The Inflatable Curtain (IC) - A New Head Protection System in Side Impacts

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ABSTRACT

Car accident investigations have shown that the head, the chest and the abdomen are the three most vulnerable body regions in side impacts, when serious-to-fatal (MAIS 3-6) injuries are considered. Injuries are much more common to occupants seated on the struck side than to those on the non-struck side. The development of new side impact protection systems has therefore been focused on struck side occupants.

The first airbag system for side impact protection, jointly developed by Volvo and Autoliv, was introduced on the market in 1994. The SIPS bag is seat-mounted and protects mainly the chest and the abdomen, and also to some extent the head, since the head's lateral relative displacement is reduced by the side airbag, thereby keeping the head inside the car's outer profile. However, if an external object is exposed in the head area, for example in a truck-to-car side impact or in a single car collision into a pole or a tree, there is a need for an additional head protection device.

Such a device, called the Inflatable Curtain (IC), jointly developed by Volvo and Autoliv, is described in this paper. The IC is an additional improvement to Volvo's unique SIPS and SIPS bag systems. It consists of two layers of fabric in what is known as one-piece woven technology. The IC is folded into a thin package, and is attached to the roof rail and the upper part of the A-pillar. When inflated, it covers the upper half of the side window, from the A to the C pillars, thereby substantially increasing head protection for both front- and rear-seat occupants. The performance and effects of the IC, in car-to-car and single car side impacts, are presented and discussed in the paper.

INTRODUCTION

Although frontal impacts still account for the largest number of injuries in crash statistics, approximately 25% of all serious-to-fatal injuries are incurred in side impact collisions, Figure 1[1].

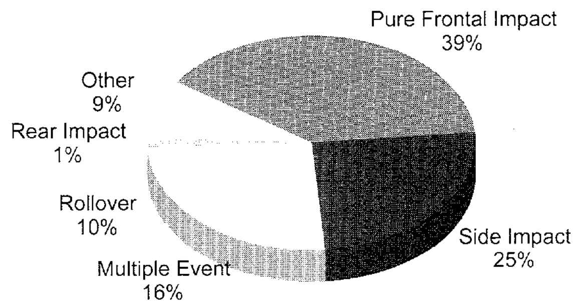

Figure 1. Distribution of serious-to-fatal crashes (MAIS 3+) by impact type. (n=1.997 occupants)

Today, frontal crash safety has been refined to such a degree that the safety benefits of a given design effort aimed at improving side impact protection are probably higher than the benefits of an increased design effort on enhanced frontal crash safety. One reason for this is that severe injuries sustained in side impacts occur over a fairly wide range of crash severities, with a relatively high frequency of injuries occurring even at low severities. Consequently, there

[1] The statistics in Figures 1 - 6 are derived from Volvo's accident data base, containing 27.500 crashes (1976-98) involving Volvo cars (only) in Sweden. The cases are selected according to a repair cost criterion. In case of an injury accident where someone has received medical attention, occupant injury data is acquired from medical case records. Of the 46.800 Volvo occupants involved in the crashes, 61% were uninjured, 34% sustained minor-to-moderate injury (MAIS 1-2), and 4% sustained serious-to-fatal injury (MAIS 3-6).

is much to gain in terms of injury reduction by improving the side impact protection characteristics, not only at high crash severities but also in the low-medium range of the crash severity distribution.

Structural reinforcements are needed to reduce the velocity of the intruding side structure in car-to-car impacts, and to provide a base on which interior energy absorbents will work satisfactorily. With the SIPS system, Mellander H. et al [1], Volvo took a first step towards increased occupant protection against side impacts by reinforcing many systems of the car, including the doors, the B pillars, the floor, the floor tunnel, the roof, and the seats. Energy-absorbing elements were also added to the car interior inside the door panels.

The SIPS bag, as described by Pilhall S. et al [7], was introduced in 1994 as standard equipment in the front seats of Volvo cars, as the first supplement to the basic Side Impact Protection System (SIPS). The bag was primarily designed to further reduce chest, abdominal and pelvic injuries, with only a moderate potential for reduction of head injuries.

Providing further interior energy absorption elements, in one form or another (foam, bags, etc.), offers a great potential for injury reduction, since this method is effective both in car-to-car impacts and in side collisions with trucks and other undeformable objects (e.g. poles, trees). These collision objects account for a considerable proportion of the severe occupant injuries in side impacts (Figure 2).

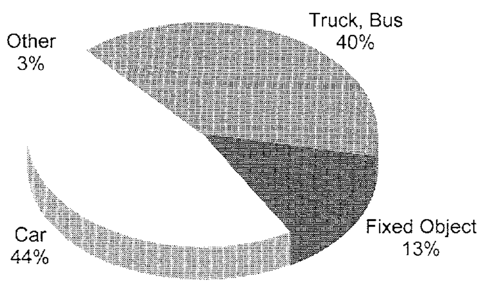

Figure 2. Distribution of serious-to-fatal side impacts (MAIS 3+) by collision object. (n=499 occupants)

In other data bases [2,3,4,5,6], the proportion of fixed objects is often higher, due to variations in road environment between countries, and the proportion of trucks/buses is lower. Together, however these collision objects still account for approximately half of the serious-to-fatal side impacts, though.

