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Investigation of Restraint Function on Male and Female Occupants in Rollover Events

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ABSTRACT

Factors influencing neck loading in rollover events were identified in a series of spit tests where vehicles were inverted. Drivers included both male and female human volunteers, as well as seated standard and standing pedestrian 50th percentile anthropomorphic dummies. The passenger sides of the vehicles were rotated down first, simulating the most dangerous rotation for the driver, a far-side roll. The variables investigated during the spit tests included body shape, pre-roll body position and vertical seat velocity. Conditions causing shoulder belt webbing to pass through to the lap belt were investigated together with the corresponding body kinematics. Early in the far-side rolls, the belt tended to slip off the shoulder and the slack was immediately passed through to the lap belt, increasing body excursion toward the roof. An alert position (i.e. sitting more upright prior to the roll) increased the body excursion in the roll and, correspondingly, the risk of neck injury. Chest geometry and compressibility caused some women to experience excessive motion toward the roof, increasing their risk of neck injury. Neither dummy adequately simulated the excursions experienced by the volunteers. Latch plates that restricted webbing pass-through to the lap belt reduced the body excursion and thus, provided better neck protection. Computer simulations using the MADYMO occupant simulator program were also performed to study the dynamic interaction of the head, torso, and roof during contact with the ground, a study which was not possible using volunteers.

INTRODUCTION

Rollover events continue to cause a large number of serious and fatal injuries. In fact, the risk of serious or fatal injury is greater in a rollover than in any other crash mode.[1,2] Many of these serious injuries and deaths result from complete or partial ejection. However, even properly-restrained occupants who remain within the vehicle are at risk and sustain paralyzing injuries. Belt restraints do not guarantee protection. This paper identifies some important risk factors affecting restrained occupants who remain within the vehicle in a rollover event.

In a roof-to-ground and then head-to-roof contact, the roof stops the head, but the thorax continues toward the head, compressing the cervical spine. Typical injuries sustained from head-to-roof contact include vertebral body burst and wedge fractures, facet dislocations, and subluxations, as well as transverse and spinous process fractures. The neck injury mechanisms include flexion-compression, lateral bending with compression, and extension-compression. In some rolls, loading on the neck may start as pure compression, but as the loading continues and the cervical spine failure is initiated, the neck can be forcefully rotated in forward or lateral flexion or extension.

These spinal injuries can be prevented or mitigated by reducing the compression force acting on the neck. This is accomplished by reducing the momentum of the thorax toward the head. The lap belt is the primary restraint for the thorax in the vertical direction. However, some amount of vertical body motion occurs before the lap belt tightens on the hips or thighs and the restraining action begins. The objective of this study was to determine the factors influencing the effectiveness of the restraint system in limiting vertical body motion toward the roof.

Other researchers have used spit tests or devices that rotated a human surrogate or anthropomorphic test dummy (ATD) upside down to study the excursion of the head toward the roof in rollover events.[3,4,5,6] Reduction in head excursion due to seat belt angle and length was studied by Moffatt, et al. and Arndt, et al. Pywell, et al. found that pretensioners acting on the lap belt significantly limit the vertical motion of the occupant. However, activation of the pretensioner requires an initiating event or impact, and rollovers frequently have no such event. Rains, et al. reported less excursion with an inflatable torso belt. But inflation also requires an initiating event. Head excursion of human volunteers was investigated by Moffatt and Arndt. Arndt used only a lap belt and Moffatt simulated only near-side rolls. In this study by Biodynamics Engineering, Inc. (BEI), the volunteers were on the opposite side (far-side), the side where occupants have the greatest vertical inverted drop in a rollover event and the greatest risk of neck injury.

The unique risks to women in rollovers have been ignored. Arndt had one female surrogate but because only a lap belt was used, the effect of pass-through as a function of female body shape and compressibility could not be determined. In the study reported here, emphasis is on women's response in rollover events. Women of various sizes served as surrogates in the study. This paper identifies some restraint problems associated with the female body shape.

