ROOFBAG-A CONCEPT STUDY TO PROVIDE ENHANCED PROTECTION FOR HEAD AND NECK IN CASE OF ROLLOVER

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ABSTRACT

The purpose of this conceptual study is to address the increasing number of fatalities and severe injuries in vehicle rollovers. A restraint concept for reducing Head and Neck loading by hard contact with the roof of the car has been developed to reduce and/or mitigate these injuries.

The human neck is capable of sustaining higher loads when it is in flexion (e.g. the head is bent forward). Therefore, moving the occupant's head to a bent forward position using a slowly deploying airbag is proposed.

The Roofbag concept includes a slide chamber and support chamber. Together, they form a multi-chamber airbag which is mounted at the top of the seat back. The inflator has an extremely slow onset, causing the airbag to deploy in about 250ms. When the slide chamber is inflated, it positions itself behind and above the occupant's head. The support chamber pushes the slide chamber forward, causing the occupant's head to bend forward.

Three advantages for this concept have been identified: the occupant's neck can sustain higher bending loads when positioned in flexion; a cushion is positioned between the occupant's head and the roof; the survival space between the head and the roof is increased.

A series of rollover tests (SAEJ2114, Curb Trip) using HIII dummies were performed to understand and demonstrate the benefits of this concept. The results show a significant reduction in head and neck injuries when the Roofbag concept is employed. Out-of-position tests show low-to-medium level loadings.

Further potential benefit could possibly result from expanding the Roofbag concept to other applications, such as head protection for convertibles or neck protection during rear impact.

INTRODUCTION

For many years Rollover has been a growing issue. According to DOT HS 809438 [3] occupant fatalities in SUV rollovers increased dramatically nearly doubling from 1991 to 2000. For comparison the rollover fatalities in passenger cars decreased and for Pick-Up Trucks and Vans it stayed constant.

Rollover – A New Challenge in Safety

When comparing Rollover with frontal or side impact accidents we find significant differences in the following parameters:

Timing; the main injuries in a side or front impact occur at about 30 ms up to 100 ms. In a rollover the time window for injuries occurs at a time later than 500 ms after the rollover is unavoidable. Hence, the rollover event is at least a ten times slower event than a front or side impact.

Multi-Directional Kinematics; in Rollovers the motion of the occupant is multi-directional and continuing for up to 5 seconds. Hence, injury contacts are much less predictable which makes it difficult to provide appropriate protection devices. Fay and Sferco [6] show that rollovers in Europe often occur in multi impact crashes as the later event. This indicates that at the time of a rollover the seating position of the occupant is already undefined.

Human Reaction; a rollover is a comparatively slow event which allows the occupants to react to the upcoming event. According to the DOT HS 809438 report [3] about 33% to 50% of the drivers attempted to avoid the rollover by a steering maneuver which is a volitional action. There is also a natural subliminal muscle tonus which starts to activate muscle action 100 ms to 200 ms after the occupant experiences quick movements [18]. Together it shows clearly that the rollover event causes human reactions – volitionally or subliminally.

Together this explains why standard safety devices for frontal and side impact are not effective for rollover.

Rollover Types, Roof Crush and Injuries; Bedewi et al [1] show that 57% of rollovers are initiated by the ground. The second most frequent initiation sources are fixed objects at 13% and contact with another vehicle accounts only for 8%. It can be assumed that ground as initiation source results in most cases in trip-over type rollovers. This is also confirmed by Eigen [5] where single vehicle trip-over accounts for 71% of rollovers. The number of quarter turns is a significant measure which correlates in many cases with injuries. One quarter turns are less frequent – they account for about 14% to 22% for all categories of vehicles [1]. Two, three or four quarter turns are most common, with an occurrence rate of 40% to 58% [1]. The remaining cases have five and more quarter turns. Hence, it can be concluded that most rollovers have at least one roof-to-ground contact. Furthermore, Bedewi et al [1] looked into the maximum roof deformation as an indicator for head-roof associated injuries. It is shown that 37% of Head-Roof AIS3+ injuries correlate with a roof deformation of 30cm up to 45cm. Another 20% of Head-Roof AIS3+ injuries correlate with a roof deformation of 15cm up to 29cm. For comparison the FMVSS 216 regulates a maximum deformation of 12.7cm (5 inches). For belted occupants roof contact is the most common injury source: passenger car 31%, pick-up 52%, SUV 33% and van 24% [1].

Non-Ejection Injuries: Digges and Eigen [2] analyzed the different categories for rollover MAIS 3+ occupants. They found the three most dominant fractions: Belted-non-ejected (35.3%), Unbelted-non-ejected (23%) and Unbelted-totally-ejected (32.5). The other categories are 5% or less. As commonly known, the unbelted driving condition is the most dangerous - not only for rollover. To cope with the ejection issue the NHTSA [4] has done extensive ejection mitigation studies which target establishing a future safety standard. It will require a reasonable level of containment for an occupant in a rollover. Therefore, in this paper we focus on injuries of non-ejected occupants. Obviously, seat belts are very effective to avoid ejection, but they also have limitations when head-to-roof contact must be avoided. As rollovers can be such chaotic events, it can be assumed that head-to-roof contact occurs mainly because of two reasons: Firstly because of roof intrusion and secondly because the shoulder belt is slipping off and then passing the gained belt slack to the pelvis belt and hence, allowing extra movability towards the roof.

INJURY MECHANISM IN A ROLLOVER

Impact Location; Literature is packed with statistical interpretation of rollover accidents and the resulting injuries.

Head, face and neck injuries represent a significant part of rollover related AIS3+ injuries.

For these body regions, literature states that the most important injury source is the roof [9] including the roof rail.

So, there is an exigent need for an additional protection system that provides enhanced performance to protect the head, face and neck region in case of a rollover.

Biomechanics; From the biomechanical point of view, the head-neck portion is a quite complex mechanism. It includes vertebral bodies connected multi-muscularly to each other, blood vessels, intervertebral disks and the spinal cord. The head rests on top of the spine. For the head's rotation, mainly the articulation between the 2 upper vertebrae Atlas (C I) and Axis (C II) is responsible. It allows humans a physiological rotation of ±45° around the yaw axis.

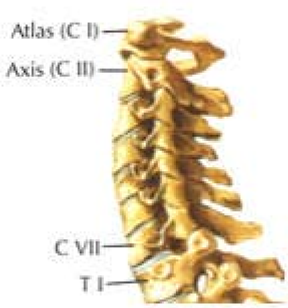

Figure 1. Cervical spine
Netter: „Atlas of human anatomy"[14].

The complete cervical spine and the atlanto-occipital junction are responsible for flexion/extension (pitch) and lateral bend (roll) as shown in Figure 2. They allow flexion of 40°, extension of -75° and a lateral bend of ±75° [22]. These multi-directional degrees of freedom and the wide ranges of physiological mobility require a fragile constitution which can be disadvantageous in the case of a rollover.

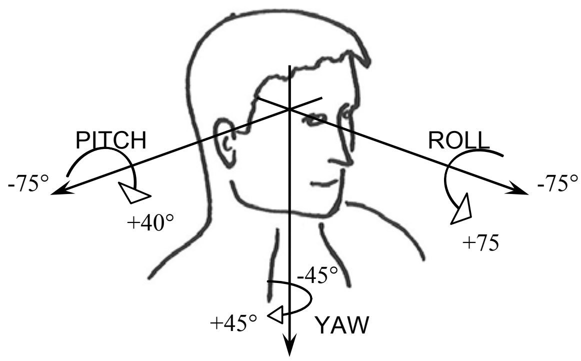

Figure 2. Axes defining physiological motions.

