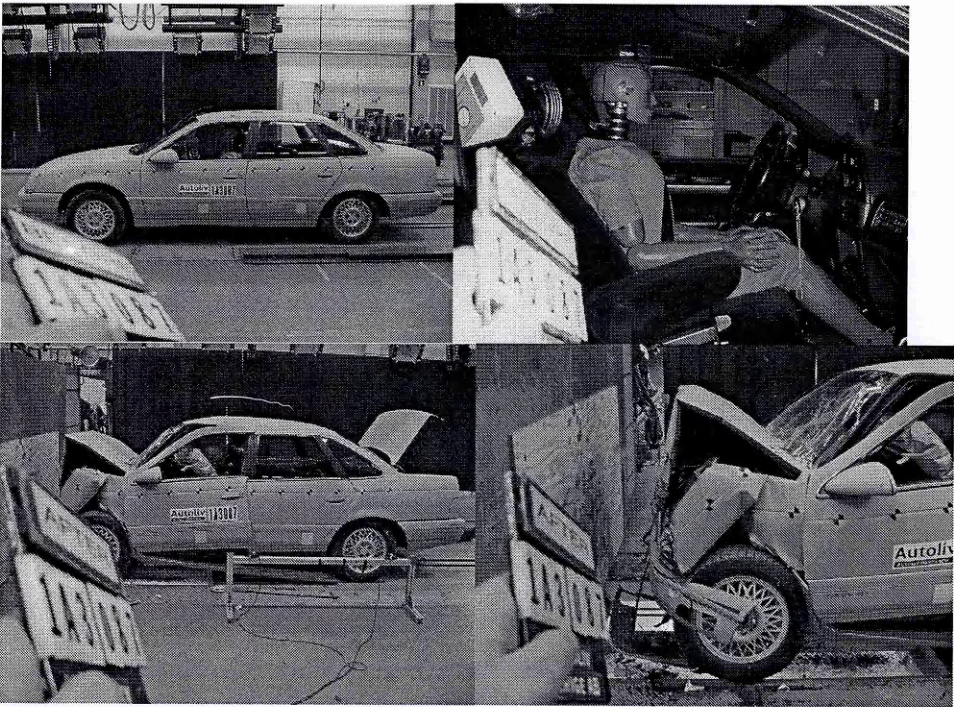


Figure 7. Dummy with belt attached.

The HIII-dummy with its attached belt.

Different body segments of the HIII-dummy came into contact with different parts of the occupant interior. The pelvis, hip and femurs were in contact with the seat. The knees and tibias were in contact with the knee bolster. The feet were in contact with the toe pan and the dash panel. The upper body and head were in contact with the airbag. All these contacts were defined in the MADYMO input file.

