Inflatable Shoulder Belts and Inboard Upper Anchor Shoulder-belt Geometry in Far-side Oblique Impacts

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Abstract Vehicle occupants in far-side oblique impacts are at risk of head and thorax injury due to impacts with interior structures and with near-side occupants after slipping out of the shoulder belt. This study evaluated the effects of inflatable seat belts, along with inboard vs. outboard and B-pillar vs. seat-integrated shoulder-belt anchorage locations, on Hybrid III and THOR-M dummy kinematics and injury metrics in simulated far-side oblique crashes. Seven simulated crashes were conducted, with a 45° principal direction of force and a 55 km/h velocity change with 23 g peak acceleration. Shoulder-belt upper anchorage location and belt type influenced the tendency for the dummy to slip out of the belt and subsequent occupant excursion. The inboard seat-integrated inflatable belt restraint system had the greatest influence, eliminating Hybrid III shoulder-belt slip out and decreasing excursion by 331 mm, compared with the conventional production B-pillar-mounted belt. The inflatable belt also showed potential to mitigate neck injuries, with low dummy injury metrics and distributed loading area.

Keywords Far-side, Inflatable seat belts, Oblique impacts, Reverse geometry seat belts, Seat belts

I. INTRODUCTION

The three-point seat belt is regarded as the most effective safety device in vehicles today. In 1955, the first patent for a three-point seat belt was awarded to Roger Griswold and Hugh De Haven [1]. This design shows the shoulder portion of the three-point belt routed over the seat-back and mounted to the vehicle floor behind the seat. Seven years later, Volvo engineer Nils Bohlin was granted a patent for an improved three-point belt configuration, which largely resembles belts found in vehicles to this day [2]. In order to eliminate seat strength as a variable and to limit adverse compression forces on the spine, Bohlin's design specified that the shoulder belt be anchored to the vehicle body 'at a point substantially on a level with and substantially behind and on one side of the shoulder'. The most practical location for meeting these requirements was, and still is, the vehicle B-pillar. In 1963, Volvo implemented this design as standard equipment on its vehicles sold in the United States [3].

Since then, numerous studies have demonstrated the effectiveness of three-point seat belts. In 2014, NHTSA (National Highway Traffic Safety Administration) reported that seat belts had saved as many as 12,802 lives [4]. However, the three-point seat belt was designed primarily for frontal impacts, and has diminished restraint potential when the principal direction of force (PDOF) in the crash is from the inboard side of the seat occupant (i.e. far-side) [5]. The standard configuration of the three-point seat belt, with the D-ring mounted to the B-pillar, can leave the occupant vulnerable to slipping out of the shoulder belt and contacting interior hard surfaces and other occupants in both far-side frontal and far-side side impacts, which comprise 19% of frontal occupants and 48% of side occupants in crashes, respectively [6,7]. Saunders *et al.* documented belt slip from the shoulder of THOR while seated on the far-side in a NHTSA oblique frontal test series [8]. Horsch *et al.* observed that, in lateral and oblique far-side sled tests, occupants restrained with a standard outboard-mounted three-point shoulder belt moved out of the belt [9,10]. Stolinski *et al*. further concluded that the upper torso slipping out of the belt was a key mechanism leading to injury in far-side

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impacts [5]. A survey of real world far-side side impacts in the UK found that in one-third of the cases the occupant came out of the shoulder portion of the belt, as determined from head contacts within the vehicle [11].

For decades, vehicle safety researchers have been investigating methods to protect occupants in far-side crashes. Concepts such as pretensioning, D-ring location optimisation, reverse geometry seat belts, centre airbags, inboard torso support and four-point harness belts have all been evaluated for effectiveness in reducing injury in far-side crashes [10,12-17]. Of these, seat-belt designs with an inboard shoulder belt, such as reverse geometry belts, have been shown to have significant potential to reduce upper torso excursion in far-side crashes [10]. These claims are coupled with a caution that reducing torso excursion by loading the neck could introduce neck injuries [10,15]. Moreover, belts with inboard attachment of the D-ring potentially leave the occupant vulnerable to slipping out of the belt in near-side crashes.

Inflatable shoulder belts offer a potential solution to concerns of neck loading from an inboard belt in far-side impacts because their inflated shape interacts with the occupant's chin in ways that limit head motion. Inflatable belts can also provide pretensioning and force limiting, like modern belts, and they have the additional advantage of distributing a load over a larger area. As early as 1975, inflatable seat belts were being evaluated as potential safety features [18,19]. More recently, inflatable seat belts have been evaluated as a means of reducing frontal crash injury in the rear seat. Forman, Kent and Sundararajan have all evaluated various designs of inflatable seat belts [20-22]. All of the updated inflatable seat-belt designs evaluated generally reduced injury metrics for both Hybrid III and post-mortem human subjects (PMHS) when compared with a standard three-point seat belt.

Though some technologies for improving far-side occupant protection have already been implemented in production vehicles, such as the front centre airbag and pretensioned seat belts, their benefit to occupants in real world far-side crashes has yet to be assessed. U.S. Federal Motor Vehicle Safety Standard (FMVSS) No. 226, Ejection Mitigation, and the Insurance Institute for Highway Safety's (IIHS) small overlap front test are encouraging safety improvements for near-side frontal crash occupants. Side-impact near-side occupant safety has already seen significant advancements, with improved structure and the addition of anti-ejection side curtain airbags, torso and pelvis airbags, pretensioned seat belts and pre-pretensioning of seat belts. Moreover, advancements in near-side side-impact safety have resulted in a dramatic reduction in death and injury rates, with vehicles rated Good in IIHS side-impact tests reporting a 70% lower risk of fatal injury than Poor rated vehicles, and Volvo vehicles equipped with an inflatable curtain, refined structure and chest airbags showing a 72% decrease in MAIS2+ injuries [23,24]. The continued progress in near-side safety affords an opportunity to explore belt designs that can provide improved occupant restraint in far-side impacts. The inboard geometry inflatable seat belt was studied to evaluate its potential to reduce upper torso and head excursion in far-side impacts, while addressing the concerns of neck injury associated with inboard-mounted shoulder belts.

