# SEAT INTEGRATED 3 POINT BELT WITH REVERSED GEOMETRY AND AN INBOARD TORSO SIDE-SUPPORT AIRBAG FOR IMPROVED PROTECTION IN ROLLOVER

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## ABSTRACT

In a rollover, the lap part of the 3-point belt certainly restrains the occupant from being fully ejected out of the vehicle, however the upper torso of the far side occupant may slip out of the shoulder belt. In this study the combination of reversed 3-point belt geometry (seat integrated), inboard torso side-support and buckle pretensioner were evaluated regarding the ability to better restrain the upper torso to the seat to prevent head-to-interior impacts.

The method of evaluation, proposed and used in this paper, was a new sled test method simulating full-scale tripped rollovers along the longitudinal axis during the initial phase of tripping, the airborne phase and the first ground impact. The roof was assumed in the tests to be able to withstand the ground impact. Since car occupants normally are seated with a certain kyfosis and may straighten and elongate their spine, standard HIII ATDs were modified with 3D-flexible lumbar spines and used in both front seat positions.

As a result, the rollover sled test method worked properly with good repeatability. While the head of the non-leading side (far-side) dummy impacted the inner roof in the standard 3-point belt configuration, the seat integrated 3-point belt with reversed geometry and buckle pretensioner showed ability to restrain the torso from moving inboard and towards the roof during the rollover tests.

## INTRODUCTION

Hassan and Mackay (1995) studied the NASS-CDS in-depth database for the years 1991-1993 and found that most rollovers of Sport Utility Vehicles occur due to a trip over. Moreover, they found almost all (97%) rollovers (of the SUVs) to have rolled one turn or less. According to Parenteau and Shah (2000) who evaluated NASS-CDS data for years 1992 to 1996, the most frequent injurious rollover event for a belted occupant is a tripped rollover (along the longitudinal axis) with a far side occupant (on the non-leading side). With the same set of crash data, Viano and Parentau (2004) found that wearing seat belt reduces the risk of serious injury to the head with 50% and to the chest with 40%, head and chest injuries being the most harmful injuries in rollovers according to Fay et al (2003). Otto et al found the MAIS3+ risk reduction wearing a seatbelt to be 80% evaluating GIDAS-data for the years 1994-2000.

Although rollover crashes involve more complex occupant motion than other crash modes (Digges 1991), a shortcoming of the standard 3- point belt in rollovers is the possibility of the far side occupant to slide out of the shoulder belt (Oberfegell et al l986, Kallieris and Schmidt 1990, Bostrom and Haland 2005). According to NHTSA (2003), who are investigating countermeasures to keep occupants better secured to the seat, it is not generally clear if reinforcing the roofs alone prevents injurious head-to-inner roof contacts.

In the absence of an accepted rollover dummy, the HIII frontal crash test dummy is often used to evaluate occupant kinematics in mechanical simulations of rollovers. However, the biofidelity is in question (Viano and Parentau 2004). For example, Moffat et al (1997) found the HIII head vertical excursion during dynamic and static rollover tests to be in the magnitude of 60 mm less compared to Post Mortem Human Subjects (PMHS).

Previously, the benefits of adding an extra seat-integrated 2-point belt to the standard 3-point belt were investigated by Bostrom and Haland (2005) by means of mechanical simulations of frontal, far side and rollover crashes. They found a considerable reduction of chest deflection in frontal crash tests, head horizontal motion in far side tests and head upward motion in the rollover tests. In order to reduce the risk of injurious belt-to-neck load caused by the 2-point belt, an inflatable side support was also used in