In collisions with trucks and fixed objects, body stiffness and strength are of lesser importance, since the collision object is undeformable. Interior energy-absorbing components, however, can considerably improve occupant protection by smoothing out the contact phase between the occupant and the interior side structure of the car.

The risk of sustaining an injury to the head, chest, abdomen, and pelvis is higher in side impacts than in other crash types (Figure 3). Head protection in frontal collisions has been continually improved through such development as the deformable steering wheel, collapsible steering column, increased belt use, and the introduction of frontal airbags. Today therefore, there is a higher risk of head injury in side collisions than in other crash types, especially when colliding with a truck or a fixed object.

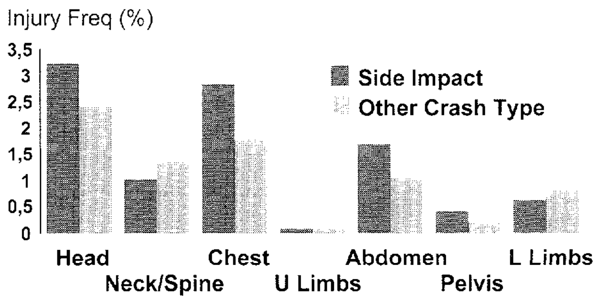

Figure 3. Injury frequency (AIS 3+) by body region (all collision objects). (n=46.856 occupants)

Head injuries are at least as common as chest injuries in side impacts, see Figure 3. This finding is supported by results from a number of sources around the world [5,8,9,10,11]. Consequently, it is highly desirable to examine the possibility of further increasing head protection in side impacts. The need for a head protection device is especially urgent in side impacts against trucks/buses and fixed objects, which together account for almost 60% of the serious-to-fatal head injuries to occupants seated on the impacted side (Figure 4)

Morris et al [12] found that almost half of all head injuries (AIS 2+) in side impacts originated from exterior contacts against other vehicles, poles, trees, etc. Door glass was the most frequent interior contact source. The severe injuries (AIS 4+) were more frequently caused by exterior sources than by interior sources.

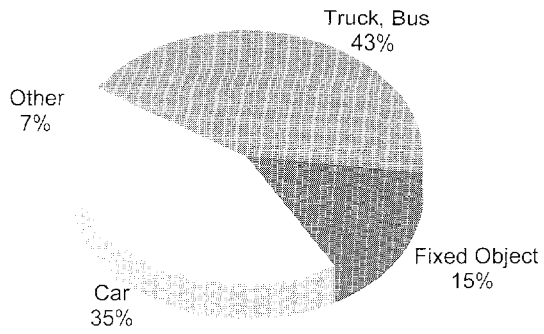

Figure 4. Distribution of collision objects among near-side occupants sustaining (AIS 3+) head injury in side impacts. (n=172 occupants)

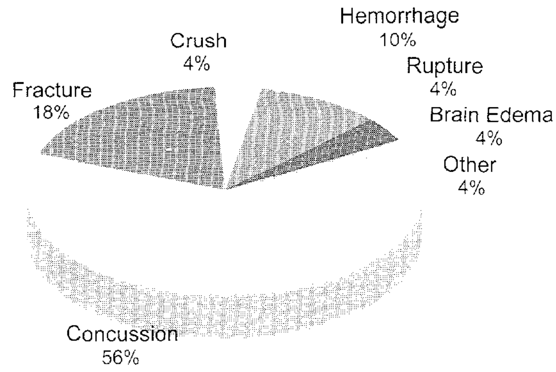

Figure 6. Distribution of AIS 2+ head injuries by injury type.
(n=302 front & rear seat near-side occupants)

An effective head protection device must cover both the front seats and the rear seat, since the risk of head injury is equally high for front or rear seat occupants (Figure 5, Volvo data base).

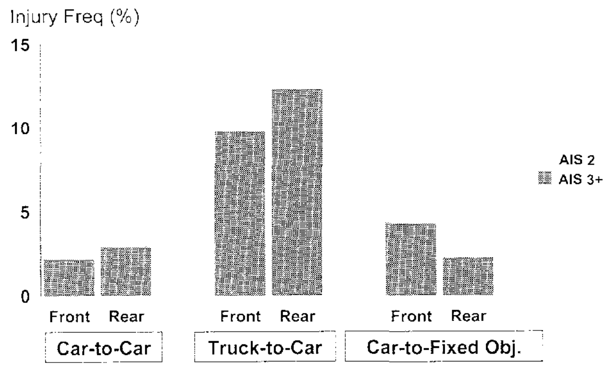

Figure 5. Head injury frequency (%) by seating position and collision object.
(3.414 front seat, 606 rear seat near-side occupants)

The types of head injury (AIS 2+) sustained by near-side occupants are mainly concussions, fractures, brain hemorrhages, brain edemas, and crush injuries (Figure 6); injuries that indicate hard head contact. Similar results were found by Morris et al [12].

In Volvo's data base, the majority (62%) of the concussions are of moderate severity (AIS 2), 35% are serious (AIS 3), and 3% are severe-to-critical (AIS 4-5).

The fractures involve a much higher threat to life: 24% AIS 2, 15% AIS 3, and 61% AIS 4-6. Of the brain hemorrhages, 69% are (AIS 4-6). The crush injuries are exclusively critical-to-fatal (AIS 5-6) as are most of the brain edemas. The ruptures (of the brain stem) are all fatal (AIS 6).