Injuries and Injury Mechanisms; Injuries of the cervical spine are typically caused by exceeding spinal motion limits or force limits. In case of an accident, high forces induced by the vehicle's kinematics and by the inertia of the torso and head effect serious damages. Typical injuries of the cervical spine during a rollover are mainly caused by bending, compression, tension, torque and shear of the upper spine. The injuries express themselves in wedge fractures, burst fractures and dislocations [11 and 13].

Head injuries of restrained occupants are typically caused by high velocity contacts of the head to interior parts, mainly the roof and roof rail. No matter if the roof is crushed or not and independent from the restraint use, the head's injuries are a great fraction of the injury distribution. Typical head injuries are fractures of the skullcap or serious damages of the brain, e.g. epidural hematomae.
The high risk of spinal cord and brain injuries and the consequences that arise out of these injuries like paralyzation or death is what makes rollover injuries so dangerous and expensive for the entire society.
Head-roof contact, being the main cause of head and neck injuries [9], occurs when the occupant moves out of its seat towards the roof or roof rail.
When being turned upside down, the force of the entire body mass is imposed on the head-neck complex in a mainly axial direction.
The injury mechanisms of the spine have been simulated in cadaver tests of the upper spine and head region.
Nightingale, Myers and McElhaney et al [16, 13] describe test methods for analyzing injuries of the upper spine of cadavers. A head-spine test specimen, connected to a simulated torso mass of 16 kg, is dropped from a height of 0.53m. Objective of the analyses is the influence of varying underground properties and angles.

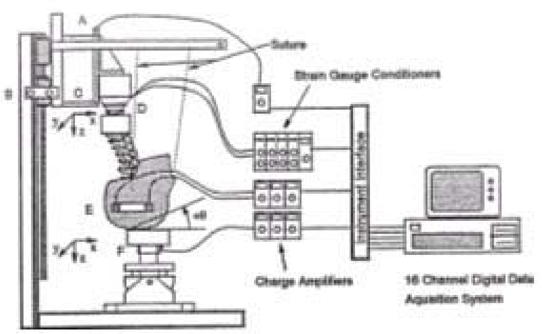

Figure 3. The dynamics of head and neck impact Myers, Nightingale: IRCOBI 1997 [13].

It has shown to be advantageous if axial and vertical loads are induced to the spine in a pitched head position (posterior head impact).
It has also shown that a soft padded surface, being able to deform upon the load of the head, can be disadvantageous under certain circumstances. It can deform, thus build a pocket that will trap the head and hinder it from flexing out of the force path.

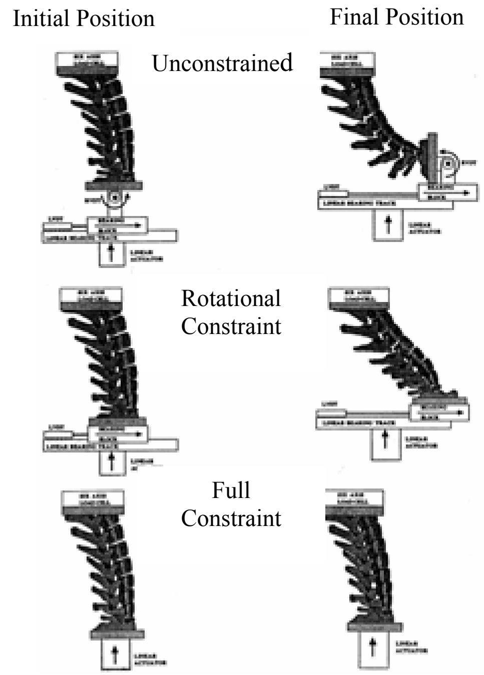

Figure 4. End condition on cervical spine McElhaney and Myers et al: SAE 912915 [11].

In "The influence of end condition on human cervical spine injury mechanism" [15], Myers and McElhaney et al. examine axial loads on the human spine.
Figure 4 shows the motion patterns of loaded cadaveric cervical spines in the above mentioned study upon different constraint types of the neck.
The axial loads and moments on the spine decrease from the fully constrained to the unconstrained type.
The unconstrained type shows how the spine reacts to an axial force if the head has the possibility to give way and flex out of the force path. The higher the constrictions on the degrees of freedom are, the higher the risk of injury.
Spinal injuries can be prevented or mitigated by reducing the compression force acting on the neck.
The unconstrained resulting motion is desirable for the upper spine in case of a rollover event.
The movement pattern is similar to the natural or physiological protection position, if it is possible for the occupant to react in a timely manner (Figure 4).
Occupants, when realizing a dangerous situation, will actively increase the head-to-roof clearance by flexing the head-neck complex as shown in Figure 4 [8].

Figure 5. Restrained occupant in a 180° roll Friedman: SAE 980212 [7].

Pocketing is an effect that leads to undesired constraints in the head's linear and rotational movability and should thus be avoided.
Pocketing can be caused by a vertical excursion of the occupant towards a soft roof liner structure. The head, being axially loaded by the neck and the effective torso mass, will dive into the soft roof liner material, thus deforming it and building a form-closed connection which reduces the head's capability to escape linear forces and rotational moments.

Roof Crush or roof intrusion worsens the situation. Injuries caused by compression forces of restrained occupants in rollovers appear to result also from an intruding roof that decreases the head-roof clearance.

The collapsing roof can also form a pocket around the head which results in an undesired motion pattern [7].

Padding on the roof during a head-roof contact has a significantly positive effect on the head injury values. Nightingale et al. [16] show that padded surfaces have a direct influence on the forces acting on the head. But padding also can be disadvantageous. By introducing padding materials, the risk of "pocketing" the head is increased as well.

The challenge is to get padding without generating a pocketing effect.

Figure 5 illustrates an occupant in a 180° roll. The differences in head-roof distance in the bent and unbent head-neck complex are apparent. On the left side, there is a high risk for injuries due to little roof clearance, axial load of the spine and only little space for padding. Since the forces of the torso weight will be transmitted to the roof nearly perpendicularly, there is also a high risk of "pocketing". On the right side, a greater head-to-roof clearance is apparent, also a posterior initiation of forces and space for padding elements. In case of rollover, the position of the right occupant is advantageous.

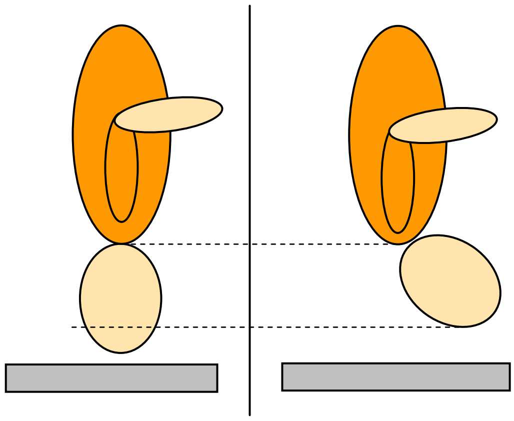

Figure 6. Increasing head-roof clearance by flexion of the neck at a 180° roll.

Summarizing the causes for head-neck injuries in a rollover event, it can be said that not only avoiding some of the mentioned dangerous conditions, but avoiding all of them must be the goal.