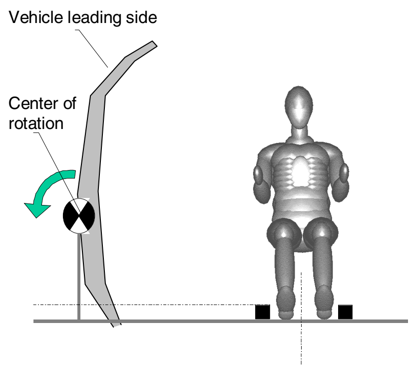



**Figure 1. In a previously used sled test rollover method, the centre of rotation was fixed during the tests according to the picture.**

combination with the extra belt. The rollover test set-up in this evaluation consisted of a steel construction, a platform simulating the compartment of a car able to translate laterally and rotate with a fixed rotation axis. This rotation axis, see Figure 1, was a compromise of the true rotation axis, which in a soil tripped rollover in the simplified case moves from a location around the tires of the leading side in the tripping phase to the centre of mass in the airborne phase. The ATD used was a BioSID with a modified lumbar spine (allowing an extension of the spine of 70 mm), seated in a non-leading position. The buck was accelerated with a low g-level (peak 3g), and at a speed of 36 km/h the buck was decelerated and rotated until reaching a stop at 160 degrees, which simulated a car-to-ground impact phase.

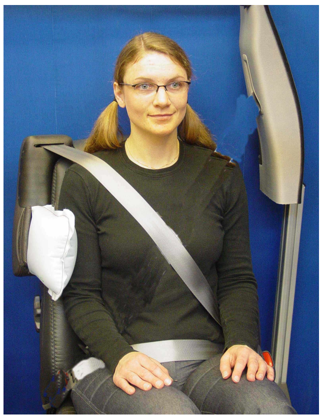
Kallieries and Schmidt (1990) evaluated the concept of a 3-point belt with reversed geometry, noting the potential beneficial effect of restraining the occupant laterally. It is tempting to believe, the beneficial features of an extra 2-point belt and an inboard side support airbag for far side occupants in rollover (Bostrom and Haland 2005) are also applicable for a seat integrated 3-p belt system with reversed belt geometry and an inboard side support airbag, see Figure 2.

The aim of this paper was threefold. Firstly, a new cost efficient tripped rollover sled test method (one ground impact) was proposed and evaluated. Secondly, 3D-flexible lumbar spring spines for HIII ATDs was proposed. Thirdly, the method and the modified dummies were used to evaluate the far-side occupant benefit of an inboard side support airbag and reversed seat integrated belt system with buckle pretensioning.

## METHOD

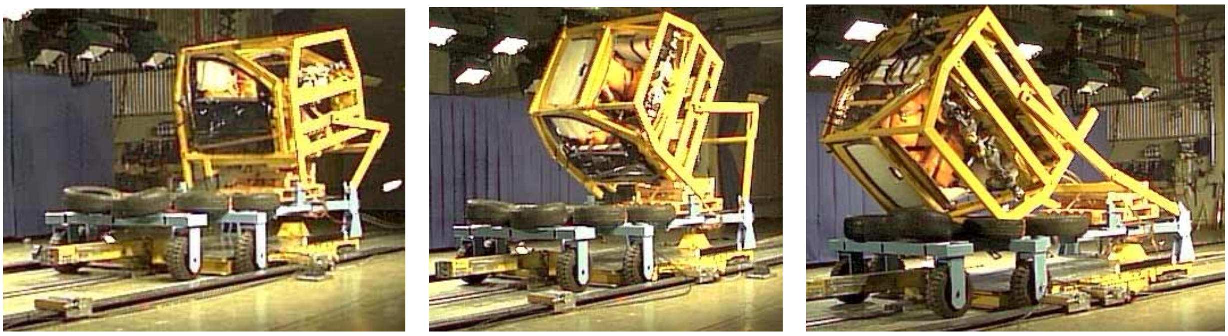
The sled test method used in this paper was designed to evaluate occupant protection in tripped rollover until first ground impact in a robust and repeatable way for most common passenger vehicle types, vehicle speeds, and tripping-accelerations. The majority of rollovers occur off-road (Viano and Parenatu 2004) and the variety of the surrounding road environments is vast. Therefore the real-life ground impact circumstances vary considerably and an occupant injury risk evaluation may be restricted to an analysis of the occupant restraint situation just before first ground impact, such as whether the shoulder belt has slipped off or not. Also, the ATD head excursion during the first ground impact may be evaluated in conjunction with a possible roof crush.