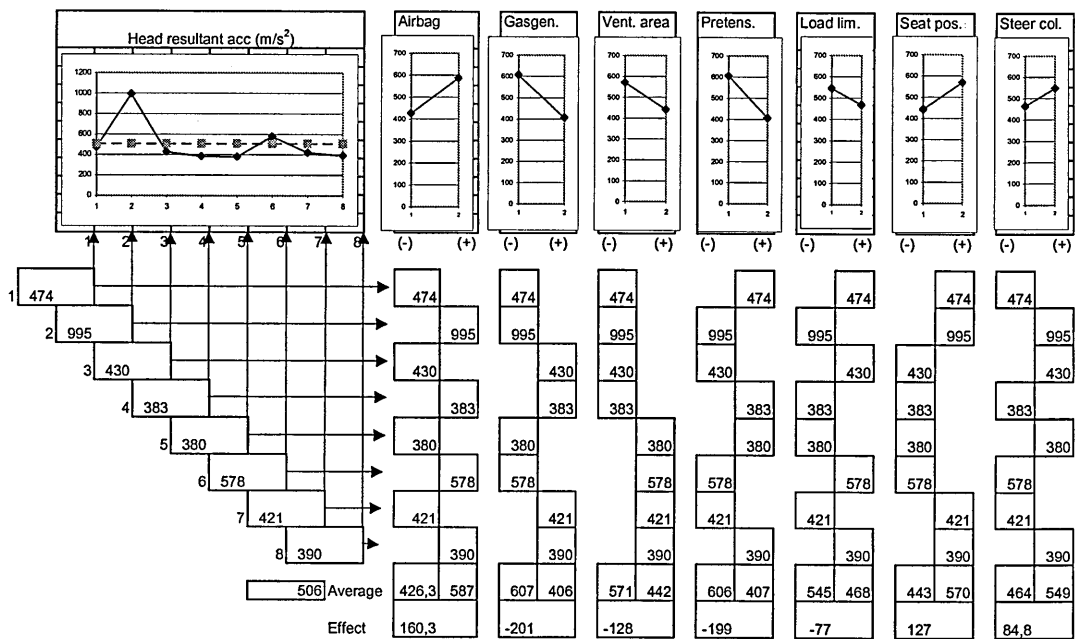
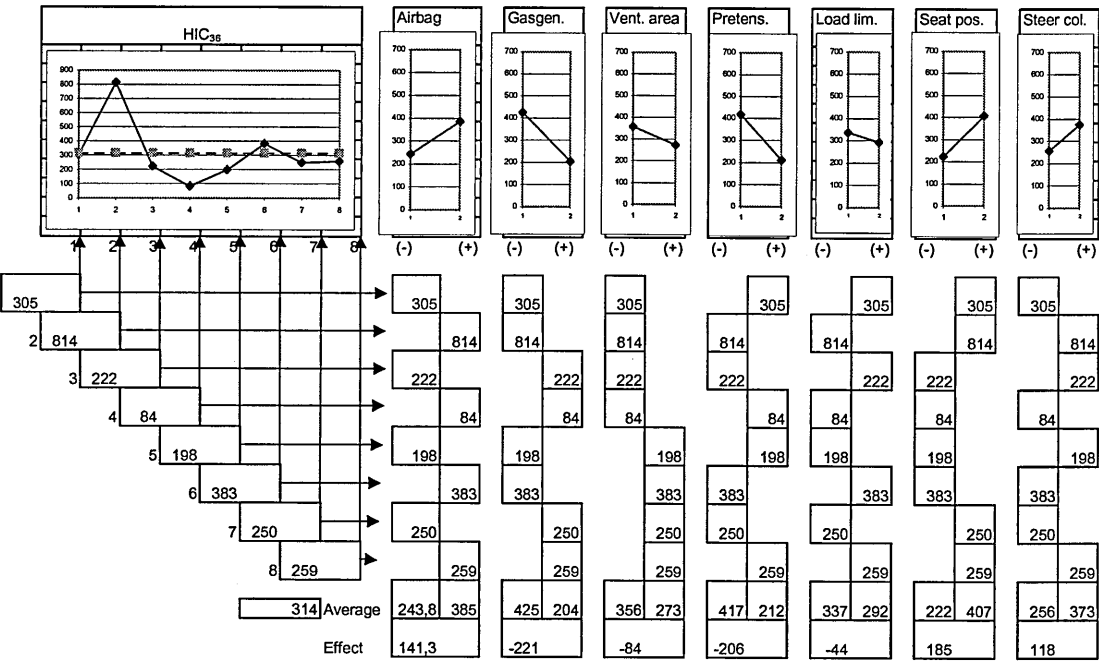
24 Appendix C