- Avoiding cervical injuries by not transmitting the load vertically and axially to the upper spine [17].
- Increasing the head-roof clearance by neck flexion has substantial potential for injury reduction.
- Introduction of padding in the area of head-roof contact to reduce head injuries, thus to reduce forces in axial direction, but without creating the pocketing effect.

All points together have been realized in a newly developed airbag that has high potential to reduce serious injuries of the head-neck complex in the case of a rollover event significantly.

ROOFBAG CONCEPT

The Roofbag is a multi-functional rollover protection system. It has been designed to mitigate / avoid the large fraction of head, face and upper spine injuries which in the field represent a significant part of rollover related AIS3+ injuries.

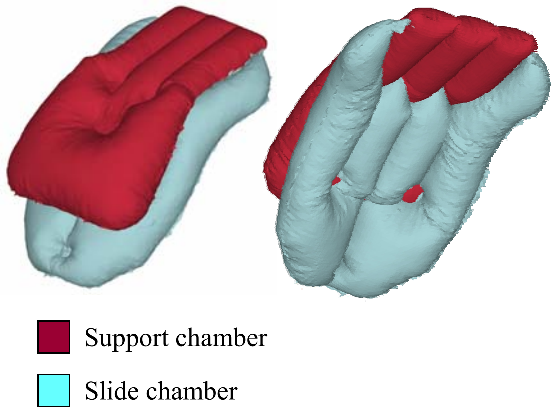

Figure 7. Roofbag simulation model.

Roofbag Cushion: The Roofbag cushion consists of two airtight chambers: A slide chamber which is directly connected to the inflator and will be filled by the inflator upon ignition of the airbag system.
A support chamber, which is attached to and riding on the slide chamber.

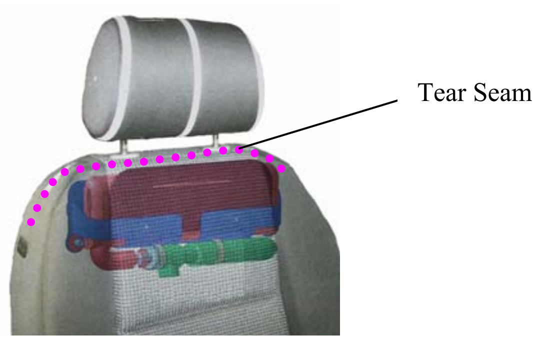

Figure 8. Roofbag assembly in seat (illustration).

Roofbag Package: The Roofbag package is mounted in the upper portion of the seat backrest. It is directly attached to the seat frame. Being deployed, it will open a tear seam applied to the seat back cover.
With its soft housing it can be implemented without disturbing the comfort function of the seat. It can be adapted to seats with an active head rest.

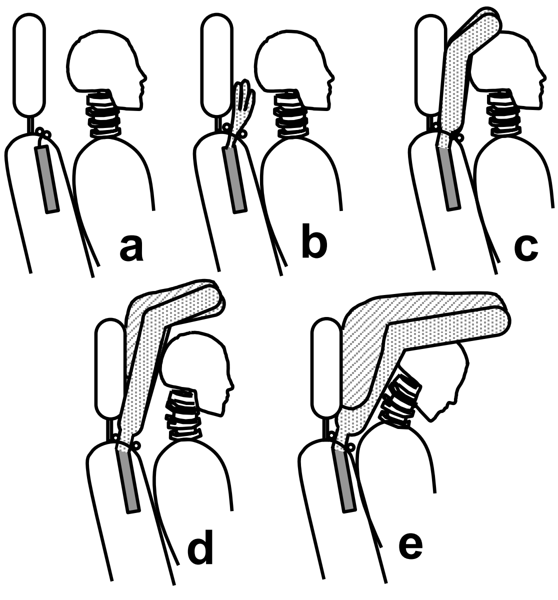

Figure 9. Roofbag function (illustration).

Roofbag Function: Different from known airbag systems, the Roofbag is designed to actively move the occupant into a "rollover-protected" position.
Upon detection of an upcoming unavoidable rollover event, the Roofbag will deploy. The slow onset inflator will open the tear seam, and deploy the slide chamber. The slide chamber (Figure 9b) with its side arms will span up the uninflated support chamber and guide it through the gap between head and head rest (Figure 9c).
The support chamber is inflated through venting ports between slide- and support chamber.

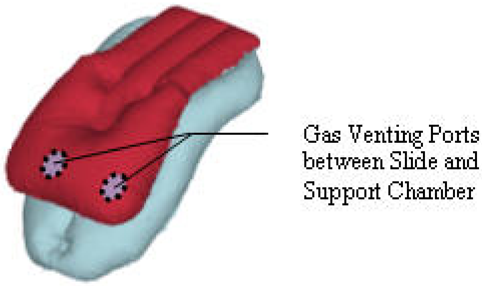

Figure 10. Gas venting ports (illustration).

Compared to the slide chamber, the support chamber is filled with a time delay.
Inflating slowly between the head rest and the slide chamber, the support chamber gently presses the occupants head into a "rollover-protected" position (Figure 9d + e).

Benefits of the "Rollover-Protected" Position:
To mitigate rollover injuries effectively, the Roofbag's rollover protection concept is threefold:

The Roofbag transforms unfavorable axial neck and spine loads into posterior loads, thus allowing the head and neck portion to escape the critical axial load path by flexing in its natural degree of freedom.
The Roofbag increases the survival space between head and roof.
The Roofbag supplies sufficient padding between head and roof structure, reducing head injuries caused by direct head-roof contact without trapping the head (pocketing effect).

Enclosing the head-neck portion from above, the Roofbag will additionally help to protect the occupants head against lateral movement.

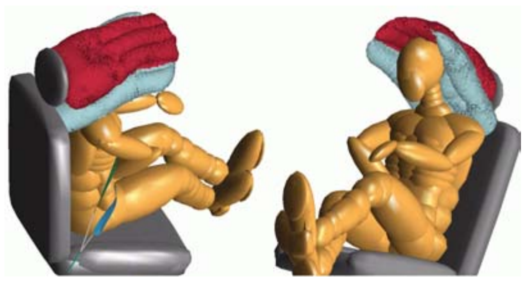

Figure 11. Roofbag CAE function testing.

<u>Roofbag Deployment:</u> Compared to other state-of-the-art side airbag systems, the Roofbag has a very low onset inflator and subsequently deploys slowly.
Its nominal time to position the cushion and also the occupant is about 400 ms [Figure 12 and 13].

This will allow deploying an airbag in the sensitive head-neck region without endangering an in position or out-of-position occupant.

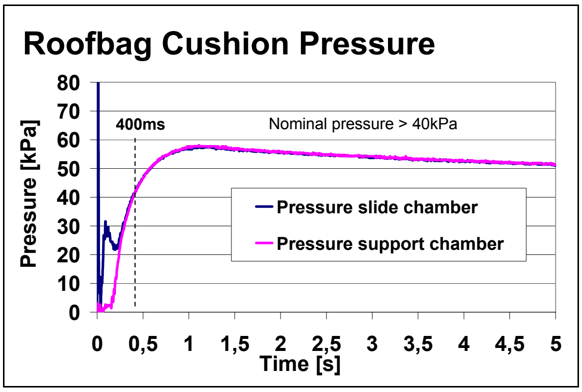

Figure 12. Roofbag RT cushion deployment pressure.