Neck injuries in side impacts are mainly of low injury severity in terms of threat to life, AIS 1. These injuries occur at all crash severities. More serious neck injuries (AIS 2+) are very rare (less than 1% injury frequency to near-side occupants). They are more likely to occur at high crash severities, most often in combination with head injury. Most of these (very rare) AIS 2+ neck injuries (73%) consist of fractures AIS 2-5 to the cervical vertebrae (C1-C7), 20% are ruptures AIS 5-6 of vertebrae C1-C4, and 7% are luxations, nerve injuries and pain AIS 2-3.

In view of the accident data presented above, it is obvious that there is an urgent need to further increase head and also neck protection in side impacts. The objective of this paper is to describe the development, design, function, and protective performance of a new dynamic head protection system, the Inflatable Curtain (IC), jointly developed by Volvo and Autoliv. The aim is to considerably reduce the risk of serious-to-fatal head and neck injuries in side impacts – for front seat as well as rear seat occupants, and especially in collisions against fixed objects (poles, trees) and trucks/buses.

DESCRIPTION OF THE INFLATABLE CURTAIN

Main Components

The system consists of two main components, (Figures 7 and 8).

The Bag, manufactured through "One-Piece-Woven" technique. Due to the technique, the bag can be folded in a thin package in the car. The bag is impregnated with a special silicone that makes it possible to maintain an adequate pressure in the bag. Thereby, significant protection is obtained also in multiple accidents. To reduce friction, a thin layer of material (light weight non-woven material) is laminated to the silicone. This makes it easier for the bag to unfold during deployment. The low friction also contributes to avoid adhesive contacts to the occupants.

The Gas Generator is of hybrid type, using a pyrotechnic propellant. When activated by a sensor, gas is generated to open a mechanism that leads into a pressure vessel containing inert gases, 95% argon and 5% helium. The cold gases in the vessel are mixed with the hot gases generated by the propellant. The result is a low temperature of the gas filling the IC, which is important for maintaining a good pressure in the bag. The gas generator is placed in the D-pillar.

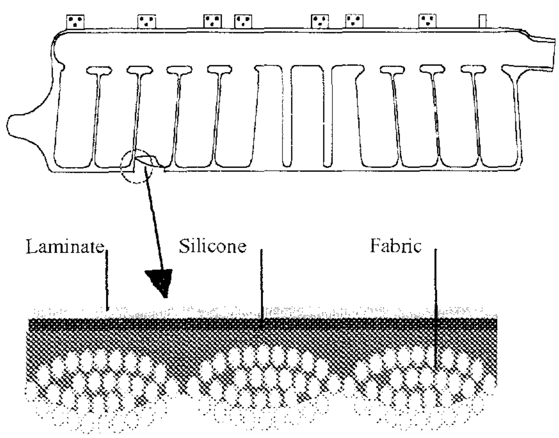

Figure 7. The IC bag.

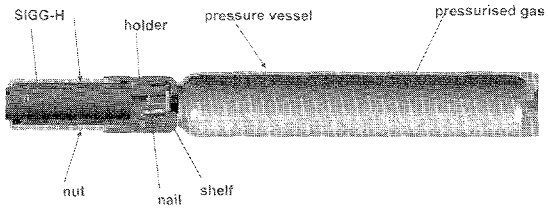

Figure 8. The IC gas generator.

Covering Area

One of the basic principles of the system is to provide an adequate protection area to occupants in both the front and the rear seats. Various occupant sizes and seating positions should also be considered. The protection area can be divided into two different types (Figure 9).

1) The zone where the head is likely to be directly exposed to the pillars, the roof rails, the door glass, and objects outside the car. Impact energy absorbtion is needed in this area.

2) The rest of the area "only" helps protect the occupants by keeping the head inside the compartment, and by preventing glass or similar objects from intruding into the area of the occupants head.

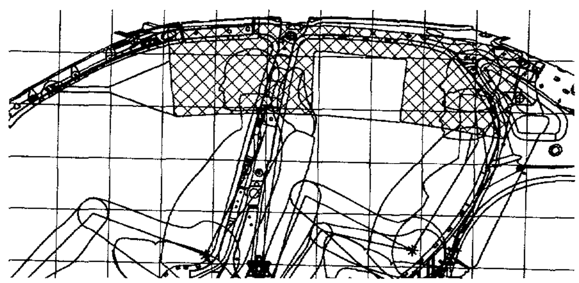

Figure 9. IC covering area.

Timing Performance

An airbag-based side impact protection system has to be very fast in terms of position performance, due to the very limited distances between the occupants and the interior of the car. This is valid for both chest/pelvis protection and head protection. In order to protect the occupants, the IC must be fully deployed after about 30 ms from initial crash contact in high severity side collisions.

The IC is fully deployed at about 25 ms after ignition of the inflator (Figure 10.).