a)



b)

**Figure 2. Occupant a) restrained by a 3+2 point belt and a side support airbag (as previosly described and evaluated) and b) restrained by a seat integrated belt with reversed geometry and a side support airbag.**



a) b) c)

**Figure 3. The sled test rig in the a) tripping phase, b) airborne phase and c) first ground impact phase.**

**General description**

In a tripped rollover the rotational acceleration of the car equals the

Tripping torque on the car / Moment of inertia (1).

Consider a car with mass $m$, track width $T$, height of centre of mass from tripping axis $H$ and a roll moment of inertia around centre of mass $I$. If the sliding or tripping acceleration of the car is $a$, the tripping torque is the force of the ground transmitted by the leading side wheels times the moment arm, $maH$ initially, opposed by the torque of gravity, $mgT/2$ initially. This means a vehicle starts to roll if the sliding acceleration exceeds $T/(2H)$. That is the total mass of the car is irrelevant. This also means, if the mass-normalized moment of inertia around the tripping axis

$$(I + (T/2)^2+H^2)/m \qquad (2).$$

and the tripping acceleration (acceleration at the axis of tripping) are replicated in a mechanical simulation, the rotation and translation are replicated. Once airborne, the vehicle follows a trajectory dictated by the tripping history of rotation and translation and remains with the same rotation velocity given at the time of becoming airborne. This is the general idea behind the present rollover sled test method. The idea was first applied by Torstensson and Klasson (2003). The sled test rig consists of the following components:

1. A buck with a certain track width, $T$, height of centre of mass from tripping axis $H$ and mass-normalized moment of inertia around tripping axis = $(I + (T/2)^2+H^2)/m$.
2. A pair of guiding steel pivoting arms on each sides of the buck to restrain the buck within the sled area without considerably influencing the tripping and airborne phase.
3. A buck on a wheeled carrier is fastened on the sled. As the carrier is decelerated, the buck is tripped, causing it to freely rotate. It subsequently lands on the forward area of the carrier, which has been covered by car tires.
4. A sled, which is decelerated by means of a set of brakes (see next).
5. A set of pneumatically controlled brakes, previously described by Rossey (2001) but upgraded with a mechanically controlled release function after an arbitrary distance of braking.

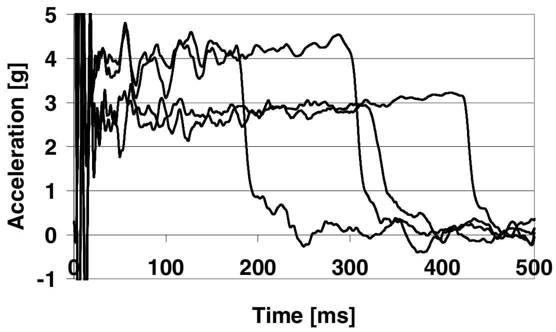
See Figure 3 for views from the three phases of tripping, airborne and first ground impact. If the sled is still moving at the start of the airborne phase, higher sled speeds do not alter the simulation outcome as the deceleration of the sled is not dependent on the pre-roll sled speed (in contrast to some real-life situations). That is, with the possibility of releasing the brakes (see description 5. above), the pre-roll speed of the sled is less relevant. See Figure 4 for 45 km/h pre-roll speed rollover simulations with two deceleration levels, with and without release of the brakes during the tripping phase, giving different rotation accelerations and rotation speeds. In the following sub-sections the buck, pulse, ATDs, restraint systems, and evaluation parameters for the present test series are described.