II. METHODS

A total of seven sled tests were conducted on an acceleration sled at an impact angle of 45°, representing far-side oblique impact conditions. Gabler *et al.* previously reported that a PDOF of 60° +/- 15° accounts for 60% of serious injuries in far-side crashes where the area of most damage is on the left or right side of the vehicle [7]. Hybrid III and THOR-M with the SD-3 shoulder were used as human surrogates for these oblique tests. Since Hybrid III was designed primarily for frontal impacts, the most longitudinal angle of Gabler's reported range was chosen for the impact angle. Hybrid III has established Injury Assessment Reference Values (IARVs), but underestimates head excursions compared with PMHSs in 45° oblique tests [25,26]. THOR neck injury risk curves have yet to be established, however, THOR-NT has been reported to demonstrate adequate biofidelity for designing restraint systems for far-side impact conditions at 60° and 90° oblique angles. The updated THOR-NT, with the SD-1 shoulder, has shown biofidelic improvement over previous THOR models in shoulder belt engagement in 45° far-side tests, but overestimates head excursion compared with PMHSs [25,26].

In the absence of available crash pulse data for 45° impacts, a crash pulse was derived based on features from IIHS side-impact, IIHS small overlap and NHTSA oblique crash pulses. A collection of forty-eight IIHS side impacts tests, a collection of fourteen NHTSA Oblique tests and a collection of six IIHS small overlap tests were each averaged to achieve their respective pulses shown in Fig. 1; these respective pulses were then used in the derivation of the crash pulse used for testing, also shown in Fig. 1. The initial peak observed in the IIHS side-impact and NHTSA oblique pulses were incorporated into the target pulse. Delta V for the target pulse was 55 km/h (34 mph), similar to the longitudinal component of both the IIHS small overlap and NHTSA oblique pulses. The target pulse peak acceleration time of 62 ms was chosen to balance between the NHTSA oblique and the IIHS small overlap pulses, and the magnitude of 23 g aligns with the IIHS small overlap resultant pulse.

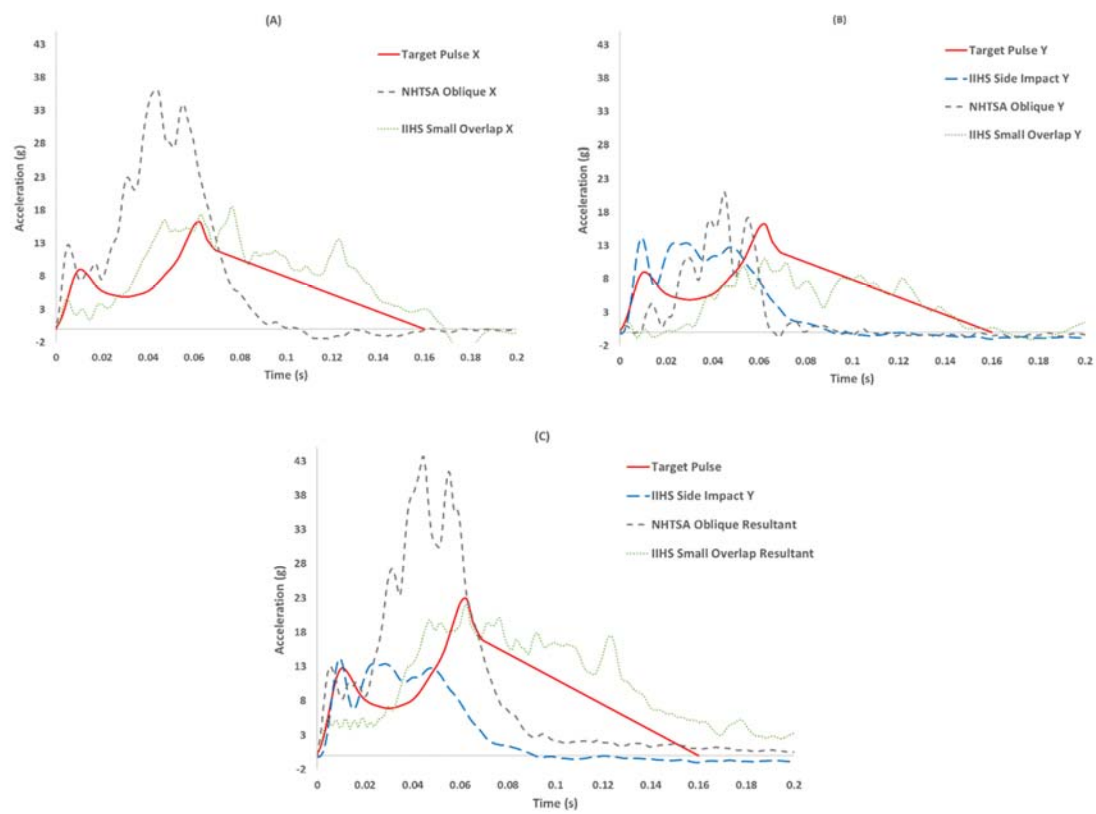


Fig. 1. (A)-(C): target test pulse for sled tests, with crash pulses used in the derivation of the target pulse. A: longitudinal acceleration. B: lateral acceleration. C: resultant acceleration

The oblique crash mode was simulated by positioning production vehicle seats and occupants at a 45° angle to the direction of sled acceleration, as illustrated in Fig. 2. Test conditions represent impact from the inboard side of the occupant, therefore outboard vehicle structure was not included. A knee bolster and simulated centre console matching the geometry from the same model vehicle as the seats were used to adequately represent the vehicle environment in an oblique impact.