METHODS

Quasistatic spit test data, obtained from human surrogates, was combined with computer simulations of dynamic vertical body motion. Human surrogates cannot be subjected to the vertical drops that occur in a rollover, but they do help identify the interaction with the restraint system. The surrogate data is also used to identify injury risk related to initial body position, sex, and body shape.

SPIT TESTS PROCEDURE

In the spit tests, the following conditions were investigated.

- An alert position of the driver (i.e., a more upright seated position)
- Pass-through versus cinching latch plates
- Dummy versus human response
- Pedestrian dummy versus seated dummy response
- Male versus female response
- Torso belt off shoulder in the inverted position
- Chest geometry variations on response

A square was cut out of the roof of each vehicle to allow the occupant's head to move through the roof. Surrogate occupants wore a separate safety harness to protect them from falling to the ground if the vehicle restraint system failed or they slipped out of the lap belt. The initial tests revealed that the more upright alert position resulted in greater vertical excursion of the surrogates. To investigate the worst condition, all human surrogate drivers were seated upright in the seat, simulating an alert position. Test subjects' heights and weights are listed in Table 1.

Table 1. Exemplar Occupant and Dummy Anthropometry

Surrogate -- Description	Seated Height (cm)	Weight (kg)	Chest Circum-ference (cm)
1 – Slim Female	86.4	56.7	99.1
2 – Average Male	93.7	72.6	90.2
3 -- Short Female	82.6	47.6	88.9
4 – Short Male	76.2	61.2	98.4
5 – Average Female	83.8	68.0	107.3
6 – 50th percentile Hybrid III, std. pelvis	88.4	76.2	98.6
7 – 50th percentile Hybrid III, ped. pelvis	88.4	76.2	98.6

Spit tests were also performed with anthropomorphic dummies to identify differences between dummy and human responses. Two different Hybrid III dummies were used, one with a standard seated pelvis (Surrogate 6) and the other with a pedestrian standing pelvis (Surrogate 7). The seated pelvis maintains the typical seated angle between the pelvis and the simulated femurs, in effect a frozen hip joint. The pedestrian pelvis allows motion at the hip joint.

In each test, the subjects were rotated through 360 degrees. Their head and shoulder positions, relative to the roof at 0 and 180 degrees, were either measured during the test or obtained from test videotapes. Vertical scales mounted on the roof structure were used to determine the head position. When the vehicle was inverted, the shoulder belt was allowed to slip off. Four video cameras recorded the driver's motion from different directions, and a fifth video camera recorded travel of the shoulder belt through the latch plate.

Spit tests were performed using both the pass-through latch plate and the cinching latch plate on all test subjects. The geometry of the three-point restraint system was not altered and the webbing was the same in all tests reported here in.

In the spit tests, the shoulder belt easily slipped off of the volunteers' shoulders. Only by active efforts on the part of the volunteers (i.e., moving their arms forward toward the steering wheel or rotating their left shoulders forward) could the shoulder belt slippage be prevented. Since the dummies could not prevent the belt from slipping off of the shoulder, all tests resulted in such belt slippage. Also, in a far-side trip, the body experiences inboard acceleration, which tends to move the torso inboard, away from the shoulder belt. It is not uncommon to see the dummy's shoulder slip out of the shoulder belt in a rollover test initiated by a far-side trip. Cooperrider, et al. reported lateral decelerations of 1.23 g's at trip in their rollover tests.[7]

SPIT TESTS RESULTS

In the spit tests with the pass-through latch plate, slack that developed as a result of the belt slipping from the shoulder immediately passed through to the lap belt, Figures 1 and 3. This increased lap belt length resulted in greater head excursion. In spit tests with the cinching latch plate, which allowed no pass-through, much less head and thorax excursion resulted, Figures 2 and 4.

Figure 1. Surrogate 1 using pass-through latch plate.

Figure 2. Surrogate 1 using belt with cinching latch plate.