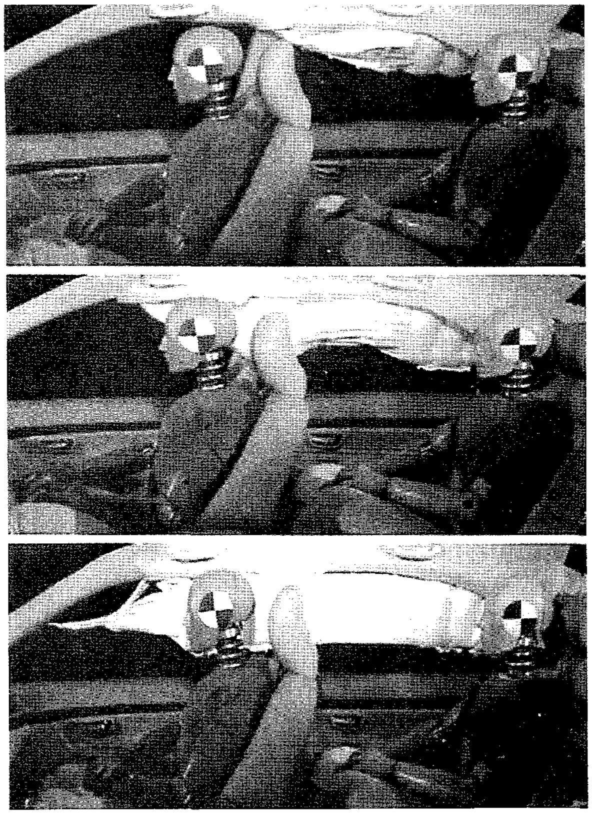

Figure 10. IC deployment at 12, 17 and 24 ms, after ignition of the inflator.

In addition to the time for complete positioning, the bag pressure time history is an important parameter. Both in terms of the time for reaching "working pressure", and for how long the bag remains inflated. (Figure 11).

At about 40 ms, the maximum pressure is reached. The remaining pressure, is adequate in providing protection for at least 3 seconds in crash situations beyond an initial side impact.

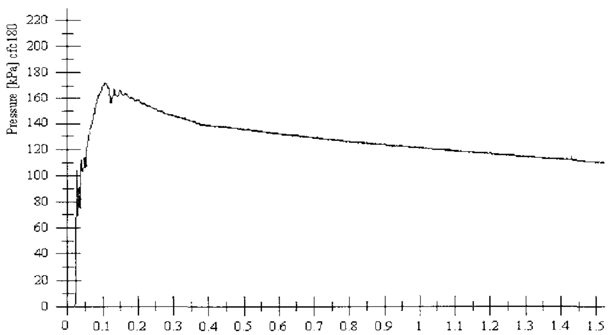

Figure 11. Bag pressure vs. time.

METHODS

Due to the specific area being quite new, and to the relative complex "field accident situation", there are not yet any generally established methods for developing dynamically deployed protection systems for improved head protection in side collisions.

However, there are tools to examine the head protection performance in some relevant situations.

In the preparatory analysis of the IC system's function and energy absorbtion properties, a simple pendulum test set-up was used to take the first development steps. Developments have then continued, mainly with pole impact sled tests and full-scale crash tests. It is thought that the pole impact mainly cover even truck/bus impact.

Pendulum Test

Depending on dummy type, crash mode, and car structure, the head will have an angular direction relative to the torso. The neck loadings will also help the head reduce its velocity. This will result in a number of different possible velocities towards an external object or against a protection device.

The method makes use of a pendulum to which a head form, with a weight of 6,8 kg and diameter of 165 mm, is attached. The head form moves in a pendulum motion and hits the impact object and the IC, in the head form's lowest point where there is a horizontal velocity component only. Behind the IC, a stiff undeformable block is placed which simulates an external contact surfaces.

For the first rough tests, an assumption has been made that the head is angled approximately 30 degrees towards the torso. This gives a horizontal velocity of 7 m/s, corresponding to a pole test at 32 km/h, which has served as an upper limit in the initial tests.

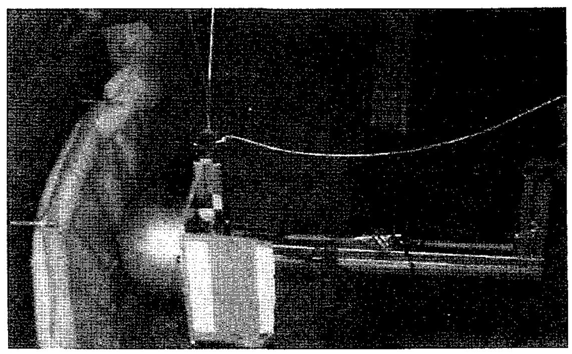

Figure 12. Pendulum test set-up.

It should be noticed, that the head form has a slightly higher weight (6,8 kg) than a real head (about 5 kg), therefore an impact velocity of 7 m/s will correspond to a slightly higher impact velocity for a real head.

Free Motion Headform (FMH) According to FMVSS 201.

The need for improved head protection has led NHTSA to establish new requirements for Upper Interior Impact Protection, in FMVSS 201. These requirements are to be phased in over five years, beginning September 1, 1998. Originally, the requirement defined a number of specific target points (Figure 13) at which a Free Motion Headform's (FMH) HIC(d) criteria must not exceed 1000, when impacting the points at 15 mph (6.7 m/s).

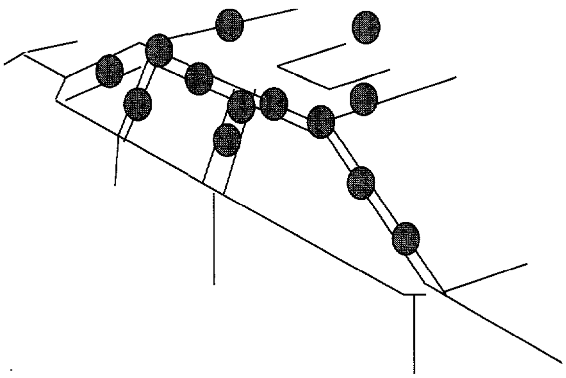

Figure 13. Target points defined in FMVSS 201.