**Table 1.**
**Rig details.**

| | W/o dummies | With dummies |
|---|---|---|
| **Track width [m]** | 1.71 | 1.71 |
| **Mass [kg]** | 790 | 946 |
| **Moment of inertia around COG [kgm$^2$]** | 342 | 398 |
| **Normalized moment of inertia [m$^2$]** | 0.43 | 0.42 |
| **Height of dummy hip point (to tripping axis) [m]** | - | 0.60 |
| **Height of COG (to tripping axis) [m]** | 0.64 | 0.64 |

**Buck**

The buck used was a frame of a SUV type of vehicle. The buck was reinforced externally, keeping the normalized moment of inertia (Equation 2), the track width and the height of the COG above an assumed tripping axis, same as the original vehicle. See Table 1 for values of these entities for the buck with and without two front seat HIII 50$^{th}$% occupants firmly attached to the seats with belts.



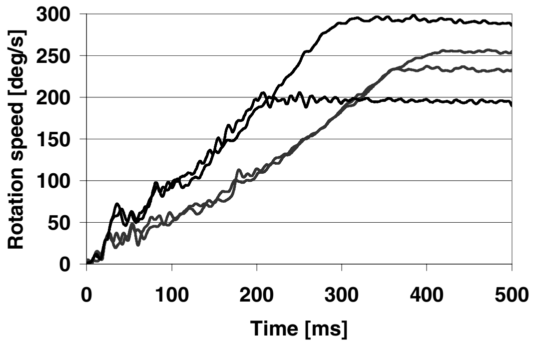




**Figure 4. Four examples of tripping pulses and the resulting rotational speeds. Two pulses of 3g and two of 4g were and were not released during the tripping phase. The pre-roll speed was 45 km/h.**

**Pulse**

The pulse chosen in the present evaluation, 45 km/h impact speed and a tripping acceleration of 3g, was replicated from in house full-scale soil-tripped rollovers resulting in one roof impact.

**Dummies**

Two HIII 50$^{th}$% ATDs were positioned in the front seats, and positioned according to OEM specifications. The upper arms of the dummies were removed to prevent obstruction of the film view of the head. The ATDs, were modified with 3D-flexible lumbar spines, see Figure 5. The modification was performed by replacing the rubber interface between the lumbar spine end plates by a steel spring-coil with shearing and

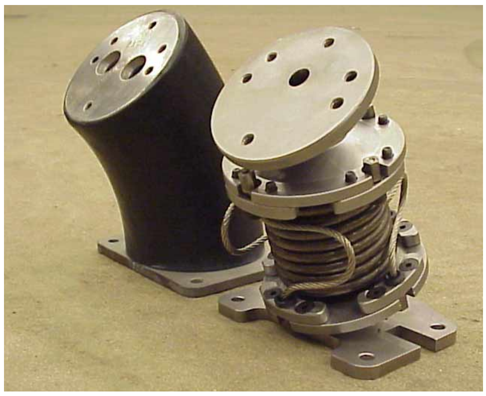


**Figure 5. The original and the modified HIII lumbar spine. The rubber was replaced with a spring coil and the four wires limits the elongation to 60 mm.**

**Table 2.**
**Test matrix.**

| Test | Belt | Retractor pretensioner | Buckle pretensioner | SSA* | IC** |
|---|---|---|---|---|---|
| **1** | Standard | Yes | - | - | Yes |
| **2** | Standard | Yes | - | - | Yes |
| **3** | Standard | Yes | - | - | Yes |
| **4** | Reversed | - | Yes | Yes | Yes |
| **5** | Reversed | - | Yes | Yes | Yes |
| **6** | Reversed | - | Yes | Yes | Yes |

*only for non-leading side occupant **only for leading side occupant

elongating features of 10 N/mm. The elongation was restricted to 60 mm by four wires. The elongation characteristics were chosen based on simple estimations. First, straightening of the lumbar lordosis and thoracic kyfosis of a normally seated occupant was estimated to be associated to 30 mm of elongation without much force. Secondly, according to Brown et al (2002) the lumbar joints may each elongate about 6 mm within the physiological range with an elasticity of about 20 N/mm. Therefore the modified lumbar spine, simulating both the possibilities of lumbar elongation as well the overall spine straightening, within the physiological range, was designed to elongate 60 mm with 10 N/mm. This is in accordance with the observed spine elongation of up to 3 inches of astronauts in gravity-free space (NASA 2005) and the observed elongation differences between HIII and PMHS subjected for both static and dynamic rollover tests (Moffat et al 1997). Also, the shearing and elongation characteristics implemented in a modified lumbar spring spine of the BioSID have been shown to enable replication of PMHS kinematics in a far side crash simulation (Fildes et al 2005).