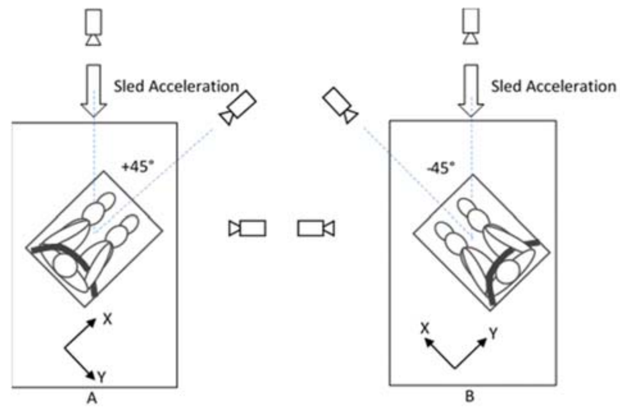


Fig. 2. A: inboard belt geometry, the seat-belt upper anchor is on impact side of the occupant and the torso and neck move into the belt. B: outboard belt geometry, the seat-belt upper anchor is opposite the impact side of the occupant and the torso and neck move away from the restraint of the belt.

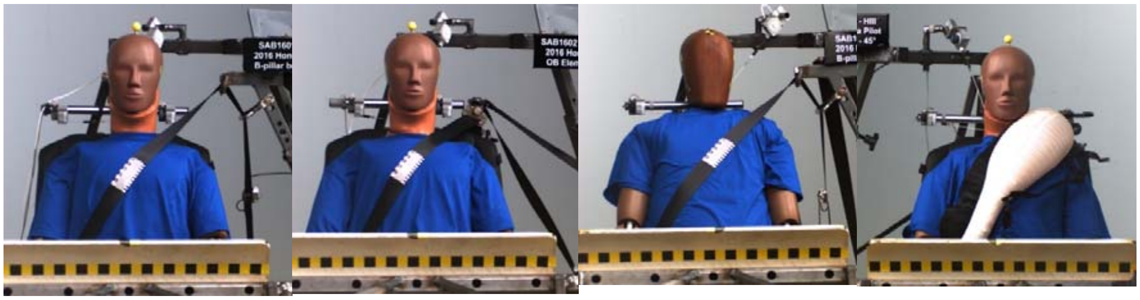
Three belt parameters were studied in this test series: inboard and outboard belt geometry; production webbing shoulder belts and inflatable shoulder belts; and D-ring location relative to the seat-back. All conditions were evaluated with Hybrid III, while only two conditions were evaluated with THOR-M. The test matrix is given in Table I.

TABLE I
TEST MATRIX

Dummy	Belt Geometry	Restraint System	D-ring Location
Hybrid III	Outboard	Production belt	B-pillar
		Production belt	Seat-integrated (SI)
		Inflatable belt	Seat-integrated (SI)
	Inboard	Production belt	Seat-integrated (SI)
		Inflatable belt	Seat-integrated (SI)
THOR-M	Outboard	Production belt	B-pillar
	Inboard	Inflatable belt	Seat-integrated (SI)

The upper anchorage location stayed on the left side of the dummy for all the belt conditions. Instead of moving the shoulder belt across the dummy to represent inboard and outboard belt geometry, the angle of the seat relative to the direction of impact was changed from +45° to -45°, as illustrated in Fig. 2.

The production restraint system was a driver-side three-point seat belt matching the model of the seats. This restraint system had a shoulder-belt retractor with a pretensioner and 2.6 kN load limiter. The production seat belt also included an outboard lap-belt pretensioner, which was not fired to remain comparable with the inflatable restraint system. The prototype inflatable restraint system was also a three-point belt but integrated a conical, tapered inflatable shoulder belt where the largest volume was between the dummy's head and shoulder. The tapered shape was chosen to maximise load area on the head and neck and thereby minimise the loads experienced by the neck. The inflatable shoulder belt also had a retractor with a force limiting threshold of 2.6 kN, matching the production belt, but without a pretensioner. The lap-belt portion of this restraint system was a fixed length piece of webbing separate from the shoulder belt. The inflator was positioned at the buckle end of the belt, though the belt was fixed and did not have a traditional buckle. The retractor pretensioner for the production belt and the inflator for the inflatable shoulder belt were both set to deploy approximately 7.0 ms from the onset of acceleration. The restraint system was replaced for every test. The belt conditions are shown in Fig. 3 (A)–(D).



(A) HIII, Prod., B-pillar. (B) HIII, Production, SI. (C) THOR, Prod, B-pillar. (D) HIII, Inflatable, SI.

Fig. 3. (A)–(D): belt test conditions.

Production driver and passenger seats from the same model vehicle were used for all tests; the seat was replaced for every test. Seat position and belt anchorage location were replicated from the production model vehicle, with the seat positioned according to the IIHS guidelines for UMTRI ATD positioning and the upper anchorage adjusted to the topmost position [27]. The alternate D-ring location simulated the geometry of a seat-integrated (SI) belt, since this is a likely configuration for an inboard-mounted seat belt.

Hybrid III was positioned by matching targets defined in the UMTRI procedure: H-point from SAE J826 manikin; torso angle 11.5°; pelvic angle 22.5°; and head level [27]. THOR was positioned as closely as possible to the draft THOR Seating Procedure without adjusting the seat from the UMTRI position. Priority was given to matching the H-point targets with the published offsets off +20 mm in the x-axis and -20 mm in the z-axis and levelling the head [28].

For both dummies, measured injury metrics included head and chest triaxial accelerations, head triaxial angular rates and upper and lower neck forces and moments. Hybrid III chest deflection was measured with a single rotary potentiometer, while THOR-M chest deflection was measured with four three-dimensional Infra-red Telescoping Rods for the assessment of Chest Compression (IR-TRACCs). Filters frequencies specified in SAE J211 were used for all channels [29]. Seat-belt load was measured between the D-ring and the retractor for all tests because the inflatable belt did not allow room for a load sensor in front of the D-ring. A preliminary test of the outboard condition with the production belt showed that the shoulder-belt loads in front of the D-ring were 44% higher than the loads measured at the retractor. Four camera views were used for each test: overhead; in line with impact direction; in line with seat orientation; and orthogonal to impact direction. Dummy excursion was measured with film analysis from the overhead camera view and validated for a selection of tests by calculating the intersection point of three string potentiometers attached at the base of the neck and fixed to points behind the seat-back. An estimate of the time the shoulder left the restraint of the belt was made based on video footage from various camera views. Figure 2 includes illustration of the camera positions.