However, since making this rule, NHTSA has subsequently published a Notice of Proposed Rulemaking, in August 26, 1997, that makes possible, but does not mandate, some alternative requirements to use as possible options for "Dynamic Head Protection Systems".

One of these options, a full scale side impact into a fixed pole, also takes into consideration crash situations in which the occupants directly impact an external object.

By using the FMH test set-up, it is possible to evaluate the HIC-reducing effects of the IC, over a wide range of bag pressures and impact velocities, in a way that is both simple and adequate.

In order to isolate the evaluation of the HIC performance vs bag pressure, a fixed block was used, positioned outside the front door window, simulating a rigid external crash object. The FMH head was directed at this fixed block. The FMH head then impacted the IC, which covered the fixed block (Figure 14).

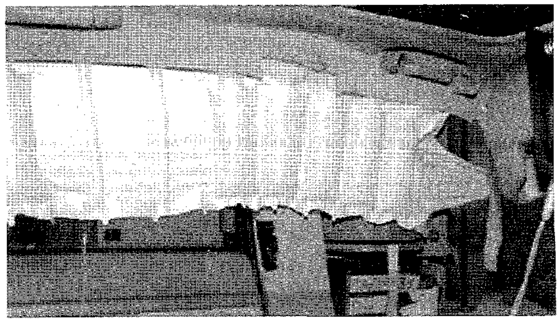

Figure 14. FMH test set-up (head to the right).

Tests have been conducted at two different impact velocities and at bag pressures from 100 to 300 kPa.

Pole Impact Sled Test

The pole impact sled test method (Figure 15),.is based on a full-scale test with a Volvo 850 which is crashed into a pole at 28 km/h. The pole has a diameter of 300 mm. The dummy values measured (Eurosid dummy) have been used as a reference for the development of the pole method.

In the method, the predeformed car body and the pole are placed in a fixed position. The seat including a SIPS bag, and a dummy are placed on a sled and crashed against the pole at chosen velocities. Between each test, door padding is changed to achieve the right torso responses.

Figure 15. Pole impact sled test set-up.

There is a reaction time difference between the pole impact sled method and the full-scale of approximately 8 ms, corresponding to the time for door deformation. This is compensated for by selecting trigger time to reach a good correlation.

In the test series, two different dummies have been used: Eurosid and the US-SID/H3 according to NHTSA's proposal for FMVSS 201, option 3. The primary response measured was head acceleration. In tests with the US-SID/H3 dummy, neck forces were also measured. Head rotation acceleration was measured in test series at 32km/h.

Computer Simulated Pole Impact

In order to predict the relationship between pressure and HIC, and to get a better understanding of this relationship, a mathematical model was developed. The model consists of vehicle structure, intruding pole, dummy, sidebag and IC (Figure 16).

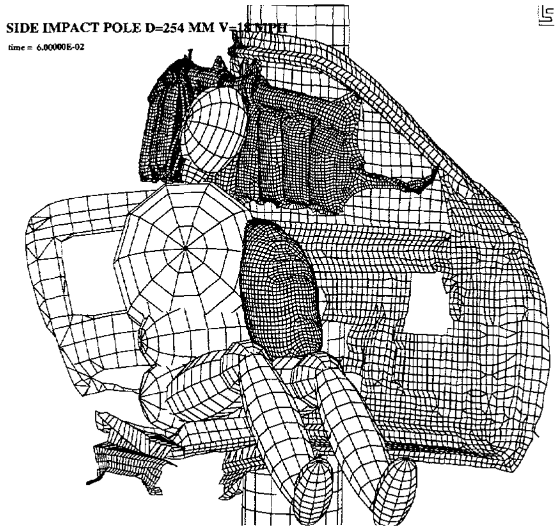

Figure 16. Computer Simulated Pole Impact.

The hybrid approach was chosen for the model development. The vehicle structure was modeled by means of finite elements, while the dummy and pole were modeled by means of rigid bodies. The number of elements and nodes in the model were 64447 and 64778, respectively. The dummy was a model of the US-SID dummy. The pole was a model of a luminary pole, with a diameter of 254 mm. In the simulations, the center of the pole was lined up with the center of gravity of the head and the vehicle traveled sideways towards the pole, with an initial velocity of 18 mph (29 km/h). The initial velocity was not varied in the study. The pressure in the IC, however, was varied from 180 kPa to 240 kPa.

RESULTS

Pendulum Test

HIC vs Cell Thickness - To position the bag quickly and at the same time achieve good injury reduction, the width of the cells is an important parameter in optimization. Performance tests have been conducted in a pendulum rig to produce an indication of the HIC reduction. In the tests, the thickness of the vertical cells and the velocity of the head form have been varied. In all tests the bag pressure was 150 kPa.

The result indicated good injury reduction in all cases (Figure 17).