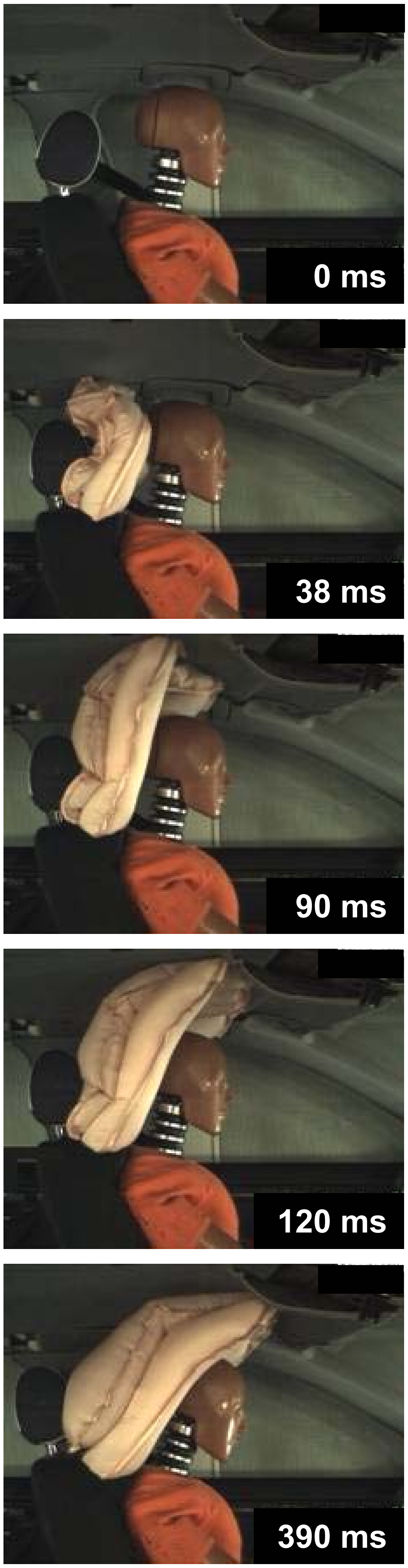

Figure 13. Roofbag deployment (50% Hybrid III).

__Dummy Neck vs. Human Neck:__
A 50 % Hybrid III dummy was used for development tests. The Hybrid III dummy, being a standard in rollover testing, has a stiffer neck compared to the human neck.
The Roofbag's flexing effect is not as visible when used with a Hybrid III dummy.
The Roofbag is far more effective in flexing a human occupants head and neck portion into a "rollover-protected" position.

Figure 14/15. Comparison human / dummy response.

__Collaboration with other Restraints:__
The Roofbag has been developed to collaborate with other occupant restraint systems.

In combination with rollover-optimized seat belts and curtain airbags, it will effectively protect the occupants head against roof and roof rail impacts and to a certain extent also against lateral head movement.

For unrestrained occupants, a benefit can be expected for rollovers, when the occupant is still in the protection area of the cushion.
Since in later rollover phases the occupant's position is likely to change drastically, an additional benefit for unrestrained occupants is uncertain.

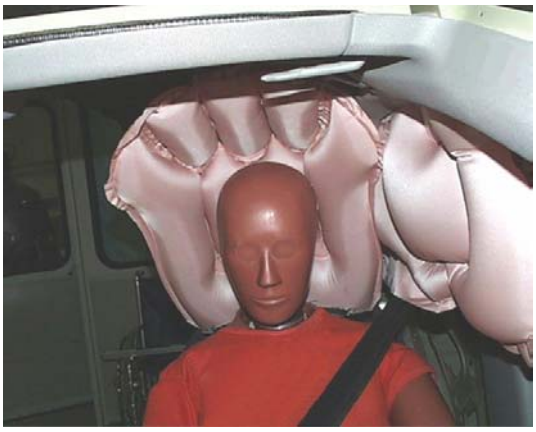

Figure 16. Combination of rollover relevant restraints.

TEST RESULTS

Pendulum Test Results

Several tests were conducted to check the performance of the developed system.
First a falling pendulum test was designed to be adequate for a first evaluation system. The aim was to simulate the kinematics between the dummy head and the intrusion of the roof.
A falling pendulum is mounted to a rigid wall and a linear guided drop plate is raised to a certain height.

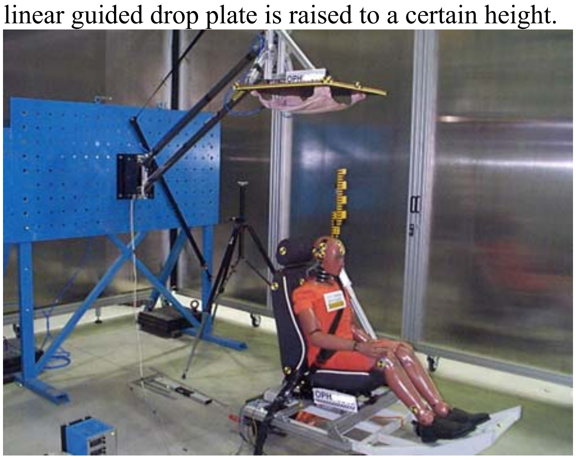

Figure 17. Fall pendulum test setup with dummy Hybrid III 50%.

The pendulum energy as result of the drop height and the mass of the drop plate was defined considering to the assumptions of the investigations by B. Myers [13]. The mass of the drop plate was defined as effective torso mass at 16 kg, the resulting energy was adjusted by the drop height and ranges up to 110 Joule.

First, a baseline test without a protection system was conducted. The pendulum performance tests were conducted with an unfolded cushion that was filled with compressed air. In parallel, the deployment behavior and the cushion folding were developed. The ideal pressure was detected by a series of pretests (see chapter roofbag concept) and defined as a target pressure of about 50 kPa.

For all following tests the Hybrid III 50% dummy was used. This dummy is regulated in the FMVSS208 rollover test and most popular in other papers and publications for rollover evaluation.

The energy of the pendulum was defined by 110 Joule (mass= 16 kg, v=4.7 m/s). The most important resulting dummy loads are shown in table 1.

Table 1.
Results of Baseline Test without Roofbag.

Dummy Load	Value
Axial compressive Neck Force	-7.6 kN
Flexion Bending Moment	28.4 Nm
Extension Bending Moment	-34.1 Nm
HIC_{15}	191
NIJ	1.3

As expected and seen in table 1 the body regions of interest were the head and the neck of the dummy.
The Injury-Assessment Reference Values for Hybrid III-Type adult Dummies (IARV) by Mertz [12] have been suggested as guidelines for assessing injury potentials associated with measurements made with Hybrid III-type 50% adult dummy. Additionally, the Neck Injury Criteria [23] (NIJ) was regarded as the limit for the neck loads. The relevant limits for the test are shown in table 2.

Table 2.
IARV Dummy Limits according to Mertz [12].

Dummy Load	Limits
Axial compressive Neck Force	-4.0 kN
Flexion Bending Moment	190 Nm
Extension Bending Moment	-57 Nm
HIC_{15}	1000
NIJ	1.0

Especially the neck compression force with -7.6 kN is nearly two times higher than the limit of -4.0 kN. The NIJ is exceeding the limit.
Several pendulum tests were done to improve and to show the performance of the system.