III. RESULTS

Belt Slip and Dummy Excursion

Estimated belt slip times are given in Table II, and still images taken at the same time are shown in Fig. 5 (A)–(D). Maximum excursion of the dummy, measured at the lower neck, is listed in Table II and illustrated in Fig. 4. Dummy kinematics at the time of maximum excursion are shown in Fig. 6.

TABLE II
EXCURSION AND BELT SLIP TIMES

Belt Geometry	Description (Dummy, belt, D-ring location)	Estimated Belt Slip Time (ms)	X Excursion (mm)	Y Excursion (mm)	Resultant Excursion (mm)
Outboard	HIII, Production, SI	122	227	420	477
	HIII, Production, B-pillar	108	322	443	548
	HIII, Inflatable, SI	100	230	573	617
	THOR, Production, B-pillar	68	345**	393**	523**
Inboard	HIII, Production, SI	NA	174	389*	426
	HIII, Inflatable, SI	NA	50	211*	217
	THOR, Inflatable, SI	NA	59	307*	313

*Sign was inverted for comparison.

**Excursion values for this test condition were influenced by interaction between the dummy's elbow and a bolster meant to limit extreme excursion. Reported values are likely lower than if bolster contact had not occurred.

The effect of D-ring location was studied by moving the production shoulder-belt upper anchor from the simulated B-pillar to the simulated seat-mount location with Hybrid III in the outboard configuration. The shoulder belt slipped off the shoulder in both upper anchor locations; however, having the D-ring located closer to the seat-back, simulating a seat-integrated belt, resulted in the belt remaining on the shoulder 14 ms longer and reduced dummy excursions from 548 mm to 477 mm, a reduction of 71 mm. After slipping off the shoulder, both belts became trapped in the joint between the arm and shoulder, an artifact of the dummy design. With the D-ring mounted in the seat-integrated belt configuration, the belt remained trapped until the dummy rebounded. With the D-ring mounted to the B-pillar, the belt remained trapped in the joint for about 40 ms.

The potential for reducing occupant excursion with an inboard-mounted belt was assessed by moving the production belt with a seat-integrated D-ring location to the inboard side of the occupant. Moving the production belt inboard of the occupant eliminated belt slip from the shoulder and reduced excursions by 51 mm, from 477 mm to 426 mm, compared to the seat-integrated outboard configuration. Additionally, the significant lateral rotation observed with the outboard-mounted belt was minimised with the inboard-mounted belt.

The influence of adding an inflatable shoulder belt to the inboard configuration was studied by comparing the inboard-mounted production belt to the inboard-mounted inflatable belt with Hybrid III. As with the inboard production belt, the inboard inflatable belt eliminated belt slip from the shoulder. However, while the production belt concentrated loading on the shoulder and lower neck, the inflatable belt distributed loading to the shoulder, upper and lower neck and head. The distributed loading of the inboard inflatable belt further reduced dummy excursions by 209 mm, from 426 mm to 217 mm, compared with the production belt. To investigate whether different levels of pelvic restraint also could have been a factor, motion analysis was conducted using the overhead camera view and landmarks on the dummy thigh. Prior to dummy interaction with the simulated centre console, resultant and component displacement time histories were within 1 mm for the production belt system and the inflatable belt system. The influence of adding an inflatable belt was also studied in the outboard configuration. The inflatable belt allowed the shoulder to slip from the restraint of the belt 22 ms earlier than the production belt in the same condition, which resulted in 140 mm greater excursion. However, the inflatable belt did not get trapped in the arm-shoulder joint as the production belt did, which limits the value of the excursion comparison between the two belts in the outboard configuration.

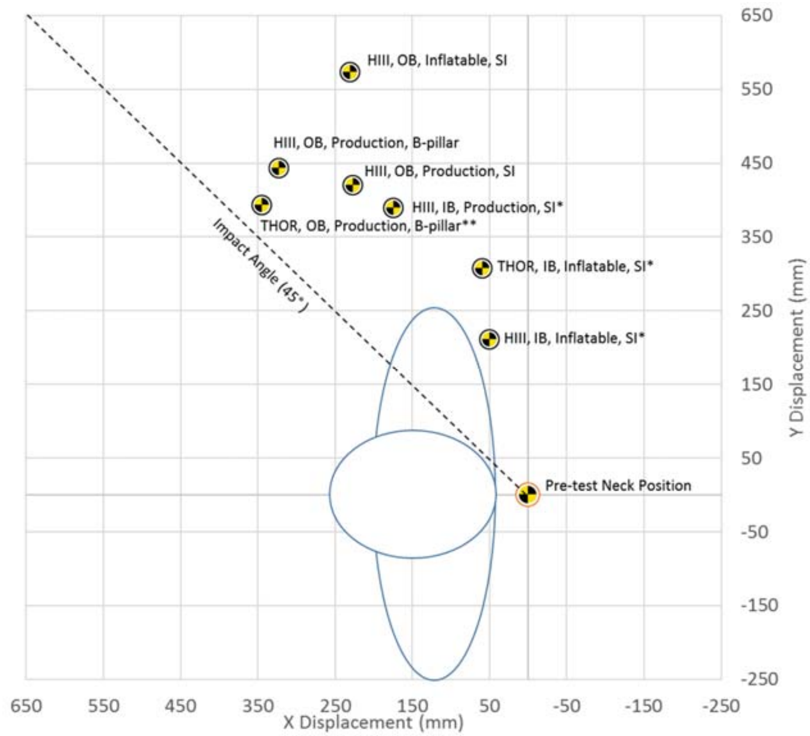
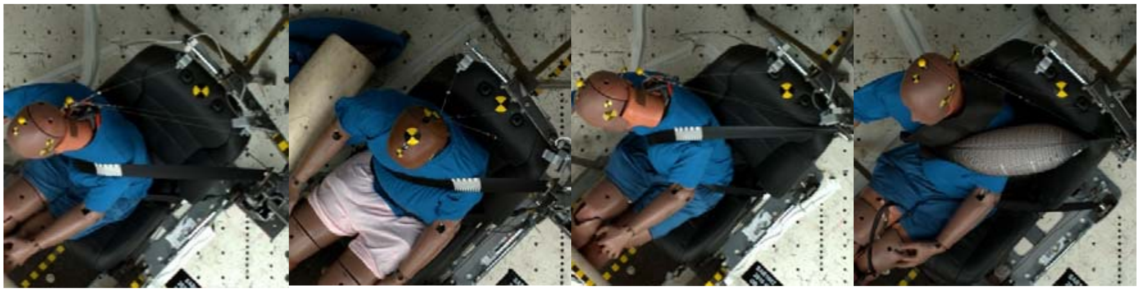