Figure 3. Surrogate 2 using pass-through latch plate.

Figure 4. Surrogate 2 using belt with cinching latch plate.

Head and shoulder displacements for pass-through and the cinching latch plates are compared in Table 2. Figure 5 shows head displacements in a bar chart.

Table 2. Head and shoulder displacements.

Head Displacement (cm)

Surrogate	Latch Plate	
	Cinching	Pass-Through
1 - Slim Female	15.2	22.9
2 - Average Male	8.9	24.1
3 - Short Female	11.5	26.7
4 - Short Male	10.2	22.9
5 - Average Female	11.5	27.9
6 - Standard Dummy	4.8	6.6
7 - Pedestrian Dummy	2.5	8.6

Shoulder Displacement (cm)

Surrogate	Latch Plate	
	Cinching	Pass-Through
1 - Slim Female	12.7	22.9
2 - Average Male	20.3	31.8
3 - Short Female	11.4	22.9
4 - Short Male	15.2	26
5 - Average Female	22.8	36.8
6 - Standard Dummy	9.9	13
7 - Pedestrian Dummy	8.9	13.5

Body shape is a major factor affecting the length of belt passing through the latch plate. Some women's breasts positioned the shoulder belt several inches away from the sternum. This increased the slack passed through to the lap belt when the belt slipped off of the left shoulder and breast. As a result, Surrogate 5 experienced the greatest head excursion and thus, would be more at risk in a rollover than the male surrogates and some of the small female surrogates.

In the spit tests where the pass-through latch plate was used, the difference in volunteer head position between 0 and 180 degrees (upright to upside-down) was between 22.9 and 27.9 cm. That is, their heads moved 22.9 and 27.9 cm toward the roof and, in all cases, passed through the roof opening. Their shoulders also moved toward the roof. Differences in shoulder position when the vehicle was inverted varied from 22.9 to 36.8 cm. Shoulder positions varied according to the volunteers' state of relaxation and arm position. As a result, shoulder displacements were not directly proportional to the head excursion or the increase in belt length.

In the spit tests with the cinching latch plate, the volunteers' heads moved between 10.2 and 15.2 cm, and their shoulders moved 11.4 and 22.9 cm toward the roof. As a group, the volunteers using the cinching latch plate experienced much less head excursion that the volunteers using the pass-through latch plate. Their head excursion was on average reduced by 53 percent.

Table 2 shows results of the spit tests performed with dummies in the driver's seat. The standard seated dummy experienced only 6.6 cm of head motion with the sliding latch plate and 4.8 cm with the cinching latch