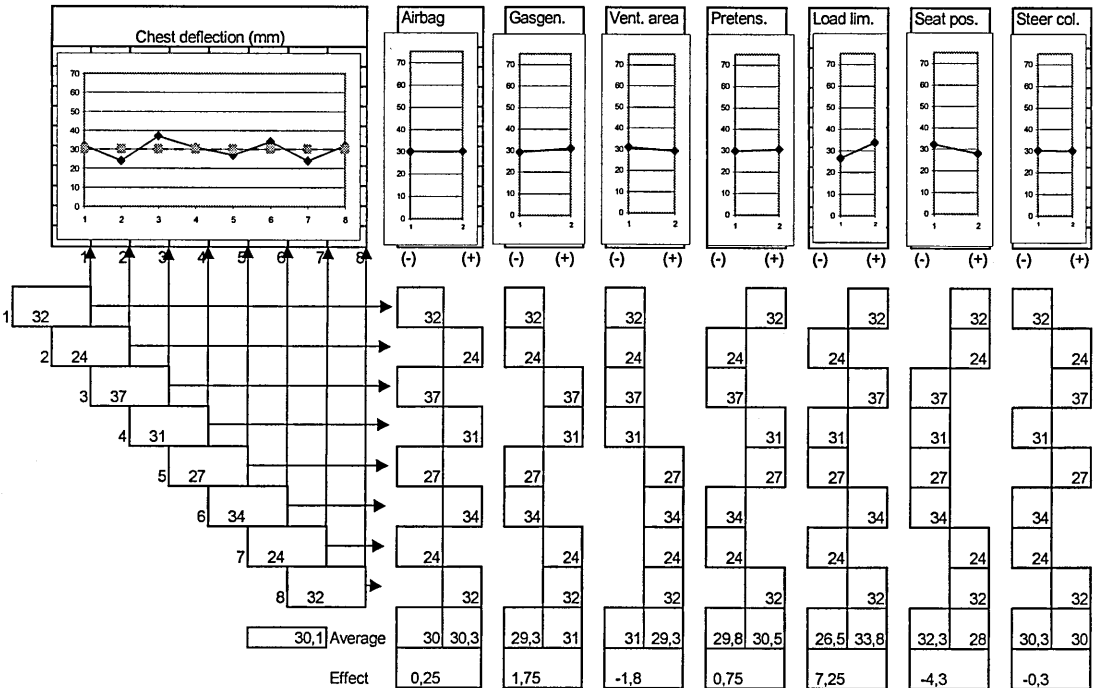
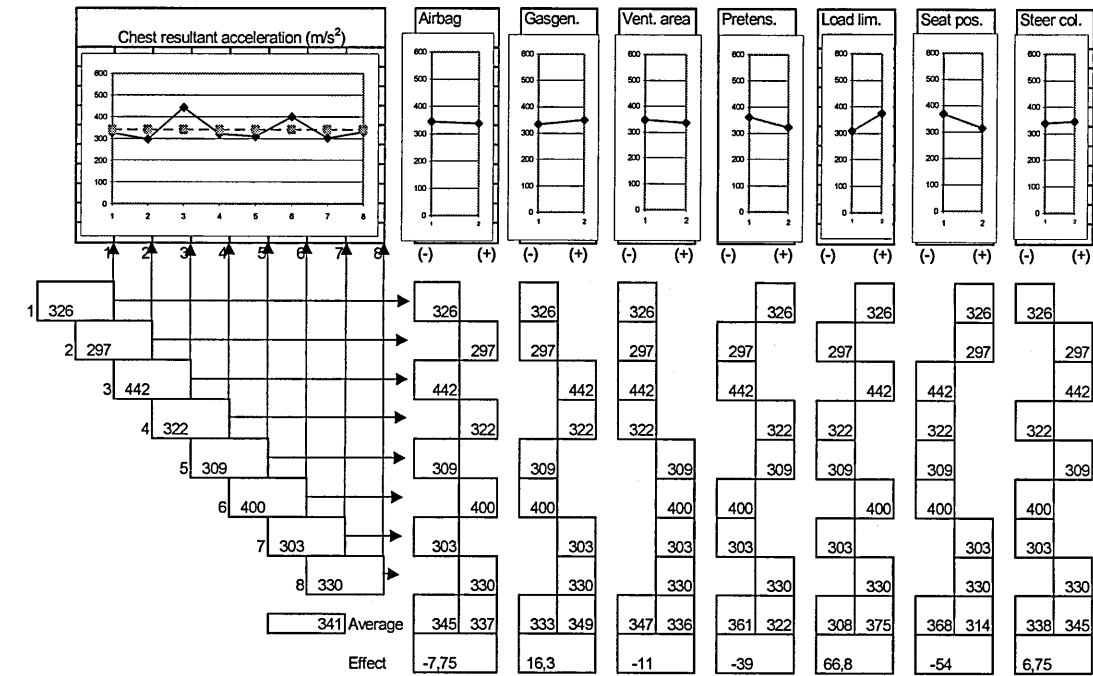
Ford Taurus before and after barrier impact at 80 km/h.