**Restraint system**

According to the aim of this paper, tests were performed both with standard geometry 3-point belts as well as reversed geometry seat-integrated 3-point belts. In the reference tests, front seat seat belts with retractor pretensioners were used. In the reversed case no retractor was used. Instead, the belts were statically secured and buckle pretensioners were triggered, see Table 2 for the complete test matrix. In order to prevent harmful belt-to-neck interactions in the case of reversed belt geometry, the upper belt guides were oriented vertically and an inboard side support airbag, SSA, was installed in the non-leading (far-side) seat. The SSA consisted of a non-ventilated 3 litre bag, a production gas generator (for a near (outboard) side airbag) and a bracket mounted at the inboard

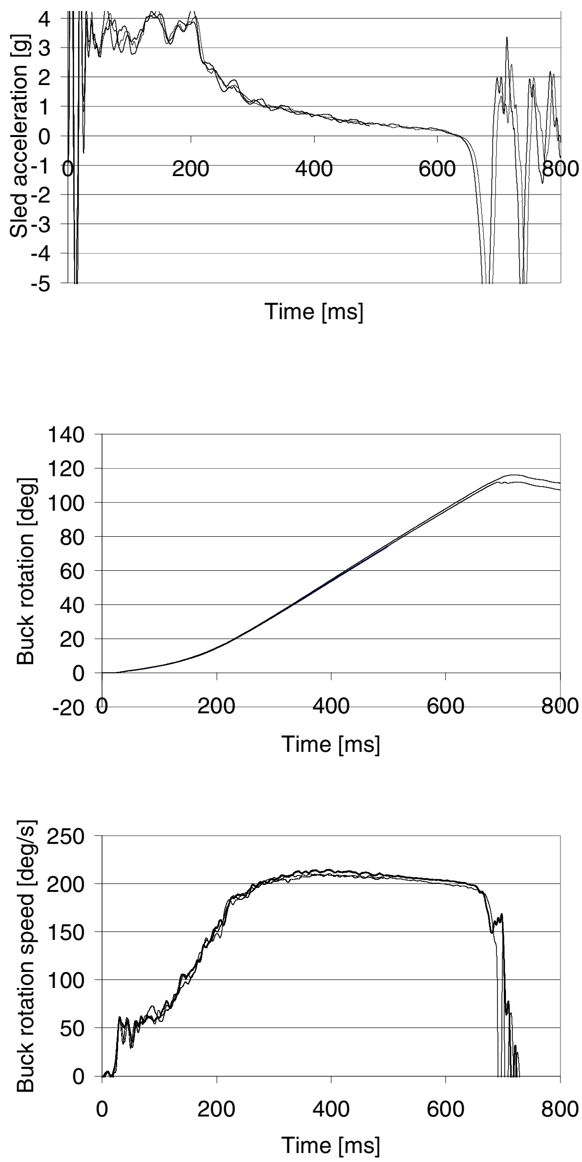



**Figure 6 – The sled deceleration, buck rotational speed and rotation for the three reference tests versus time for the first 800 ms. In Test 1, the data was captured only the first 500 ms.**

side of the seat frame, see Figure 2. The seats were reinforced standard seats. In all tests, standard inflatable head curtain airbags (IC) were installed on the leading side. The triggering time for all pretensioners, side support airbags and curtains was 140 ms corresponding to a roll angle and roll angle speed of 7 degrees and 100 deg/sec respectively.