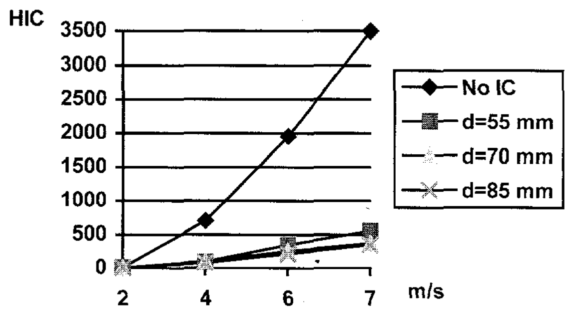

Figure 17. HIC vs velocity, at different cell thicknesses.

A cell with thickness of 85 mm gives a HIC reduction of approximately 90%, at all tested velocities.

A cell with a thickness of 70 mm gives a reduction of 88%, and a cell thickness of 55 mm gives a reduction of approximately 84%.

If the thickness of the cell is increased too much, there will be an unacceptable variations in head loading when comparing an impact to the top of a chamber or between two chambers. Besides, there will be other negative effects, such as increased time to positioning and increased bag volume, which will require an increased gas generator capacity in order to reach an adequate pressure.

A thickness of 70 mm and a pressure higher than 1.5 bar kept the head form from bottoming out the IC at an impacting velocity of 7 m/s.

Absorption of Impact Energy - By throttling the inlet to the vertical cells, the energy absorbtion can be increased. When the head hits the curtain, an amount of work has to be performed to push the air out of the vertical cell to the rest of the curtain. By throttling the inlets, the amount of work is increased (Figure 18).

The absorption in the pendulum tests only takes into account the lateral velocity. When testing with a dummy, in full scale tests, other parameters influence the absorption such as rotation, neck moments, stiffness in the neck etc. However, if the inlets are throttled too much, the time to position and pressurize the curtain will be delayed.

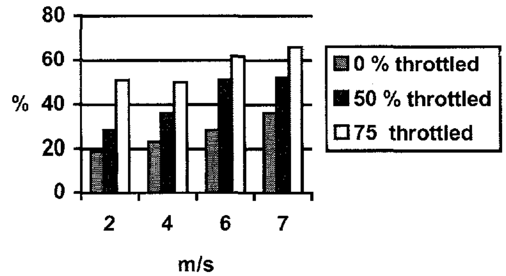

Figure 18. Energy absorption vs impact velocity, at different throttle rates.

Free Motion Headform (FMH), According to FMVSS 201

At "normal working pressure"(140 to 160 kPa), (Figure 12) the HIC(d) value was about 600 at 15,5 mph and around 400 at 12,5 mph (Figure 19). At the lower impact speed, the HIC(d) was about constant in the tested interval.

Two effects were seen at the higher velocity. The performance was quite constant down to about 150 kPa, when the head started to bottom up into the fixed block. On the other hand, the HIC(d) values started to increase when the pressure had exceeded 250 kPa.

The results indicate that the pressure level 160 to 220 kPa is favorable to cover impact velocity up to 15 mph.

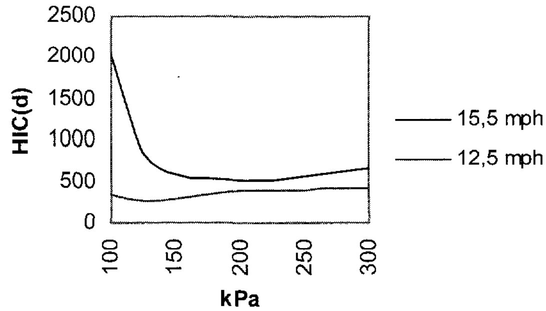

Figure 19. HIC(d) vs bag pressure

Pole Impact Sled Test

There was a major reduction of the HIC value, as well as the head acceleration maximum value, with the IC, at both impact velocities in the simulated pole impact using the Eurosid dummy. The duration of the acceleration were increased (Figure 20). The same tendencies were also found in the simulated pole impact with the US-SID/H3 dummy. The risk of skull fractures were reduced almost 100%, according to risk curves by Mertz H. et al. [17].

The maximum head angular acceleration and the maximum head angular velocity was reduced by the IC, both around the x-axis and the z-axis (Table 1).

In simulated FMVSS 214 sled tests, the neck loading duration decreased with the IC (Figure 21).Computer Simulated Pole Impact

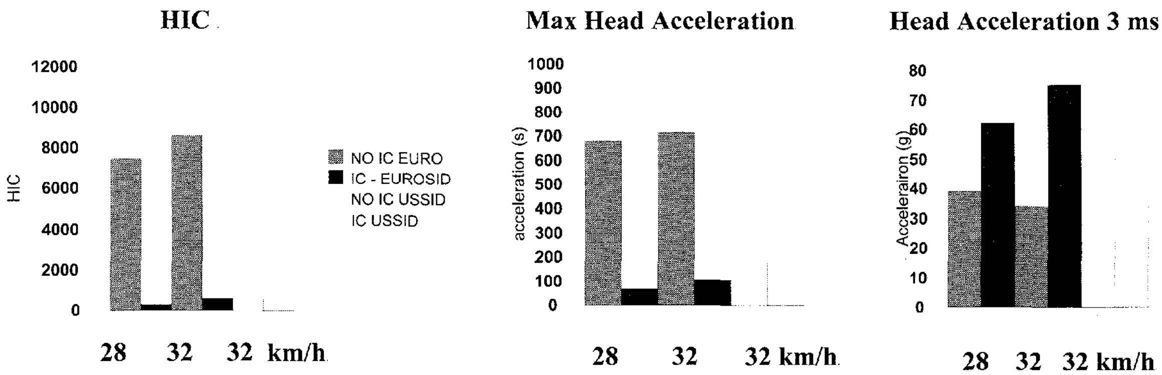

Figure 20. Head acceleration results from pole impact with the Eurosid at two different impact velocities.