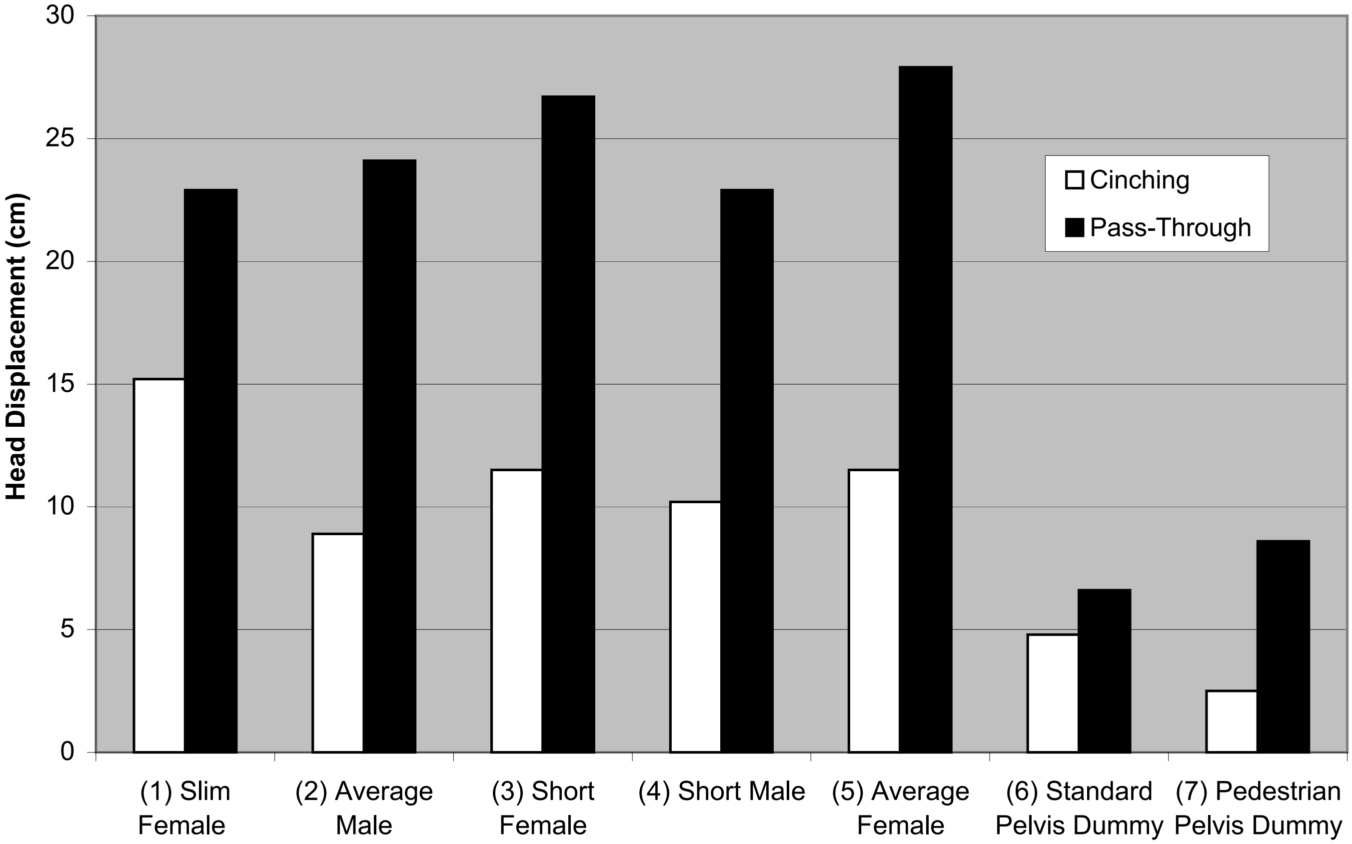

Figure 5. Head displacements for cinching versus pass-through latch plates.

plate. Although the improvement was 27 percent, the magnitude of the movement was small, with or without the cinching latch plate. The pedestrian dummy head experienced slightly more motion with the sliding latch plate, 8.6 cm compared to only 2.5 cm with the cinching latch plate, an improvement of 70 percent. However, both dummies moved far less than the human subjects. The human subjects moved three to four times further.

MADYMO Simulations

To evaluate the effect of the increased lap belt length due to the pass-through latch plate, a seated occupant was modeled using the MADYMO computer program. A Hybrid III Dummy, TNO version 5.3, was used to simulate the body of the occupant. This dummy model was modified. A more compliant, compressible biofidelic neck[8] consistant with cadaver data[9,10] was used. In all simulations, the neck was initially nearly straight (13.75 degrees forward relative to the thorax).

The body and seat were inverted with the seat attached to a frame structure, Figure 6. The frame structure included a simulated roof and roof liner. The frame, seat and occupant were allowed to fall due to gravity from various heights. Since the lap belt provided the only effective restraint in the spit tests, only the lap belt was modeled. The simulated belt webbing had 10 percent elongation, which was selected from the available TNO database. Increased length due to pass-through from the shoulder belt was modeled by increasing the lap belt length (introducing slack in the belt). Anchor points for the lap belt and seat geometry were the same as in the spit tests. The inboard lap belt angles, at the inboard pelvis contact point, were 37 degrees rearward and 30 degrees inboard from vertical. The outboard lap belt angles, at the outboard pelvis contact point, were 13 degrees rearward and 10 degrees outboard from vertical. Drop heights of 15.2, 61, and 91.4 cm were simulated.