**Evaluation parameters**

Throughout this paper, all coordinate systems and filter classifications used are according to SAEJ211 standard. Two high-speed cameras were mounted on the buck in front of each ATD. Two film analysis markers were placed 130 mm apart on the dummy faces. The markers were tracked using TEMA software, giving the motion in the buck y-z plane of these two markers. With a Faro-arm device, the interior and head of the dummy surfaces were pre-measured in the dummy motion plane.

Head acceleration and upper neck load were measured in both dummies. The lower neck load was measured in the non-leading side dummy in order to evaluate the belt-to-neck interaction in the reversed geometry test.

**RESULTS**

The sled x-acceleration and buck y-acceleration and the buck rotational speed time histories for the three reference tests are shown in Figure 6. In Figure 7, the y-z plane trajectory of the head upper marker in the three reference tests is shown. According to the buck and dummy head motion visualized in Figure 6 and 7, the repeatability of the method was good.

**Table 3 .**
**Nij and HIC values for all tests (except Test 1 where the data were captured only the first 500 ms).**

| Test | HIC36 | Nij |
|---|---|---|
| **1** | Data loss | Data loss |
| **2** | 415 | 1.13 (NCF) |
| **3** | 572 | 0.45 (NCF) |
| **4** | 65 | 0.22 (NTE) |
| **5** | 32 | 0.24 (NTE) |
| **6** | 29 | 0.20 (NTE) |

In all reference tests the non-leading side dummy's upper torso slipped out of the shoulder belt in the tripping phase after about 170 ms corresponding to a buck rotation of 13 degrees. The belt pretensioner, triggered after 140 ms, acted on the ATD, which at that time, already had moved in the in-board direction. Thereafter, at about 350 ms after the start of the roll, the ATD moved in the out-board direction. At ground impact the dummy was only restrained by the lap part of the belt. In addition, a considerable belt slack was introduced when the dummy initially moved inboards, a slack which was not reduced by the pretensioner due to too the late deployment time. In all the three reference tests (Tests 1-3), the ATD head hit the inner roof at the event of ground impact. The maximum upper neck loads occurred in Test 2 where the Nij value was 1.1 (Table 3), mainly due to 6.6 kN of compression force when the head and neck was compressed between a moving torso and a grounded roof. On the other hand, in all reversed belt geometry tests, the shoulder belt did not slip off the shoulder and therefore restrained the dummy from moving too far towards the roof in the ground impact phase. See Figure 8 for inboard and outboard views for both belt geometries at 120, 200, 500 and 1000 ms. Furthermore, for the reversed geometry, the shoulder belt interacted with the dummy neck with the flat side. Although there exists no established tolerance levels, the lower neck loads (Fy) was considered to be low (<1 kN) indicating a harmless belt-to-neck interaction. See Table 3 for all Nij and HIC values.

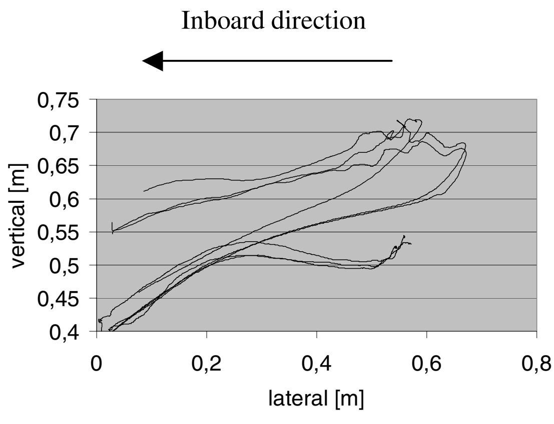



**Figure 7 - The first 850 ms motion in the y-z plane of the head upper marker for the three reference tests. The head first moved inboard and downwards and thereafter outboard and upward.**