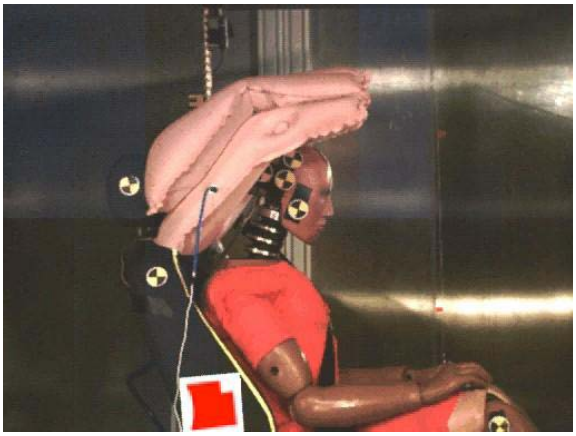

Figure 18. Fall pendulum test setup with dummy Hybrid III 50% and deployed roofbag before test.

The results of the tests are shown in table 3. The pendulum tests have shown that the roofbag is able to reduce the critical axial neck compression force from -7.6 kN to an uncritical -1.25 kN. The flexion neck moment is reduced from 28.4 Nm to 11.3 Nm. The extension neck moment virtually stays the same and has to be observed for further tests, also considering the limit of -57 Nm. Beside the axial neck compression force there is also an impressive improvement regarding the HIC (191 w/o roofbag, ≈0 with roofbag) and the NIJ reduction (1.3 w/o roofbag, 0.3 with roofbag).
The dummy sensor curves are listed in the Appendix (see Appendix Figure A1 for neck loads and Figure A2 for resultant head acceleration).

Table 3.
Results of Performance Pendulum Test with and without Roofbag.

Dummy Load	Limits	Baseline	With Roofbag
Axial compr. Neck Force	-4.0 kN	-7.6 kN	-1.25 kN
Flexion Moment	190 Nm	28.4 Nm	11.3 Nm
Extension Moment	-57 Nm	-34.1 Nm	-37.9 Nm
HIC_{15}	1000	191	≈ 0
NIJ	1.0	1.3	0.3

Rollover Test Results

Two standard rollover crash tests according to the FMVSS208 have been confirmed with 2 Hybrid III 50% dummies in the front seat row (driver and passenger side).

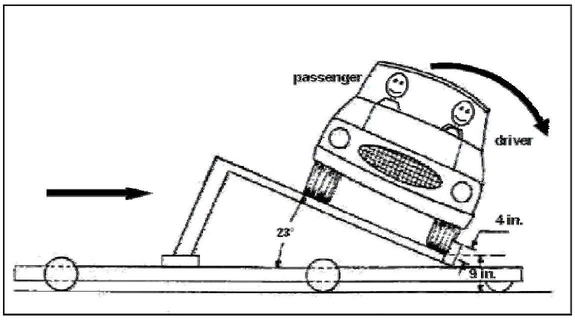

Figure 19. Rollover test setup according to FMVSS208.

The vehicle was a current popular European passenger car. The first car was equipped without additional safety devices; the second car was equipped with the roofbag system. During the rollover all dummy signals were recorded to document the dummy loads and the performance of the roofbag.
Figure 20 shows the dummy on the driver side with the deployed roofbag module in test position.

Figure 20. H III 50% dummy on driver side with deployed roofbag in test position.

Table 4 shows the dummy loads on the driver side, table 5 shows the results on the passenger side dummy in relation to the limits.

Table 4.
Dummy Loads on the Driver Side.

Driver Position			
Dummy Load	**Limits**	**Baseline**	**With Roofbag**
Axial compr. Neck Force	-4.0 kN	-2.4 kN	-0.85 kN
Flexion Moment	190 Nm	8.4 Nm	12.1 Nm
Extension Moment	-57 Nm	-9.1 Nm	-18.1 Nm
HIC_{36}	1000	27.4	20
NIJ	1.0	0.4	0.26

Table 5.
Dummy Loads on the Passenger Side.

Passenger Position			
Dummy Load	**Limits**	**Baseline**	**With Roofbag**
Axial compr. Neck Force	-4.0 kN	-12.0 kN	-0.80 kN
Flexion Moment	190 Nm	53.2 Nm	20.1 Nm
Extension Moment	-57 Nm	-12.7 Nm	-19.4 Nm
HIC_{36}	1000	102	72
NIJ	1.0	2.07	0.27

A comparison of the different results on each individual value shows the tendency that the dummy loads on the passenger side are higher compared to the values on the driver side. The reason is the rotation of the vehicle during the rollover. The driver is on the "near side " to the ground and below the axis of rotation of the vehicle; the passenger is so called " far side" and has much more energy of rotation during the first roll. The performance of the roofbag as seen in the pendulum tests is confirmed by the results in table 4 and table 5.
The most impressive reduction is seen on the passenger side. The compression neck force reduces from -12.0 kN (w/o roofbag) to 0.8 kN (with roofbag) and the reduction of the NIJ from 2.07 to 0.27(with roofbag). The other dummy loads cannot be improved in a clear way, but those values are not critical. The reduction of the compression neck force and the NIJ is the result of the changed kinematics of the dummy. The reason for this change of kinematics is the influence of the roofbag that forces the dummy into the rollover protected position.
The passenger dummy sensor curves are listed in the Appendix (see Appendix Figure B1 for neck loads and Figure B2 for resultant head acceleration).

Out-of-position Tests

Another important point beside the performance during a crash is the low aggressiveness in out-of-position situations. Out-of-position tests are defined for frontal airbags [24] and side airbags [10]. New test positions were designed, in accordance with the known out-of-position setups. The following dummies were chosen to be important: Hybrid III 5% female, Hybrid III 6 year old dummy, Hybrid III 3 year old dummy.
Table 6 shows the defined dummy positions.

Table 6.
Out-of-position Dummy Positions.

Dummy	Position
Hybrid III 5% Female	Sleeping Position
Hybrid III 6 year Child	Rearward facing kneeling on Seat
	Forward facing on Cube
Hybrid III 3 year Child	Forehead on Tear Seam
	Forward facing on Booster Cube

The positions were defined to produce the worst possible interaction between dummy and roofbag module. Nevertheless the positions should not be too unrealistic; all tests were conducted with head rest in the seat back and with one type of seat.
Limit values for the head, neck and thorax were defined, to have a guideline and to assess the results. The limits for the relevant dummies were taken from the TWG [10] limits for side airbags. Those relevant limits are shown in table C1 and C2 in the Appendix. The TWG [10] distinguishes between reference values, which are established and significant and the research values, which have to be considered for further developments and have a biomechanical and scientific basis. For the Roofbag study, all values were taken to be equivalently important.
Figure 21 and Figure 22 show typical newly defined testing positions.

Figure 21. Out-of-position configuration "sleeping female" for Hybrid III female dummy.

Figure 22. Out-of-position configuration "forehead on tear seam" for Hybrid III 3 year old child dummy.

The results of the tests are shown in table C3 in the Appendix, in each case the 5 highest values were presented as percentage of the limit values (table C1 and table C2 in the Appendix). All tests showed acceptable injury risks for dummies out-of position.
Only one of the conducted tests has a maximum dummy load above 40% relative to the limit, which is the position rearward kneeling on booster (see Figure 23).

Figure 23. Out-of-position configuration "rearward kneeling on booster" for Hybrid III 6 year old child dummy.

As seen in table C3 (Appendix) there were two dummy loads above 40%, the highest load is the extension moment in the lower neck with 74% followed by the NIJ with 70%. Both loads are directly induced by the deploying roofbag, the cushion strikes directly to the dummy head with a load path into the direction of the center of gravity of the head. The booster used in this configuration caused highest loads on the head, so higher loads in variations of this position were not expected, in other words, this seems to be the worst case. Nearly all test positions can be rated as uncritical. Nevertheless there are parameters like, the finish of the tear seam and the cover fabric of the back rest which can directly influence the out-of-position performance. Thus the out-of-position performance should be checked continuously in parallel with the further development or, while changing the vehicle surrounding.