Fig. 4. Maximum dummy excursions, measured at the lower neck, relative to the initial position of the dummy and measured neck bracket. *Y values were inverted for better comparison. **Excursion values for this test condition were influenced by interaction between the dummy's elbow and a bolster meant to limit extreme excursion. Reported values are likely lower than if bolster contact had not occurred.

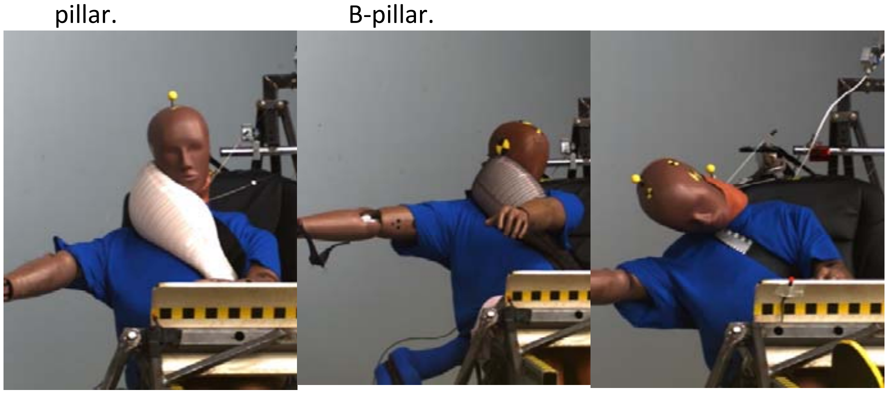
Both Hybrid III and THOR-M were studied with the traditional outboard, B-pillar mounted production belt and the inboard, seat-integrated mounted inflatable belt. For Hybrid III, the inboard inflatable belt eliminated belt slip from the shoulder and reduced excursions from 548 mm to 217 mm, compared with the traditional three-point belt. For THOR-M, the inboard inflatable belt also eliminated belt slip from the shoulder and reduced excursions from 523 mm to 313 mm, compared with the traditional three-point belt. However, excursion values for THOR-M in the outboard configuration were influenced by inadvertent interaction from the dummy's elbow with a bolster meant to limit extreme excursion; reported values for this test condition were likely lower than if bolster contact had not occurred. With the traditional three-point belt, the belt slipped from THOR's shoulder 40 ms earlier than Hybrid III. With the inboard inflatable belt, THOR-M demonstrated an excursion of 313 mm, 96 mm greater than Hybrid III. The increased lateral torso excursion resulted in greater loading of the head and neck by the inflatable belt. Instead of the dummy's head rotating over the inflatable belt toward the impact direction as Hybrid III did, THOR-M's head rotated away from the direction of impact.



(A) HIII, Prod., B-pillar. (B) THOR, Prod, B-pillar. (C) HIII, Prod., SI. (D) HIII, Inflatable, SI.

Fig. 5. (A)–(D): dummy shoulder engagement with shoulder belt at estimated belt slip time.

(A) OB, HIII, Prod., B-pillar. (B) OB, THOR, Prod., B-pillar. (C) OB, HIII, Prod., SI. (D) OB, HIII, Inflatable, SI.



(E) IB, HIII, Inflatable, SI*. (F) IB, THOR, Inflatable, SI*. (G) IB, HIII, Prod., SI*.

Fig. 6. (A)–(G): dummy kinematics at the time of measured maximum excursion: outboard (OB), inboard (IB), Hybrid III 50th (HIII), THOR 50th (THOR), Production belt (Prod.), Inflatable belt (Inflatable), B-pillar upper anchor mount (B-pillar) and simulated seat-integrated upper anchor mount (SI). *Pictures were reversed for better comparison.*

Dummy Injury Metrics

Head resultant acceleration, HIC-15, BrIC, upper and lower neck forces and moments, NIJ, chest acceleration and chest deflection are reported in the Appendix. All values in all test conditions for Hybrid III are well below injury assessment reference values (IARVs). Figure 7 illustrates the percent IARV for neck forces and moments for the traditional outboard B-pillar-mounted production belt, the inboard-mounted production belt and the inboard-mounted inflatable belt. Many neck injury metrics were similar between the traditional three-point belt and the inboard-mounted production belt configuration. While the inboard configuration reduced upper and lower neck tension, 182 N and 595 N (5% and 15% of IARV), respectively, it also increased lower neck shear 611 N (20% of IARV), increased lower neck flexion 35 Nm (9% of IARV) and increased lower neck lateral moment 25 Nm (8% of IARV). Compared with the inboard production belt, the inboard inflatable belt decreased lower neck lateral moment 74 Nm (26% of IARV), but it increased lower neck torsion and lower neck lateral shear 28 Nm and 621 N (29% and 20% of IARV), respectively.