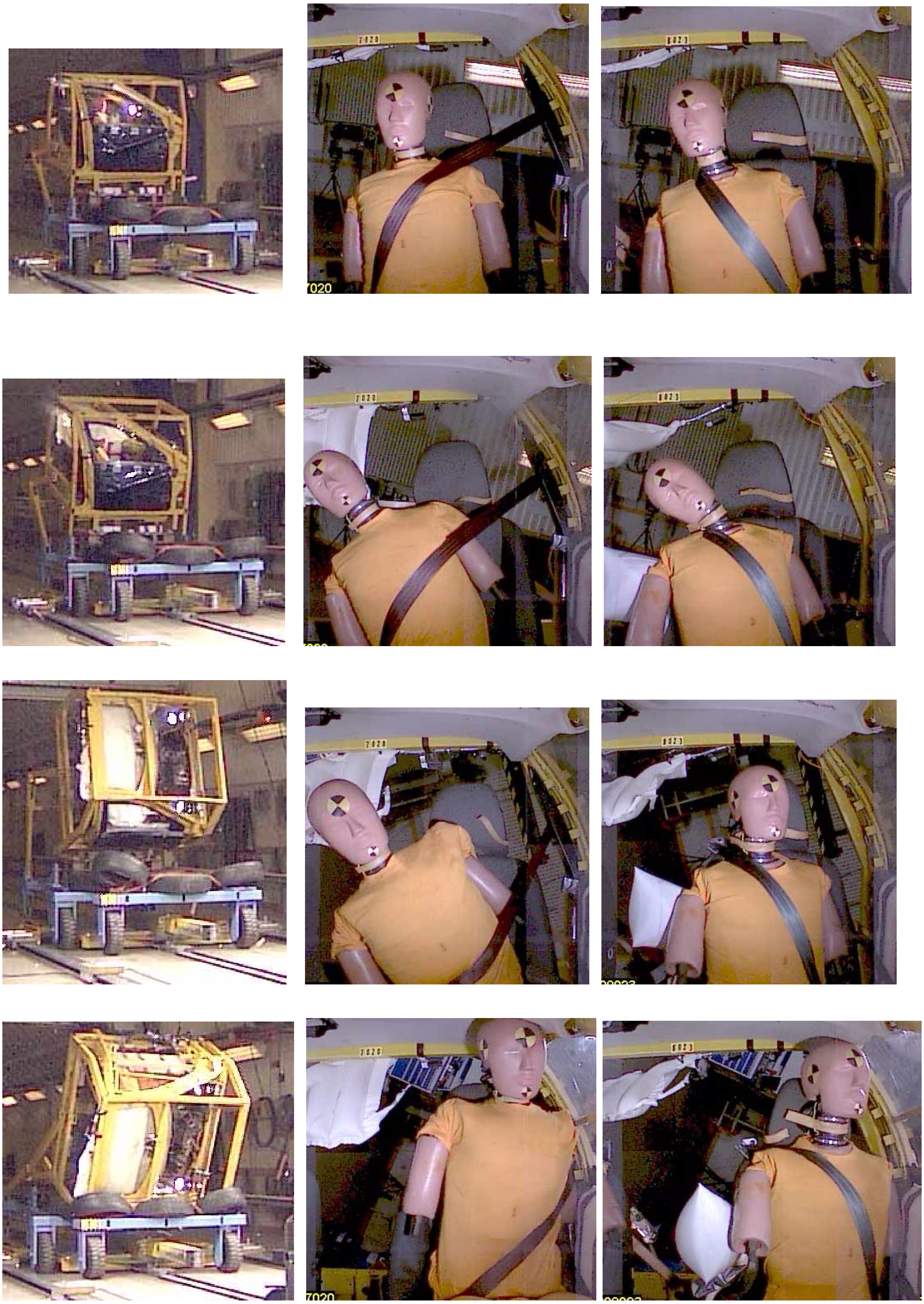



**Figure 7. Outboard and inboard non-leading occupant views for standard and reversed belt geometry at 140, 200, 500 and 700 ms .**