DISCUSSION

Seatbelt Use vs. Head-to-Roof Contact

Among other topics NHTSA has declared Rollover and also seatbelt use as top priority. Increasing seatbelt use will reduce injuries for frontal and side impacts and also for rollover. For rollover the most important benefit will be a huge reduction in ejections. But even if seatbelts were to be used by 100% of all vehicle occupants there would still be a considerable number of injuries [2]. Up-to-date seatbelts are equipped with pretensioners and energy absorbing devices which are designed for frontal impact performance. In case of a rollover the pretensioner will reduce the belt slack and hence the mobility of the occupant towards the roof will be limited. Despite up-to-date seatbelts there is still a risk for head-to-roof contact. First, we have to consider that in the chaotic event of a rollover the occupant may slip out of the shoulder belt and hence gain additional mobility towards the roof. Second, there are considerable numbers of vehicles that experience a large roof intrusion during a rollover which causes a high injury risk regardless of seatbelt use. Together it can be seen that head-to-roof contacts can not be avoided in a rollover. Therefore, we need safety devices for rollovers which provide safety beyond seatbelts. The target is to avoid Head-to-Roof contact. The roofbag concept has shown its capability to do so.

Ejection Mitigation vs. Head-to-Roof Contact

Injury field statistics show that in many cases occupants were not belted when experiencing a rollover. Subsequently many of those occupants were ejected from the vehicle and seriously injured. Currently, the injuries caused by total or partial ejection outnumber the other injuries. Hence ejection must be avoided. NHTSA and industry are putting high priority on pursuing advanced restraints which prevent ejection through the side window. Only after such advanced ejection mitigation restraints are introduced to the fleet should we think about the second priority which is to avoid head-to-roof contact. As seen from the shown test results a concept like the roofbag will be highly beneficial.

Dummy (HIII vs. ESII)

Throughout the roofbag concept study the Hybrid III dummies were used (50%; 5%; 6year old and 3 year old). However it can be argued that this is not a suitable dummy for Rollover testing. The ESII dummy or WorldSID would have been a better choice for lateral injuries. A RID (Rear Impact Dummy) could have been a better predictor when it comes to neck and spine injuries. To enlarge the testing program to those additional dummies the time and finance budget would have been multiplied several times. Therefore, it was decided to focus on an evaluation program around the Hybrid III family. The results provided show the high potential of the roofbag concept. If we were to consider a mass production close application of the roofbag concept, the roofbag will need further detailed evaluation and possibly more optimization.

Restraint Performance beyond Rollover

All evaluations which were done were focused on rollover protection. When deployed - the roofbag is located between the head rest of the seat and the head of an occupant. This makes the roofbag concept a potential candidate to reduce rear impact induced injuries. At a timing of approx. 40 ms the roofbag fills already the gap between the head rest and the occupants head. At this timing the pressure inside the roofbag is above 20 kPa. It is yet to be evaluated how effective the roofbag concept could be used in case of a rear impact situation. If we can define a positive balance between rear impact vs. rollover and cost vs. benefit - then the roofbag concept will earn additional credit points for implementation.

CONCLUSIONS

The roofbag concept is a brand new idea on how to reduce head and neck injuries which are caused by head-to-roof contacts. From biomechanics we learn how to bring the occupant into the best “rollover-protected” position (i.e. bending the occupants head and neck actively forward). Deployment tests and pendulum tests show the basic performance and benefit. The pendulum tests show the following drastic injury reductions (100% are equal to limit value):

- Axial compression neck forces were reduced by 158%
- Neck Flexion Moment were reduce by 9%
- HIC was reduced to from 191 to ≈ 0
- NIJ was reduced by 100%

FMVSS 208 rollover tests were conducted to evaluate the dynamic performance. Different benefit values could be achieved for driver and passenger occupants. For the driver (near-side seating position) the following was achieved:

- Axial compression neck forces were reduced by 38%
- The flexion moment was increased from 8.4 Nm to 12.1 Nm. This increase is not critical at all since the limit is set at 190 Nm.
- The extension moment was increased from -9.1 Nm to -18.1 Nm. Again this is not critical as the limit is set at -57 Nm.
- The HIC was reduced from 27.4 to 20

- NIC was reduced by 14% to a uncritical 0.26

The benefit for the passenger side occupant (far-side seating position) was more significant. This was not a surprising result as this seating position usually experiences higher rotational forces. The following was achieved:

- Axial compression neck forces were reduced by 280%
- The flexion moment was reduced by 17%
- The extension moment was increased from -12.7 Nm to -19.4 Nm. This is not critical as the limit is set at -57 Nm.
- The HIC was reduced from 102 to 72
- NIC was reduced by 180% to a uncritical 0.27

Finally tests were done to evaluate the potential risks for in or out-of-position seating situations. These evaluations show no significant injury risk for dummies in-position and acceptable injury risks for dummies out-of-position.

In summary the effective use of the roofbag concept was shown in various conditions. Further efforts will be needed to reduce serious and fatal injuries in case of rollovers. Also efforts will be beneficial which direct to technologies and consumer education to avoid rollovers as a whole.