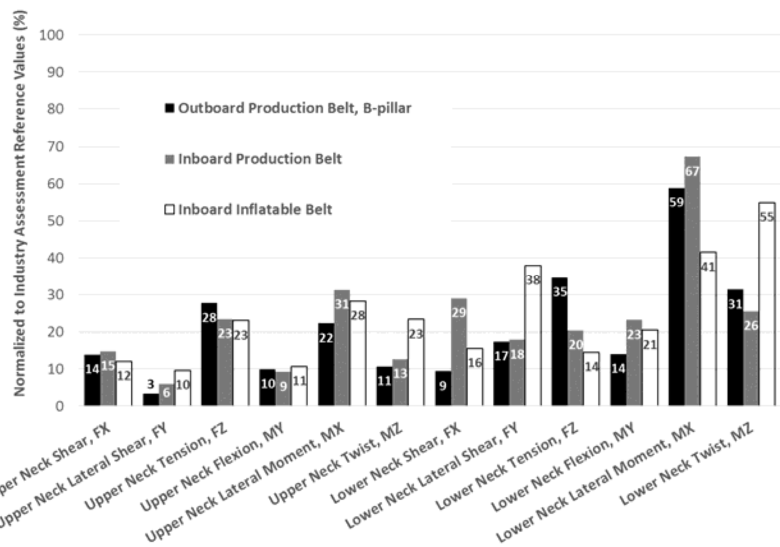


Fig. 7. Upper and lower neck metrics normalised to IARV for the inboard production restraint system and the inboard inflatable restraint system.

Chest acceleration (3 ms) and chest deflection were below IARVs for Hybrid III. Hybrid III chest accelerations were slightly higher on the inboard side compared with the outboard; chest deflections were generally the same in both configurations. The inflatable belt had similar chest deflections on the inboard side as the production belt. Chest accelerations for THOR-M were 8 g higher than Hybrid III in the matched inboard inflatable belt condition. For THOR-M, the lower right IR-TRACC registered the highest deflection at 43 mm. This location coincides with the load path of the belt at the time of maximum deflection, as well as the smallest diameter portion of the inflatable belt.

Belt Loading

The belt loads measured are shown in Fig. 8 and Fig. 9. One test, where the dummy unintentionally contacted the bolster, experienced a malfunction of the seat-belt load sensor. Both the production system and the inflatable system demonstrated similar load limiting, as intended. The production belt in the outboard configuration with seat-integrated geometry resulted in a more gradual, longer duration decrease in belt load, with a dramatic drop at approximately 230 ms, corresponding to the time during rebound that the belt comes out of the arm-shoulder joint. The inflatable belt in the outboard condition exhibited a similar gradual decrease in belt load. All belt conditions in the inboard configuration exhibited similar load patterns.

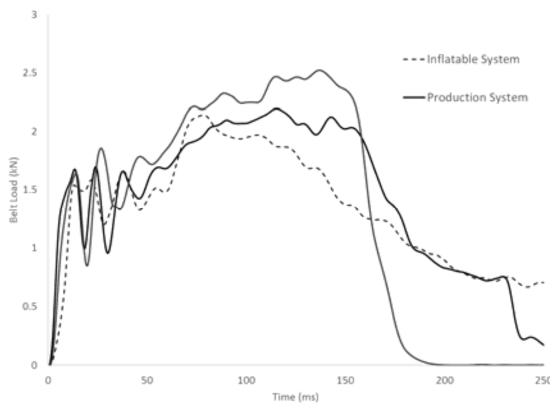


Fig. 8. Belt load time history for outboard configuration.

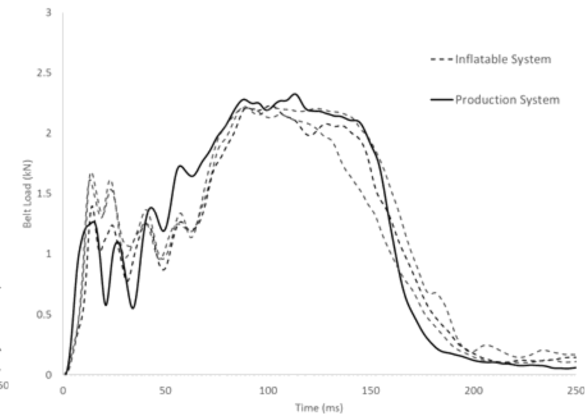


Fig. 9. Belt load time history for inboard configuration.

IV. DISCUSSION

This series of sled tests was conducted to assess the potential of inboard-mounted inflatable belts to reduce risk of head and thorax injury by limiting inboard excursion while also minimising potential injurious neck loads resulting from restraint by an inboard belt. In the 45° impact angle tested, the traditional outboard-mounted shoulder belt slipped off the shoulder of both Hybrid III and THOR-M. The resulting excursions were of a magnitude to put the occupant at risk for contact with interior vehicle components or an adjacent occupant. These results align with Mackay *et al.*, who observed belt slip from the shoulder of far-side occupants, with subsequent vehicle interior head contacts, in one-third of the real world cases evaluated [11]. In the current study, the belt slipped off the shoulder of THOR-M earlier than Hybrid III. The chest shape and size differ between the dummies, which influenced the initial position of the shoulder belt, as seen in Fig. 3. A and C. THOR's belt was positioned closer to the edge of the shoulder and likely influenced the belt slip time. Tornvall *et al.*, in a study with Hybrid III and THOR Alpha, attributed the difference in shoulder-belt interaction to the THOR Alpha's thicker, larger shoulder padding [30].

Two D-ring locations were evaluated to parse the effect of moving the shoulder-belt anchor inboard from the effect of moving the anchor location from the B-pillar to the seat-back, which is the most likely mounting location on the inboard side. Having the D-ring closer to the occupant's shoulder increased the time the belt remained on the shoulder and decreased the excursion of the occupant. Excursion measures in the outboard configuration, however, may have been influenced by the production belt getting caught in the dummy shoulder joint. Douglas *et al.* also found that, for outboard belts, lowering the D-ring relative to the shoulder, when paired with pretensioning, reduced the likelihood of the shoulder belt slipping off the shoulder [13]. Pintar *et al.* studied D-ring location for inboard belts with PMHS in far-side impacts and concluded that keeping the belt anchorage height level with the shoulder, rather than higher, was important in minimising the incidence of carotid artery trauma [25].