## DISCUSSION

The method used in this paper was designed to simulate tripped rollover until the first ground impact. As the speed and tripping acceleration may be varied, the method includes the possibilities of simulation of most types of soil and curb type of tripped rollovers and therefore most types of real-life rollovers. The present benefit analysis was limited to an analysis of the observation of the belt staying on the shoulder or not and the consequent head excursion towards a roof that did not intrude. Also, a limitation was the chosen pulse, 45 km/h and 3g, a replication of what is believed to be a typical tripped rollover with one roof impact. According to Digges and Eigen (2003) the number of roof impacts is an appropriate severity indicator for belted occupants, two or more impacts covering the majority of rollovers causing AIS3+ injuries. Therefore, according to Digges and Eigen the present pulse may be considered representing a rollover with a rather low severity (although their study involved all types of cars). Therefore, the shortcomings of the standard belt found in this paper would probably not improve while the benefits of the evaluated countermeasures do not necessarily apply to cars with extensive roof crush. This needs to be further evaluated.

The spring lumbar spine modification to the HIII ATD improved both the lateral and upward motion of the ATD during the rollover simulations. It is the authors' belief that the modification had a great impact on the results and conclusions of this paper, and that this was an important step towards more human-like rollover simulations of occupant motion.

To obtain a low belt-to-neck load an inboard side support airbag was included in the reversed belt configuration in order to off-load the belt for occupant inboard movement. Also, the upper belt guide was aligning the belt vertically in order to promote a flat belt alignment to the neck. Regarding the offload effect, the torso side support airbag has in previous far side impact tests (Bostrom and Haland 2005) shown its ability to keep the occupant (driver) within the seat with standard geometry belts, for a lateral acceleration of 10g, both in 90 degree (3 a'clock) as well as 60 degree (2 a 'clock) tests. While there are accepted limits on the loads and moments applied to the neck for evaluating vertebral bone and ligament injuries, there are no currently accepted load limits for evaluating direct interaction of a torso belt with the soft tissues of the neck. Nevertheless, the direct belt loading to the neck caused by the reversed belt measured by the lower neck load cell was considered by the authors to be low (<1 kN).

Introducing a torso side support airbag on the inboard side of the seat, and reversing the belt geometry, may have implications in out-of-positions and crash circumstances not evaluated in this paper. The side support airbag may need to be tuned for these out-of-positions. Further tests need also to be performed to evaluate the impact of reversing the belt in frontal and near side crashes. Nevertheless, the deployment time of this small bag with relatively high pressure (2 bar) can be as long as 30–40 ms, which is a good prerequisite for a benign out-of-position performance.

Regarding the leading side occupant, the inflatable curtain successfully protected the head for both belt configurations; see Figure 9 for inboard views

**Figure 9 - Inboard views at the event of ground impact for the leading side occupant for both belt geometries. No side window was present.**

at the event of ground impact

Although the aim of this paper was to evaluate the benefits in rollover, far side tests were performed with reversed belt geometry and the side support airbag. Not so surprisingly, the results resembled the results for an extra 2-point belt evaluated by Bostrom and Haland (2005). The inboard belt restrained the occupant from moving inboard and the side support airbag off-loaded the belt-to-neck loading, thus indicating also a benefit in far side crashes.

The proposed countermeasure evaluated in this paper may be optimized to provide even better protection for the far-side occupant in rollover crashes. For example, a decreased triggering time of the SSA and the buckle pretensioner would reduce the initial lateral motion of the occupant and thereby reduce the remaining belt slack after the belt pretensioning. A reduced belt slack would decrease the occupant upward motion even further.

## SUMMARY

A series of tests with spine modified HIII dummies and a new sled test method for tripped rollover (along the longitudinal axis) until first ground impact was performed. The benefit of a seat integrated, buckle pretensioned, 3-point belt with reversed geometry and an inflatable inboard torso side support was evaluated. The repeatability of the method in terms of the buck and ATD motion (kinematics) was concluded to be good. The spine modifications did withstand the test series and enabled an elongation of the ATD's back during vertical tension. Reversing the geometry of a 3-point seat belt showed improvement of the shoulder belts ability to restrain the torso of a non-leading side occupant in a tripped rollover without causing harmful belt-to-neck loading.

## ACKNOWLEDGEMENT

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