A New Prototype 4-Point Seatbelt Design to Help Improve Occupant Protection in Frontal Oblique Crashes

Jingwen Hu, Kyle Boyle, Kurt Fischer, Alex Schroeder, Angelo Adler, Matthew P. Reed

Abstract The objective of this study was to develop and demonstrate a prototype 4-point seatbelt system that has the potential to help reduce injuries for front right passengers in left (far-side) oblique frontal crashes. Three series of oblique frontal sled tests and computational simulations were conducted with the 50th percentile male THOR. The baseline sled test with a 3-point belt showed the potential for THOR to engage the airbag at an angle and roll out of the seat belt system, which resulted in increased lateral head rotation and potential head-to-instrument-panel contact. The observed chest deflection was also elevated in the baseline test. A prototype suspender 4-point belt was then used in three sled tests and MADYMO parametric studies. Results suggested that uneven load limits at two shoulders are significant to help control the occupant kinematics. A higher load limit at the striking side of the shoulder allowed for THOR's torso to rotate laterally towards the impact, which may reduce the lateral head rotation, and consequently reduce the BrIC value from the baseline test. The prototype suspender 4-point belt also helped reduce the chest deflections due to belt loadings mainly transferred through the clavicles, not the ribs. A final sled test with the model-predicted improved prototype restraint design showed reduced BrIC value (1.55 to 0.53) and reduced maximal chest deflection (50 to 38 mm) from the baseline test. These results demonstrated that the prototype suspender 4-point belt has the potential to improve the occupant protection in oblique frontal crashes.

Keywords chest injury, 4-point seatbelt, frontal oblique crash, head injury, occupant protection

I. INTRODUCTION

Reports published by National Highway Traffic Safety Administration (NHTSA) on seatbelt and airbag effectiveness in different types of crashes in the U.S. have shown the reduced injury potential of using restraint systems [1-4]. However, buckling up and having an airbag does not ensure complete occupant protection in all accidents. This means that properly restrained occupants can still be injured in frontal crashes. In-depth review studies [1,5,6] on fatal frontal crash cases with belted occupants in newer vehicles showed that one of the reasons people can still be fatally injured is because some crashes involve poor structural engagement between the vehicle and its collision partner in oblique and small overlap crashes. Further analyses of injury causation in small overlap and oblique frontal crashes showed that the forces generated in oblique crashes could change head and chest injury sources as occupants move toward the A-pillar or the centre of the instrument panel, where the occupant is not afforded the same protection from the seatbelt and airbag as that provided in a full-frontal impact with a 0° impact angle [1,7].

Accordingly, NHTSA developed a test procedure that involves an oblique moving deformable barrier (OMDB) with 56 mph travelling speed impacting a stationary vehicle with a 35% overlap and a 15-deg angle in both left- and right-side impacts. To help mimic occupant responses and better simulate injuries in the field, the most recent version of Test device for Human Occupant Restraint (THOR) 50th percentile male anthropomorphic test device (ATD) was used. This version of the THOR is called THOR Mod Kit with SD-3 shoulder (referred as *THOR* in this paper). THOR has a more flexible spine/torso and a more humanlike shoulder than the Hybrid-III 50th percentile male ATD, so that it represents occupant kinematics in oblique crashes. NHTSA has conducted a large number of full vehicle OMDB tests. The results of these tests demonstrated kinematics and injury responses to

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the driver and front right passenger that are consistent with field data. In particular, in NHTSA OMDB tests, the near-side occupant has the potential to engage the airbag at an angle, resulting in elevated head angular velocity and Brain Injury Criteria (BrIC) values than in 0° frontal crashes [8]. On the other hand, the far-side occupant tended to shift out of the shoulder belt and possibly impact the instrument panel (IP). Prototype designs or modifications could tune restraint systems to help better protect occupants in those oblique crash situations. Due to the lack of curtain airbag protection to the far-side occupants, occupant protection in far-side oblique impacts may be more challenging than near-side oblique impacts.

Several prototype seat belt designs, such as 4-point belt [9,10] and reversed 3-point belt [11], have the potential to help reduce the occupant injury risks in oblique crashes. Therefore, the objective of this study was to develop and demonstrate a new 4-point seatbelt system that can provide reduced injury potential for front right passenger in left (far-side) oblique frontal crashes through sled tests and computational crash simulations. However, we did not evaluate consumer acceptance or the feasibility for original equipment manufacturers to integrate these prototype systems into a particular vehicle environment.

II. METHODS

Three series (baseline, 4-point trail, and final) with a total of five sled tests and hundreds of computational simulations were conducted with the 50th percentile male THOR in the passenger far-side oblique frontal crash condition. The baseline sled test with a 3-point belt was conducted to produce similar THOR kinematics and injury measures to those in the NHTSA OMDB tests for small/midsize passenger cars. A prototype suspender 4-point belt, along with a slightly modified passenger airbag, were then used in three sled tests and MADYMO parametric studies to explore improved design parameters for the restraint system. A final sled test with the model-predicted improved prototype restraint design was conducted, and the injury measures to the head, neck, chest, abdomen, and lower extremities were compared between the baseline and final sled tests.