The following quantities were computed: torso and head velocities, head acceleration, belt force, neck compression force, and neck moments at C1 and C7. Simulations were performed with the head on the roof and the head 5.1 cm away from the roof. See Figure 6.

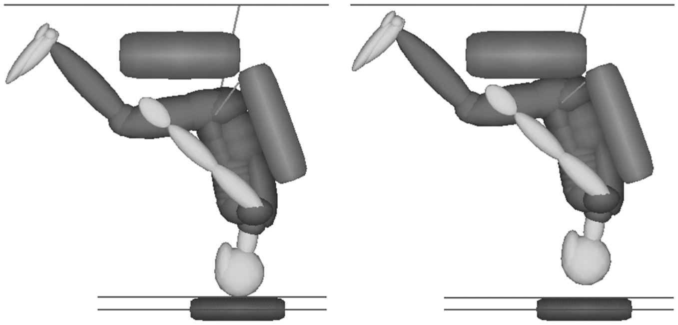

Figure 6. MADYMO model showing head in contact with the roof and with 5.1 cm headroom.

MADYMO SIMULATION RESULTS

The results of the MADYMO simulations are shown in Tables 3 through 6. These results show that a cinching latch plate that provides 5.1 cm of head clearance in the inverted position provides good protection in drop heights up to 91.4 cm. Table 3 shows that neck compression and bending moments at C7 are greatly reduced, when compared to the same quantities where the head is against the roof in the inverted position. Other response parameters are reduced, but to a lesser degree.

Belts with 0, 5.1, and 10.2 cm of slack were used in calculations for the 61 cm drop height simulation. The unrestrained condition was also simulated. Unrestrained and restrained responses are summarized in Table 5. The results show that 10.2 cm of slack is equivalent to being unrestrained. A belt with 5.1 cm of slack or pass through offers only minimal protection over the unbelted condition.

In order to model Surrogate 1, the MADYMO body weight and the belt preload were decreased to 42.9 kg. Simulations were performed for 15.2, 61, and 91.4 cm drop heights with 0 slack in the lap belt and the head initially in contact with the roof. The maximum neck compression forces were less than injury tolerance criteria for the 5th percentile female. The results are shown in Table 6. The effect of body weight can be seen by comparing Table 6 responses to those shown in Table 3. Although the maximum head force is not appreciably changed, the neck compression force for the highest drop was reduced 26 percent and the bending moment at C7 was reduced 30 percent.

These results show that neck compression is closely related to the quality of the lap restraint.

DISCUSSION

In a far-side roll, the outboard occupant tends to slip out of the shoulder belt. The lateral deceleration preceding the roll moves the occupant inboard. Also, a far-side or far-side corner roof contact with the ground causes the occupant's upper body to move inboard. When the shoulder slipped out from under the torso belt, the webbing with a pass-through latch plate immediately passed through to the lap belt, increasing the lap belt length by that amount. Videotapes of the latch plate clearly show webbing traveling through the latch plate slot.

Body excursion toward the roof was reduced when the pass-through latch plate was replaced by a cinching latch plate. In all tests, the cinching latch plate restraint system provided better vertical restraint. The body excursion toward the roof was less, with the reduction ranging from 33 to 57 percent. Although the Moffatt, et al. study indicates that the difference in head excursion between a cinching and a pass-through latch plate is little, their dummy tests 22 and 24 using the cinching latch plate, resulted in a 25 percent reduction in head excursion.

The volunteer that experienced the greatest excursion had the greatest chest circumference. This surrogate, number 5, also experienced the greatest increase in lap belt length as the belt moved from across the chest to across the lower ribs and waist. The lap belt length increased as the torso belt shortened. Additionally, she experienced the greatest reduction in excursion when the cinching latch plate was used. Thus, chest dimensions should be considered when evaluating the restraint system in a rollover event.