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APPENDIX

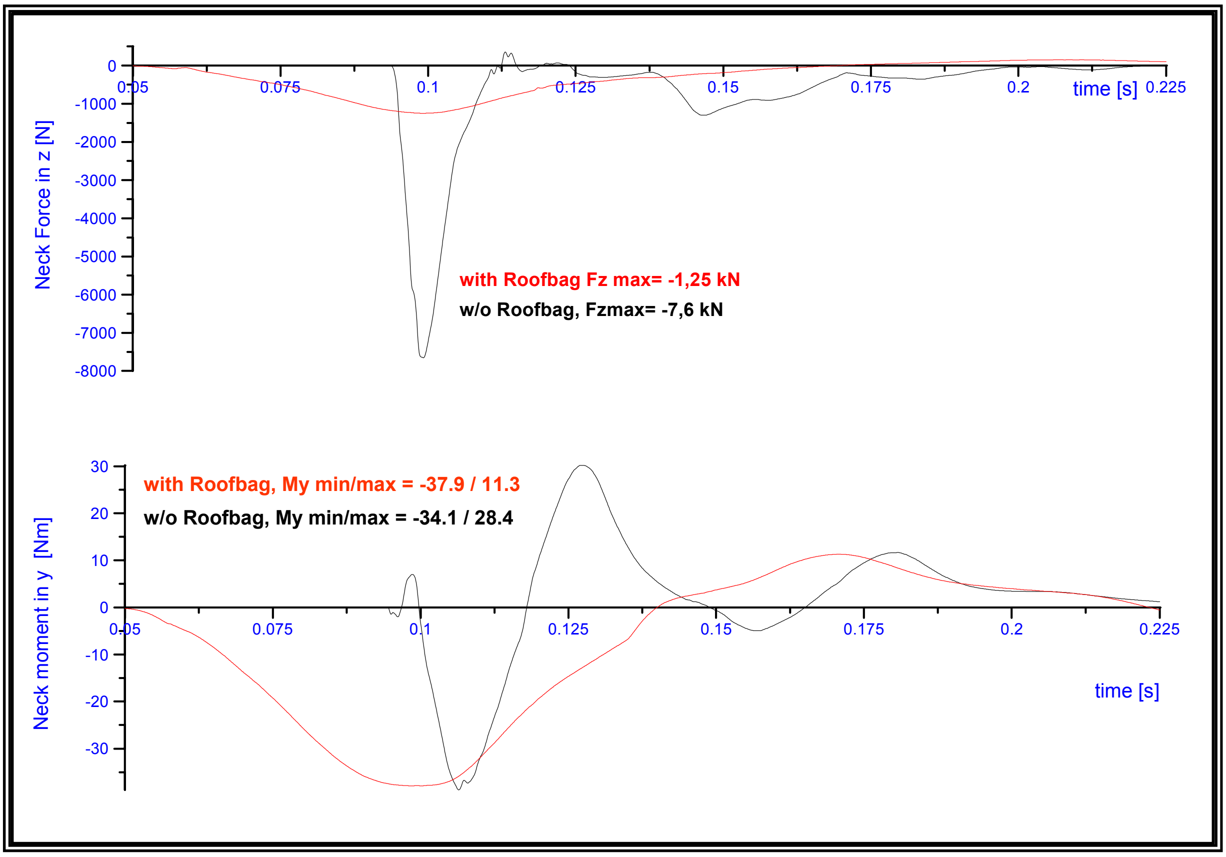

Figure A1. Comparison of neck force and neck moment in pendulum tests with and without roofbag.

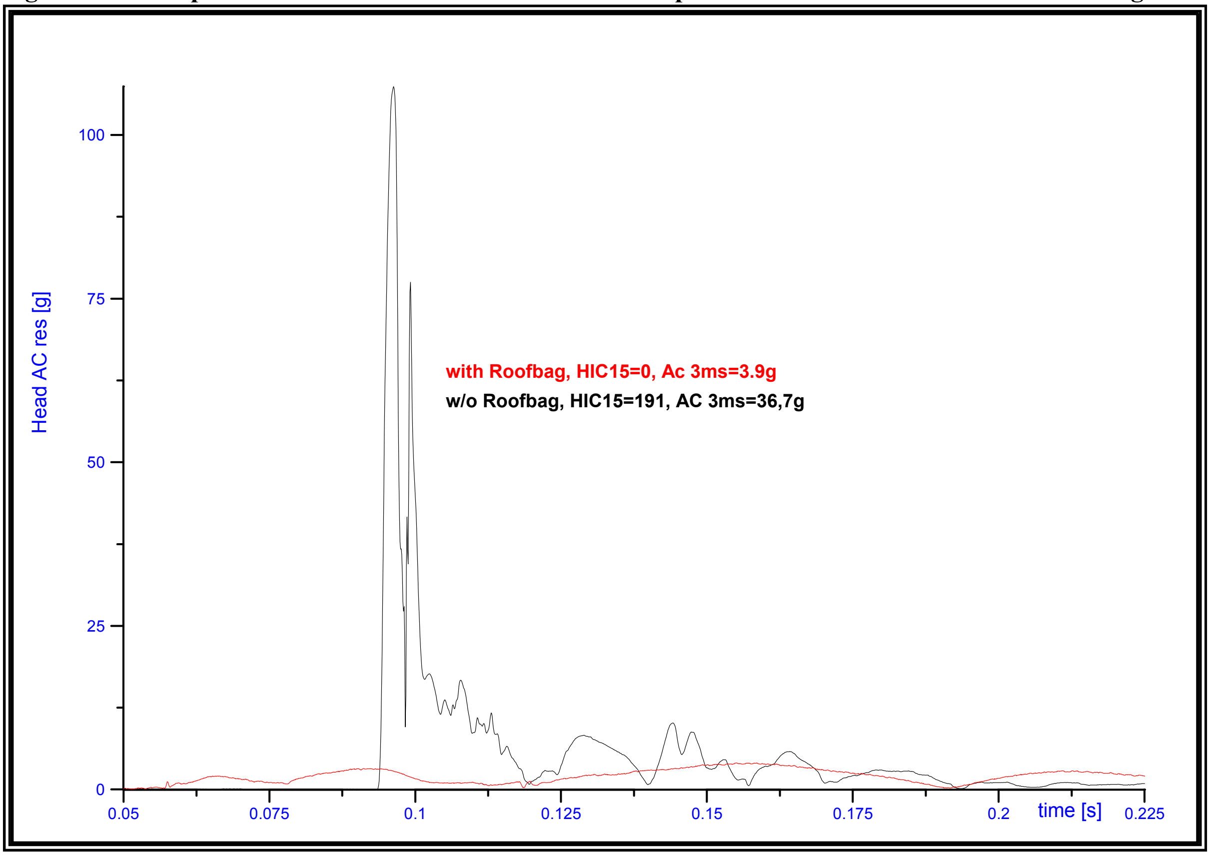

Figure A2. Comparison of resultant head acceleration in pendulum tests with and without roofbag.

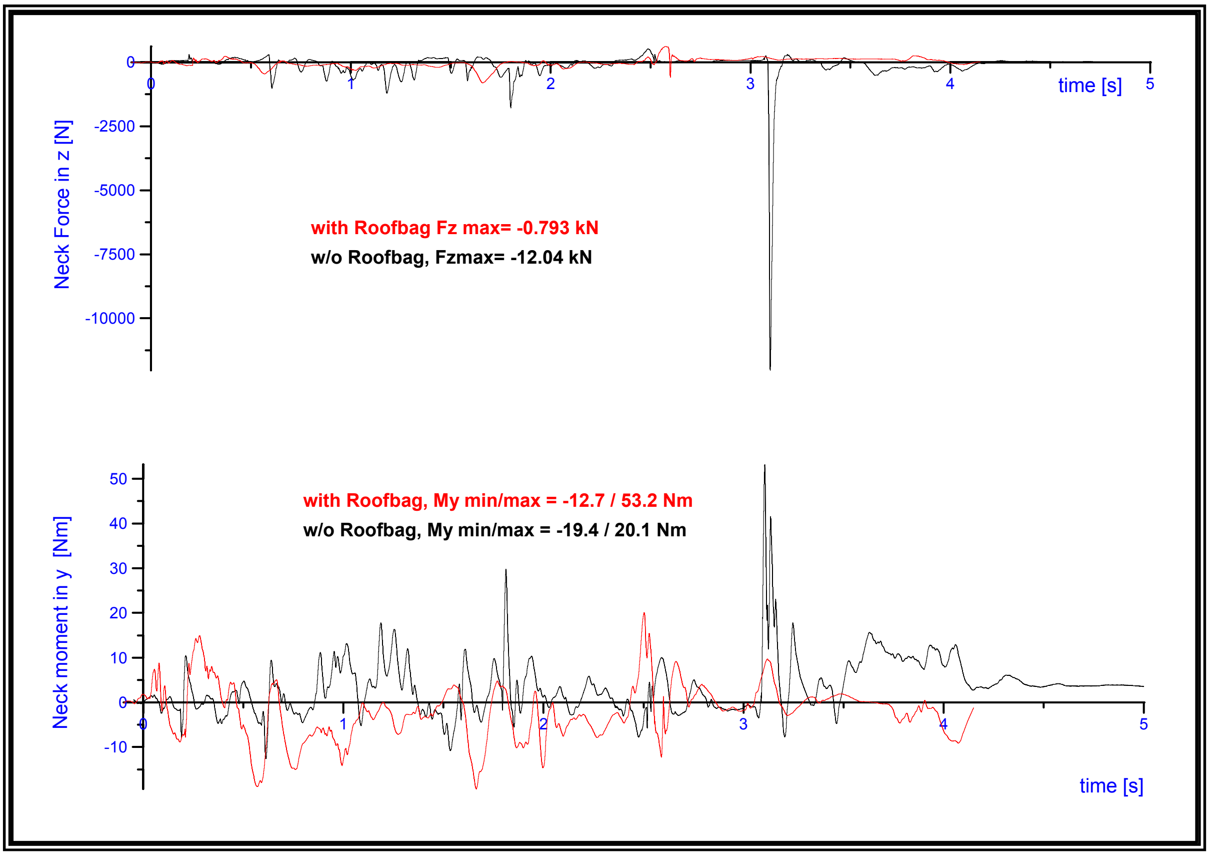

Figure B1. Comparison of neck force and neck moment in FMVSS208 rollover test with and without roofbag, passenger side.