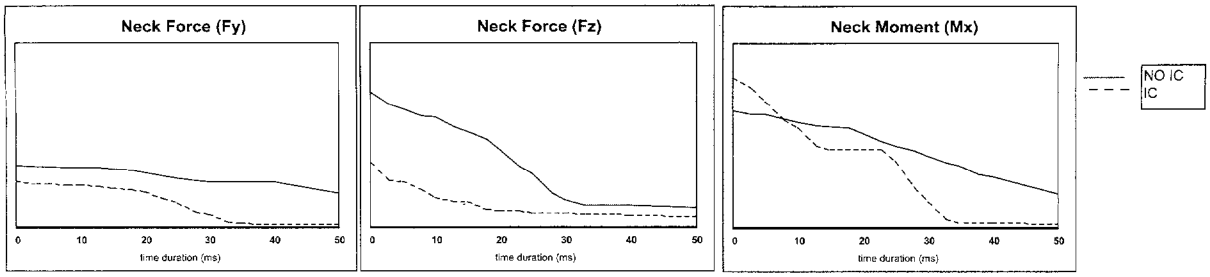

Figure 21. Neck loadings from simulated barrier sled tests with the US-SID/H3 dummy.

Table 1.
Head Angular Acceleration Results from Simulated Pole Impact with the Eurosid dummy at an Impact Velocity of 32 km/h.

	NO IC	IC
Angular acceleration around x-axis (rad/s*s)	42 500	8 200
Angular velocity around x-axis (rad/s)	39	33
Angular acceleration around z-axis (rad/s*s)	3 500	2 100
Angular velocity around z-axis (rad/s)	19	15

Computer Simulated Pole Impact

For all pressures, the HIC was below the injury criterion level of 1000. The HIC value was reduced with reduced pressure. The results indicted that further reductions in HIC could be achieved with a pressure lower than the 180 kPa used in the study (Figure 22).

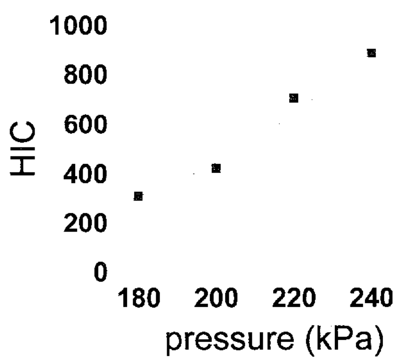

Figure 22. HIC(d) vs bag pressure.

DISCUSSION

Pole Impact Sled Test

Linear acceleration of the head - The maximum head acceleration was reduced with the IC and that was mainly due to the decreased contact force. The IC supported by the pole had much softer force-deflection characteristics than the pole itself, resulting in a much lower contact force. The IC has a thickness of 70 mm resulting in about 10 ms head contact before the head has reached its minimum distance to the pole. The velocity of the head was reduced continuously during the 10 ms penetration into the IC.

In the 28 km/h pole impact, the head velocity started to decrease (around 25 ms after car-to-pole impact) when the thorax came into contact with the side airbag. About 15 ms later, the head came into contact with the IC, and the head velocity was reduced continuously and rather smoothly, falling to zero in approximately 10 ms. Without the IC, the head velocity decreased slowly, due to the torso contact with the side airbag, but when the head came in contact with the pole, the velocity of the head decreased to zero within 1 ms, which explains the high HIC values. With the IC, the head velocity was reduced in 10 ms (Figure 23).

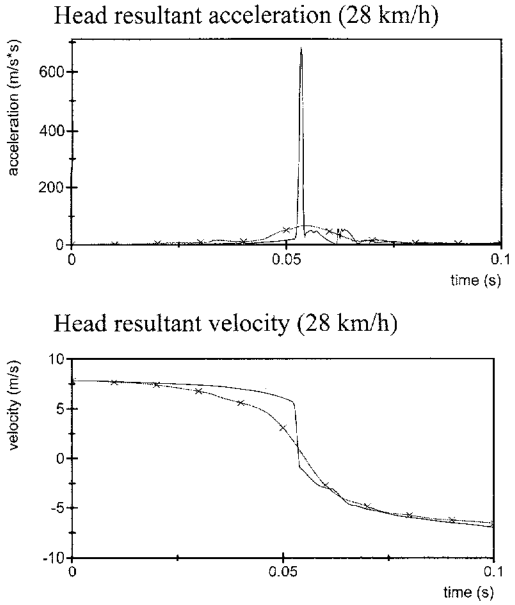

Figure 23. Head acceleration and head velocity change in pole impact sled test at 28 km/h using the EuroSid dummy, with and without the IC.

The same tendencies were shown at both impact velocities, but the dummy values were higher at 32 km/h.

The 3 ms head acceleration value increased with the use of the IC, but it was still below the recommended injury threshold (65-94% of the injury threshold of 80g FMVSS 201). The IC decreased the peak acceleration but increased the duration of the acceleration.