The importance of good lap belt restraint in protecting the neck was evaluated using the MADYMO occupant simulator program. Since the momentum of the torso compresses the neck when the roof stops the head, it directly contributes to neck injury potential. Only the lap belt can reduce the torso velocity toward the roof.

The computed neck compression force magnitudes in these simulations are conservative, since the model has no vertical body compliance except for that in the neck. Thus, the calculated compression forces are higher than would actually occur in a human under the same conditions. Also, the neck is nearly straight and the head is in the immediate vicinity of the roof when and where the roof contacts the ground. In this position, high neck compression forces will develop. The calculated neck compression force and moment magnitudes are used to show trends. However, neck compressions of 3558 to 4448 N can produce neck fractures and should be prevented.

The results in Tables 3 and 4 show the protection afforded by 5.1 cm of head-to-roof clearance. The neck compression is reduced between 47 and 65 percent. Thus, a lap belt that can keep the occupant close to their seat bottom can prevent neck fracture in rollovers (where roof crush is limited). This information, combined with the surrogate tests shows that occupants who slip out of their shoulder belts and are restrained with a pass-through latch plate are at great risk of neck injury in a rollover.

The advantages provided by a snug lap belt have been demonstrated, by Moffett, et al., in a spits test using pretensioners. The authors report that a pretensioner will reduce head excursion. They report that by using a pretensioner load of 667 N, typical vertical excursion for each test subject was reduced by about 10 cm. Digges and Malliaris report that pretensioning reduced vertical dummy excursion in all restraint types between 41 and 63 percent.

Table 5 data can also be used to show the injury risk when slack develops in the lap belt. When the pass-through webbing length equals or exceeds 10.2 cm, the neck loads are the same as those in an unrestrained occupant. A tight lap belt is needed to prevent neck injury.

The Hybrid III dummy is not a biofedelic surrogate for rollover testing based on Tables 2 and 5. The displacement is too small and the forces that develop in the dummy neck are much too high, not at all like those that develop in the human neck under the same conditions.

The simulations using a body weight of 42.9 kg show a significant reduction in neck compression compared to the same simulations using a 63.4 kg body weight. For a 91.4 cm drop, (with a simulated hard contact directly below the occupant head), the neck compression was below 3558 N. As stated above, these are conservative calculations and assume the worst possible contact with the roof and no body compliance except for the neck. The calculated forces and moments are larger than what would actually occur.

With a pass-through latch plate, the body has less vertical restraint in a roll since webbing from the shoulder portion can feed through to the lap belt. When the shoulder slips out of the torso belt, the slack, which develops immediately, feeds through to the lap belt, thus providing the occupant greater freedom to move toward the roof. If the driver adopts a more upright position in an attempt to control the vehicle, the length of webbing passing through the latch plate is increased as the belt slips off the shoulder.

The body's velocity toward the roof is directly related to the quality of the lap restraint. Without a good lap belt restraint in a rollover event, the thorax develops significant velocity toward the roof. With the head on the roof, the thorax momentum can compress the neck to the point of failure. This condition is referred to as thoracic augmentation and is similar to the neck loading experienced by a diver when diving into shallow water. Thus, good lap belt restraint is essential to the mitigation of neck injury in a rollover event.

CONCLUSIONS

1. In all of these tests, the pass-through latch plate allowed more motion toward the roof than a cinching latch plate.
2. The improvement was not the same for all human volunteers and appeared to be a function of their body shape, particularly chest circumference.
3. Body shapes that caused more webbing to pass-through to the lap when the shoulder belt slipped off of the shoulder experienced the greatest motion toward the roof and the greatest percent reduction in motion using the cinching latch plate.
4. Motion toward the roof was reduced by 53 percent on average with the cinching latch plate.
5. The dummy motion toward the roof is far less than that of the human volunteers in an alert upright position. The dummy vertical response does not accurately represent that of the human.
6. Since motion of the body toward the roof in a rollover event can contribute to catastrophic neck injury, a cinching latch plate will reduce this neck injury risk when the headroom is reasonably maintained.
7. The results of this study show a cinching latch plate would better control an occupant's motion toward the roof, and, in this author's opinion, help prevent cervical spine injury.