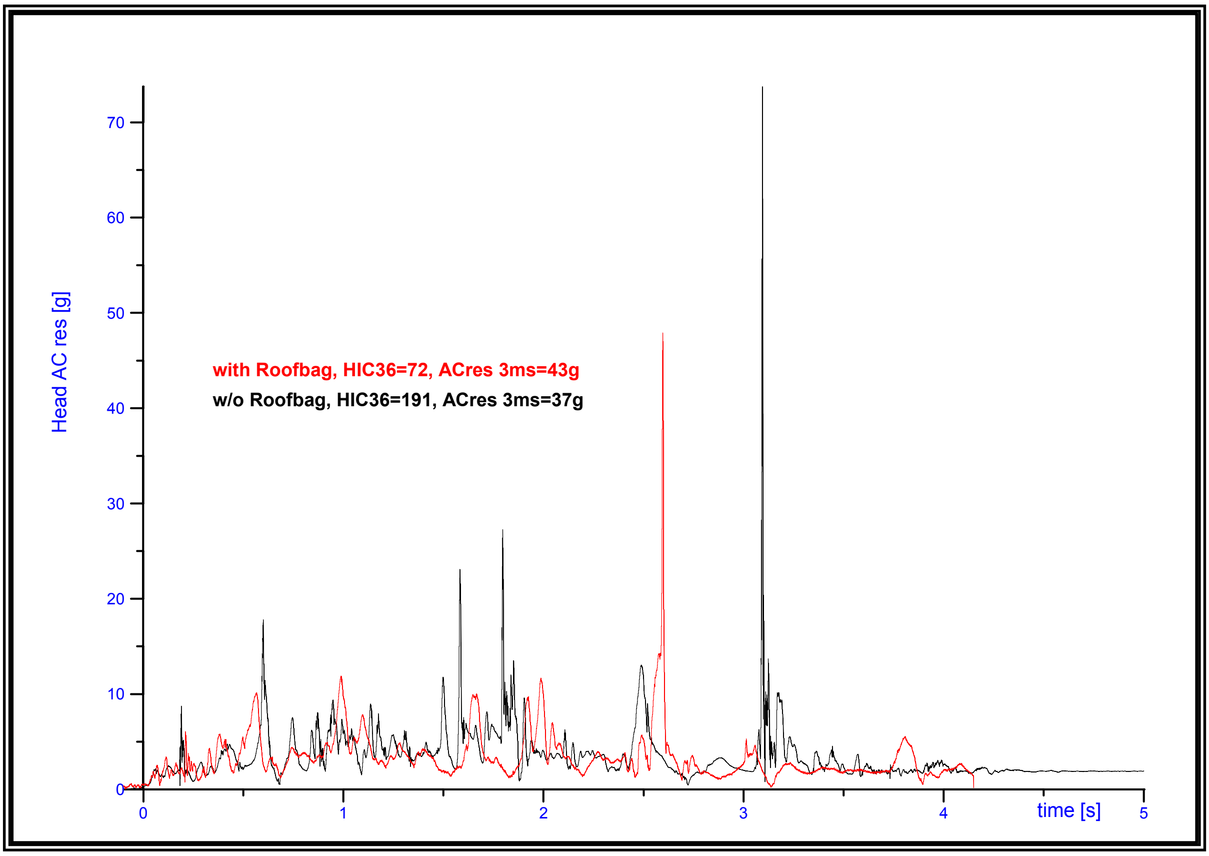

Figure B2. Comparison of resultant head acceleration in FMVSS208 rollover test with and without roofbag, passenger side.

Table C1.
Dummy Injury Reference Values for Out-of-position Testing [54].

Dummy Injury Reference Values for Out-of-Position Testing of Side Airbags			
	Dummy		
Body Region/Injury Measure	**Hybrid III 3-Year-Old Child**	**Hybrid III 6-Year-Old Child**	**Hybrid III Small Female**
Head			
15 ms HIC	570	723	779
Upper Neck			
N_{ij}	1	1	1
Intercepts			
F_T (N)	2120	2800	3880
F_C (N)	2120	2800	3880
M_F (Nm)	68	93	155
M_E (Nm)	27	37	61
Tension (N)	1130	1490	2070
Compression (N)	1380	1820	2520
Thorax			
Deflection (mm)	36	40	—
Deflection rate (m/s)	8.0	8.5	—

Table C2.
Dummy Injury Research Values for Neck and Thorax for Out-of-position Testing [54].

Dummy Injury Research Values for Out-of-Position Testing of Side Airbags			
	Dummy		
Body Region/Injury Measure	**Hybrid III 3-Year-Old Child**	**Hybrid III 6-Year-Old Child**	**Hybrid III Small Female**
Upper Neck			
Lateral moment (Nm)	30	42	67
Twist moment (Nm)	17	24	39
Lower Neck			
Flexion moment (Nm)	83	119	190
Extension moment (Nm)	34	48	77
Lateral moment (Nm)	60	84	134
Twist moment (Nm)	17	24	39
Tension (N)	1130	1490	2070
Compression (N)	1380	1820	2520
Thorax			
Spine acceleration (max g, 3 ms)	55	60	—

Table C3.
Relevant Results of the Out-of-position Tests.

picture	dummy	position	belted	remarks	max percentage of limit values		comment
	HIII 3 year old child	forward facing, on booster cube high	no	neck in front of head rest	extension moment low. neck upper neck NIJ thorax spine 01 (max ac 3ms) upper neck twist moment thorax chest04 (max ac 3ms)	37% 27% 25% 20% 18%	injury values are on a low level
	HIII 3 year old child	rearward facing,kneeing on booster (forehead on tear seam)	no	face touching back rest over cushion outlet	upper neck NIJ lower neck extension moment thorax spine 01 (max ac 3ms) upper neck compression thorax chest04 (max ac 3ms)	28% 27% 15% 12% 11%	injury values are on a low level
	HIII 6 year old child	rearward kneeing on booster, arms on head rest	no	face touching back rest over cushion outlet	lower neck extension moment upper neck NIJ upper neck tension lower neck tension lower neck twist moment	74% 70% 32% 28% 26%	direct deployment into dummies face, injury values are on an acceptable level considering the seating position
	HIII 6 year old child	forward facing, on booster cube	no	neck close to cushion outlet	lower neck extension moment upper neck twist moment lower neck twist moment upper neck NIJ lower neck flexion moment	33% 27% 26% 24% 21%	injury values are on a low level
	HIII 5% female	angle of backrest +60°	no	lying on back rest, neck close to cushion outlet	upper neck extension moment upper neck NIJ upper neck flexion moment upper neck compression upper neck tension	26% 14% 8% 5% 4%	injury values are on a low level