That Dynamic Head Protection Systems, such as the IC, offer a great potential for reduction of head injury risks is supported by NHTSA's findings, which are published in the NPRM (August 26, 1998) for Upper Interior Impact Protection in FMVSS 201.

Angular acceleration of the head - The angular acceleration and velocity around the x-axis were reduced with the IC, both in the impact direction as well as the rebound, in the simulated pole impact with the Eurosid at an impact velocity of 32 km/h (see figure 24).

A considerable reduction (80%) of the angular acceleration was found with the IC, while the angular velocity showed a smaller reduction of about 15%. Margulies et al [13] proposed a criterion tolerance for diffuse brain injury, with an angular acceleration below 4000 rad/s^2 and an angular velocity below 40 rad/s. These injury thresholds indicate a reduced risk for sustaining diffuse brain injuries with the IC.

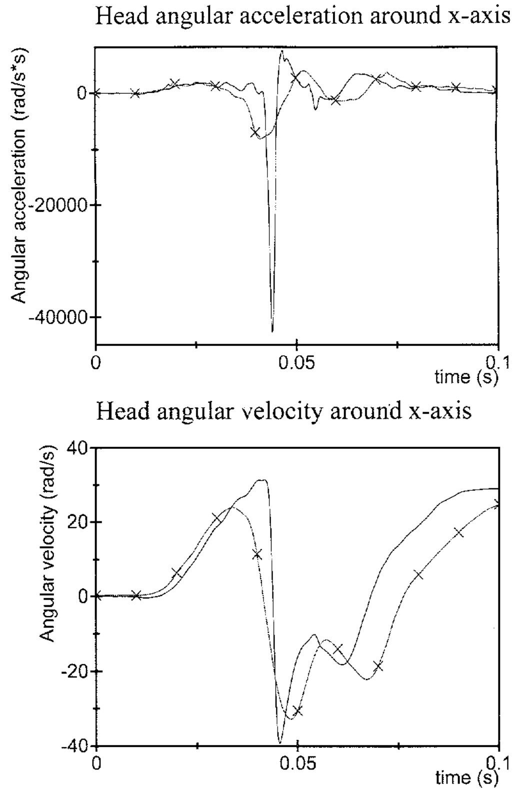

Figure 24. Head rotational motions at a pole impact 32 km/h, with the Eurosid dummy, with and without the IC.

The z-axis angular acceleration was also reduced due to the IC, about 50 %, but the amplitudes were not as high as around the x-axis. These results agree with the findings of Bohman et al. [14], that the angular acceleration around the z-axis showed a significant reduction with the IC.

Neck loading - In simulated barrier (FMVSS 214) sled tests, the neck loading as well as the head acceleration were different compared to the pole impact since there was no head impact, neither with the interior nor the exterior of the car body. Without the IC the head was partly ejected, while the head was kept inside the car with the IC. The tests were run with side thorax airbag.

There was a different pattern in the neck loading with and without the IC. The neck loading without the IC had a slightly higher lateral shear force than with the IC. The neck tension was, however, about twice as high without the IC, mainly due to the inertia loading when the head moved out of the car window. The neck loadings, with or without the IC, were below the Injury Assessment Reference Values (IARV) suggested by Mertz H., [15]. The main difference was found in the increased duration of the load without the IC, especially the lateral shear force (Figure 21).

The neck moment (Mx) was slightly higher with the IC, due to the early contact between the head and the IC, which restricted the head motion out of the window. For duration longer than 8 ms, the moment without the IC was higher than with the IC. The neck moments where compared to average values of the IARV, Mertz H., [15].

In the simulated pole impact tests at 32 km/h, the neck loadings were generally lower than in the barrier tests, except for the compression of the neck without the IC, that exceeded IARV. The neck compression was reduced 73% with the IC.

Evaluation of Possible Airbag-Induced Injuries

The IC has been tested in various ways to eliminate any kind of induced injuries. One of the test methods has focused on the out-of-position situations, (i.e. when the occupant is not properly seated). The occupant can, for instance, be leaning towards the interior side.

To evaluate these situations, tests with different occupant sizes in different occupant positions were conducted. Child dummies were also included.

No harmful values have been measured, that is, they are below the injury criteria, IARV [15].

The IC is designed so that its power decreases the further it unfolds down the side of the car. This means that smaller occupants, often children, who are more sensitive, especially in their necks, see Tarriere C. [16], will receive lighter contact with the deploying curtain.

Future Development

During the past 10 years in car development, crash safety performance has been improved a lot. In spite of this fact, there is a potential to improve the safety standards even further in the future.

For example, new sensor technologies will probably create an extended use of different safety devices. For the IC system, rollover sensors may be used to further utilize the protection potential the system offers.

CONCLUSIONS

The Inflatable Curtain is the first dynamic head protection system developed to offer improved protection for both the front and rear seat outboard positions.

The IC system specifically helps reduce the risk of serious-to-fatal head injuries, especially in side collisions with rigid and/or heavy objects. The results also indicate a reduction of head angular acceleration, thus reducing the risk of diffuse brain injuries. In side impacts, the IC keeps the head inside the car, preventing the head from hitting exterior surfaces, such as the front of an impacting vehicle

The IC also reduces the levels and durations of the various neck loadings.

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