In the current study, moving the shoulder belt inboard of the occupant eliminated belt slip from the shoulder. The inboard inflatable belt showed the greatest potential for reducing occupant excursions and, therefore, for reducing the risk of head and thorax injury from contact with vehicle interiors and other occupants. Compared with the traditional outboard mounted three-point belt, the inboard inflatable belt reduced Hybrid III excursions by 331 mm. THOR-M had slightly higher excursions with the inboard inflatable belt than Hybrid III did, likely due to its articulated, more flexible spine, but was still well restrained, with a resulting head position that indicates a low likelihood of contact with vehicle interior components.

The inflatable belt was added to the inboard configuration to address the concerns of neck injury from belt loading observed in PMHS studies. The risk of neck injury to PMHSs from inboard belt loading in far-side impacts has been documented by several researchers, who observed cervical spine injuries, neck musculature injury and abrasions on the loaded side of the neck and carotid tears on the non-loaded side of the neck [10,15,25]. More recently, however, Rouhana *et al.* studied neck injury with four-point belts in far-side impacts and concluded that the lack of injury observed with the four-point belt compared with previous studies was a result of the use of force limiters, which kept the inboard shoulder-belt loads below 2 kN [16]. The addition of an inflatable belt to a force-limited, inboard restraint system, like the system evaluated in the current tests, could further reduce the potential for neck injury. While the production belt concentrated the restraint load on the shoulders and lower neck, the larger surface area of the inflatable belt distributed the belt load over the shoulders, upper and lower neck and head for both Hybrid III and THOR. For Hybrid III, neck injury metrics for both the inboard production belt and the inflatable belt indicate a low risk of vertebral and ligamentous injury; however, neck IARV thresholds may not encompass the risk of injury from direct belt loading to the neck soft tissue [12]. The inflatable belt reduced lower lateral neck moment by 26% of IARV compared with the inboard production belt; however, transferring load to the head resulted in increased lower neck lateral shear (20% of IARV) and lower neck torsion moment (29% of IARV). These values could potentially be reduced by modifying the inflatable belt pressure. THOR neck injury risk curves have yet to be established, but all reported values with the inboard inflatable belt were low. [30]

To a limited extent, the interpretation of the outboard seat-integrated production and inflatable restraint tests can be applied in assessing the consequences of an inboard-mounted upper anchor in a near-side impact, though vehicle structure was not present. The inflatable belt slipped off the shoulder earlier than the production belt in this condition. The distributed load of the inflatable belt likely reduces its ability to hang onto the shoulder in near-side lateral loading conditions. The inboard inflatable belt design would necessitate greater emphasis on the role of near-side safety devices, such as side curtain airbags and pelvis/thorax airbags. Moreover, the prototype inflatable shoulder belt may be further optimised for near-side performance.

The results of this study are limited by the biofidelity of Hybrid III and THOR-M in oblique impacts. Together, Törnvall *et al.* 2005 and 2008 and Pintar *et al.*, have studied various build models of THOR at 30°, 45°, 60° and 90° oblique angles [25,26,30]. These studies include THOR 99, THOR Alpha, THOR-NT and THOR-NT with SD-1 shoulder. The tests in the current study were conducted with THOR-M, which has the SD-3 version of the upgraded shoulder. Further details on the THOR build modifications can be found in Appendix Table A-IV. Törnvall *et al.* 2005 found that earlier builds of THOR (Alpha) were not representative of PMHSs in the far-side 45° oblique condition, but were representative in the far-side 30° oblique condition and in both 30° and 45° near-side conditions [30]. Pintar *et al.*, found that THOR-NT (without mod-kit or SD shoulder) was adequate for designing far-side restraint systems at 60° and 90° [25]. Additionally, Pintar *et al.* also found that THOR-NT performed better at 60° than 90°, which could imply that THOR-NT biofidelity improves at more longitudinal angles [25]. Törnvall *et al.* 2008 later studied THOR-NT and the upgraded THOR-NT with SD-1 shoulder in the 45° far-side configuration and found that, like the PMHSs, the belt did not slip from the shoulder of THOR-NT with the SD-1 shoulder; an improvement over the THOR Alpha and standard THOR-NT results [26]. However, head excursions compared to PMHSs were overestimated by THOR-NT with the SD-1 shoulder in the 45° far-side configuration [26]. In all conditions of the Törnvall studies, Hybrid III underestimated head excursions compared with PMHSs [26,30].

Although THOR-M has been shown to have improved biofidelity over Hybrid III [30-32], neither dummy can identically replicate human behaviour or demonstrate neck injury of the type observed in PMHS studies. Additionally, since current neck IARVs address only vertebral and ligamentous injury, testing with PMHSs would also provide a better understanding of the risk of neck soft tissue and carotid artery injury with this design. Neck injury risk curves have yet to be established for THOR-M, therefore no conclusions about occupant neck injury from THOR-M neck metrics have been made in this study. The single rotary potentiometer of Hybrid III, located at the center of the chest, is unlikely to capture the thoracic deflections leading to fractures superior to the belt line observed by Kent *et al.* in a PMHS test in a 45° far-side configuration [33].

There are additional limitations unrelated to dummy biofidelity. Tests were only conducted at a 45° angle, without the rotations or secondary impacts often seen in real world crashes. Furthermore, other safety devices and vehicle interiors play a large role in occupant dynamics. Though an attempt was made to replicate some interior components in this testing, further investigation of this restraint concept in the vehicle environment is needed for both near-side and far-side configurations in order to determine the comprehensive effects of the design. Seat-integrated geometry was simulated with a rigid fixture in this test series because the vehicle seat-back used was not designed to withstand the forces of occupant restraint. An upper anchor attached to the seat back may move dynamically with the seat and affect the kinematic result of this design.

V. CONCLUSION

Advancements in near-side safety afford an opportunity to focus restraint optimisation on far-side safety. In the current study, traditional outboard three-point belt designs, mounted both to the B-pillar and with seat-integrated geometry, allowed the shoulder to slip out of the belt and put far-side occupants at risk for head and thorax impacts with interior vehicle components. The inboard restraint system, however, addresses the problem of belt slip from the occupant shoulder, therefore reducing the risk of head and thorax impacts with vehicle interior components. The inflatable belt further improves the inboard configuration by distributing the direct loading of the belt on the neck and lowering excursions, with resulting injury metrics that indicate a low risk of vertebral and ligamentous neck injury.