25 Appendix D

25.1 Main effects HIC and head acceleration from computer analysis at 56 km/h. Last run.

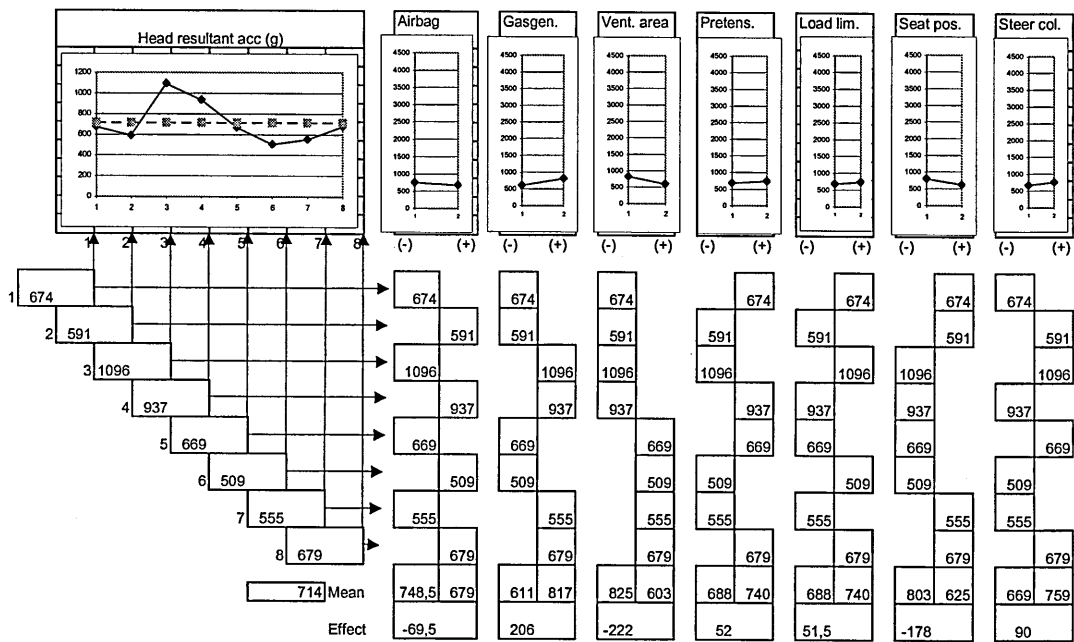
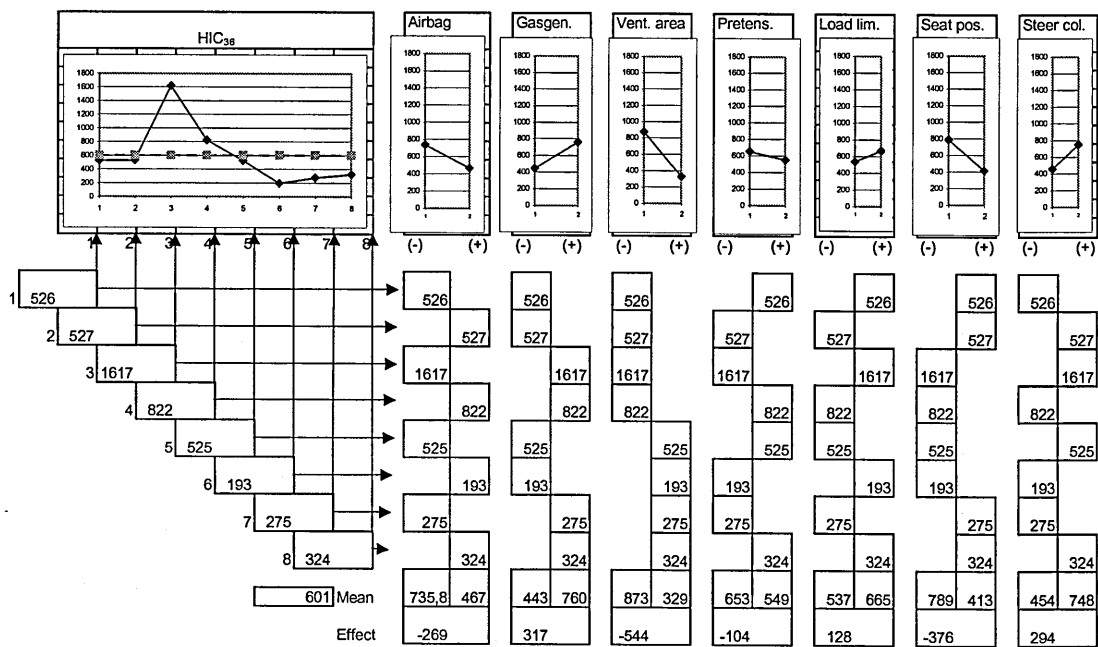


25.2 Main effects of chest acceleration and deflection from computer analysis
at 56 km/h. Last run.



26 Appendix E

26.1 Main effects of Hic and Head acceleration from computer analysis at 80 km/h. Last run.



26.2 Main effects Chest acceleration and Deflection from computer analysis at 80 km/h. Last run.