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Table 3. Head on Roof at Impact (77 Kg Occupant)

Case No.	Seat Belt Slack	Frame Drop Height	Frame Vertical Velocity	Maximum Torso Velocity	Maximum Head Velocity	Maximum Head Acceleration	Maximum Head Force	Maximum Neck Axial Force	Maximum Neck Bending Moment at C7	Maximum Neck Bending Moment at C1	Maximum Belt Force
	(cm)	(cm)	(m/s)	(m/s)	(m/s)	(g)	(N)	(N)	(N-m)	(N-m)	(N)
H-ON-R 1	0	15.2	1.74	1.9	1.8	21	2028	1735	98	16	3220
H-ON-R 2	0	61	3.44	3.6	3.6	53	5222	3621	203	39	4702
H-ON-R 3	0	91.4	4.24	4.4	4.4	75	6792	4568	256	52	5155

Table 4. Head Off Roof by 5.1 cm at Impact (77 Kg Occupant)

Case No.	Seat Belt Slack	Frame Drop Height	Frame Vertical Velocity	Maximum Torso Velocity	Maximum Head Velocity	Maximum Head Acceleration	Maximum Head Force	Maximum Neck Axial Force	Maximum Neck Bending Moment at C7	Maximum Neck Bending Moment at C1	Maximum Belt Force
	(cm)	(cm)	(m/s)	(m/s)	(m/s)	(g)	(N)	(N)	(N-m)	(N-m)	(N)
H-OF-R 1	0	15.2	1.74	1.9	1.9	17	1103	596	30	18	3180
H-OF-R 2	0	61	3.44	3.6	3.6	57	3403	1757	87	24	4675
H-OF-R 3	0	91.4	4.24	4.4	4.4	76	5551	2442	122	27	5142

Table 5. Head On Roof at Impact (Parametric Study, 77 Kg Occupant)

Case No.	Seat Belt Slack	Frame Drop Height	Frame Vertical Velocity	Maximum Torso Velocity	Maximum Head Velocity	Maximum Head Acceleration	Maximum Head Force	Maximum Neck Axial Force	Maximum Neck Bending Moment at C7	Maximum Neck Bending Moment at C1	Maximum Belt Force
	(cm)	(cm)	(m/s)	(m/s)	(m/s)	(g)	(N)	(N)	(N-m)	(N-m)	(N)
Baseline	0	61	3.44	3.6	3.6	53	5222	3621	203	39	4702
Slack 2	5.1	61	3.44	3.6	3.6	54	5511	4675	277	54	4879
Slack 4	10.2	61	3.44	3.6	3.6	54	5511	5160	335	69	4461
Unbelted	0	61	3.44	3.6	3.6	54	5511	5200	357	79	0
Hybrid III dummy	0	61	3.44	3.6	3.6	147	15795	13331	648	69	4675

Table 6. Head on Roof at Impact (52.3 Kg Occupant)

Case No.	Seat Belt Slack	Frame Drop Height	Frame Vertical Velocity	Maximum Torso Velocity	Maximum Head Velocity	Maximum Head Acceleration	Maximum Head Force	Maximum Neck Axial Force	Maximum Neck Bending Moment at C7	Maximum Neck Bending Moment at C1	Maximum Belt Force
	(cm)	(cm)	(m/s)	(m/s)	(m/s)	(g)	(N)	(N)	(N-m)	(N-m)	(N)
SH-ON-R1	0	15.2	1.73	1.9	1.8	24	1904	1388	75	12	2900
SH-ON-R2	0	61	3.44	3.6	3.6	44	3936	2753	146	27	4008
SH-ON-R3	0	91.4	4.24	4.3	4.4	65	5542	3456	184	33	4123