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VIII. APPENDIX

TABLE A-I

Belt Configuration	**Outboard**				**Inboard**			**IARV***
Dummy	HIII	HIII	HIII	THOR‡	HIII	HIII	THOR	HIII only
Restraint Type	Prod.	Prod.	Infl.	Prod.	Prod.	Infl.	Infl.	
Mounting location	B-pillar	SI	SI	B-pillar	SI	SI	SI	
Upper Neck Shear, FX (N)	430	436	366	—	460	373	280	3100
Upper Neck Lateral Shear, FY (N)	501	573	337	—	761	298	659	3100
Upper Neck Tension, FZ (N)	1160	1230	1373	—	978	964	556	4170
Upper Neck Flexion at OC, MY (Nm)	19	17	19	—	18	20	13	190
Upper Neck Lateral Moment, MX (Nm)	32	34	24	—	45	41	86	143
Upper Neck Torsion, MZ (Nm)	10	14	9	—	12	22	33	96
Lower Neck Shear, FX (N)	292	340	321	—	903	483	1355	3100
Lower Neck Lateral Shear, FY (N)	540	699	611	—	555	1176	852	3100
Lower Neck Tension, FZ (N)	1446	1279	1711	—	851	605	633	4170
Lower Neck Flexion, MY (Nm)	53	62	84	—	88	78	43	380
Lower Neck Lateral Moment, MX (Nm)	168	198	109	—	193	119	133	286
Lower Neck Torsion, MZ (Nm)	30	25	24	—	25	53	37	96
NIJ, Tension-Flexion	0.22	0.21	0.23	—	0.19	0.2	0.3†	1
NIJ Tension-Extension	0.26	0.21	0.18	—	0.11	0.15	0.24†	1
NIJ, Compression-Flexion	0	0.01	0.05	—	0.05	0	0.43†	1
NIJ, Compression-Extension	0.04	0.19	0.07	—	0	0	0.09†	1

*[34]

† [35]

‡ No meaningful data could be collected due to inadvertent contact between the dummy’s elbow and a bolster meant to limit extreme excursion.

TABLE A-II

Belt Configuration	**Outboard**				**Inboard**			**IARV***
Dummy	HIII	HIII	HIII	THOR‡	HIII	HIII	THOR	HIII only
Restraint Type	Prod.	Prod.	Infl.	Prod.	Prod.	Infl.	Infl.	
Mounting Location	B-pillar	SI	SI	B-pillar	SI	SI	SI	
Head Resultant Acceleration (g)	28	30	35	—	29	26	24	180
HIC-15	61	66	27	—	62	42	36	700
BrIC†	0.51	0.55	0.45	—	0.41	0.55	0.68	

*[34]

†[36]

‡ No meaningful data could be collected due to inadvertent contact between the dummy's elbow and a bolster meant to limit extreme excursion.

TABLE A-III

Belt Configuration	**Outboard**				**Inboard**			**IARV ***
Dummy	HIII	HIII	HIII	THOR†	HIII	HIII	THOR	
Restraint Type	Prod.	Prod.	Infl.	Prod.	Prod.	Infl.	Infl.	
Mounting Location	B-pillar	SI	SI	B-pillar	SI	SI	SI	
Chest Acceleration – 3 ms (g)	17	20	23	—	25	33	41	54
HII Chest Deflection (mm)	19	18	15	—	19	18		50
THOR – Upper Left Deflection (mm)				—			21	
THOR – Upper Right Deflection (mm)				—			27	
THOR – Lower Left Deflection (mm)				—			29	
THOR – Lower Right Deflection (mm)				—			43	
Chest Injury Risk (Deflection)**	4%	3.5%	2%		4%	3.5%	45%‡	

*[34]

**[8,34] Indicates risk of AIS 3+ injury. For Hybrid III, risk is specific to shoulder belt loading.

† No meaningful data could be collected due to inadvertent contact between the dummy's elbow and a bolster meant to limit extreme excursion.

‡ Risk function was calculated using age of 55 years.

$$P(AIS \geq 3 | \, age, R_{max}) = 1 - exp\left(-\left[\frac{R_{max}}{exp(4.4853 - 0.0113age)}\right]^{5.03896}\right)$$

TABLE A-IV

THOR Alpha 2001	**THOR-FT** 2004	**THOR-NT** 2005	**THOR-M** 2013
Integrating TAD thorax with advanced neck and THOR-Lx	Improved biofidelity thorax	Extensive set of (small) mods related to anthropometry, durability, usability, biofidelity, fit and finish of all body parts e.g.	SD3 shoulder
Neck with cervical column and muscular load paths	3-D IRTRACCs	CRUX-pots	3-D IRTRACCs
Upper and lower abdomen with deflection measurements	Foam abdomen with PVC skin	Neck change to new rubber material	Pelvis puck and knee slider stiffnesses
	Pelvis based on latest UMTRI anthropometry	Thorax biofidelity response	
	On board DAS	Integrated head skin	
Haffner et. al. ESV 2001	Van Ratingen et. al. FID final report	Shams et. al. ESV 2005	E.g. Parent et. al ESV 2013

[37]

TABLE A-V

Test Description*	**Time (ms)**	**String Potentiometer Results**				**Film Analysis Results**		
		X (mm)	**Y (mm)**	**Z (mm)**	**X-Y Resultant (mm)**	**X (mm)**	**Y (mm)**	**X-Y Resultant (mm)**
Outboard, HIII, Production, B-pillar	171	344	446	234	563	322	443	548
Inboard, HIII, Inflatable, SI**	128	36	-232	112	235	42	-224	228

*Remaining tests experienced issues with either interference of the potentiometer strings or sensor issues related to spool-in of the potentiometer strings beyond the available string length.

**These values are from a preliminary test identical to the test reported in the body of the paper, with only minor deformation of the lower inflatable belt anchor. String potentiometer values could not be calculated for the same test with no deformation, reported in the body of the paper.