Prototype Suspender 4-point Belt

A prototype suspender 4-point belt (Fig. 1) is a concept similar to an airline flight attendant's jump seat, where the seat belt positions over the occupant's shoulders from behind the head and anchors on each side of the hip without crossing on the chest as the X-type system. This distributes more of the restraining forces on the shoulders/clavicles and less on the ribs. Two retractor pretensioners (PTs) with load limiters (LLs) positioned the belt over both shoulders, and two dynamic locking tongues (DLTs) anchored the lap portion. Since this system engages both shoulders, the load may be more evenly distributed over the occupant with a more symmetrical loading to the left and right sides of the body than with a three-point belt.

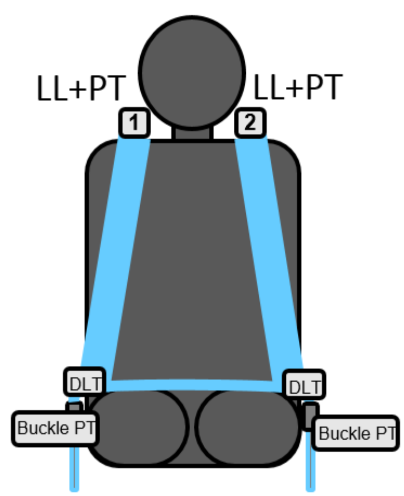
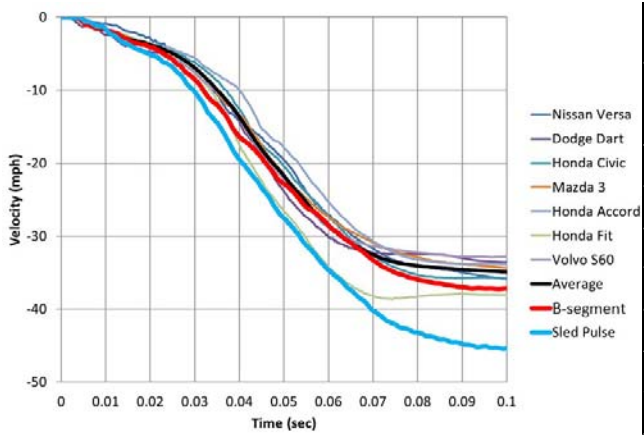


Fig. 1. Illustration of a suspender 4-point belt.

Sled Test Condition

In this study, a surrogate B-segment vehicle was used as the baseline vehicle. The crash pulse was based on the surrogate B-segment vehicle and seven other small/midsize passenger cars in the NHTSA OMDB crash conditions. Initially, the surrogate, *Average*, vehicle crash pulse was used as the baseline crash pulse for the sled tests. However, such a pulse could not reliably generate the occupant kinematics that were representative of those in the NHTSA OMDB crash tests. Therefore, the surrogate *Average* vehicle pulse was re-calculated using the resultant acceleration of the vehicle centre of gravity and represented by the *Sled Pulse* curve in Fig. 2. In a sled test, the sled (yaw) angle is generally fixed. Based on the free flight head trajectory comparison among different vehicles tested in NHTSA OMDB crash conditions, the average of the equivalent sled angle for all the tested vehicles is 17.92°. Therefore, in the current study, an 18° sled angle was used.



Vehicle	Free Flight Head Trajectory (R^2)
Mazda 3	19.16° (0.9932)
Honda Accord	19.24° (0.9927)
Volvo S60	16.19° (0.9957)
Nissan Versa	20.51° (0.9821)
Dodge Dart	17.77° (0.9955)
Honda Fit	15.45° (0.9988)
Honda Civic	17.12° (0.9959)
B-Segment	**17.71° (0.9945)**
Average*	**17.92°**

(a) Velocity profile (b) Equivalent sled angle

Fig. 2. Impact kinematics for eight vehicles in NHTSA oblique crash tests.

A sled buck representing the surrogate B-segment vehicle front-seat passenger compartments was adapted to be positioned at an initial sled angle 18° to the right to simulate far-side oblique impact. THOR was positioned following the NHTSA OMDB THOR positioning procedure [12]. The passenger seat was moved 40 mm rearward from the mid-track position to be more representative for small/midsize passenger cars. A 3-D coordinate measurement device was used to measure the initial ATD position/posture and restraint system configuration in the test to achieve test repeatability and document initial conditions that were used in the simulation studies. The measurements in each test followed NHTSA's specifications on THOR. The restraint systems used in the baseline sled tests were consistent to those used in the surrogate B-segment vehicle, which included a two-stage passenger airbag and 3-point belts with retractor pretensioner and switchable load limiting (SLL). The restraint firing times were based on those in the NHTSA OMDB tests, with 13/23 ms for passenger airbag (PAB) Stage 1 and Stage 2 and 11 ms for seatbelt retractor pre-tensioner.

In the second series of sled tests with suspender 4-point belt and the final sled test, the crash conditions were the same as the baseline tests, except for restraint systems. The restraint systems used in all five sled tests are shown in Table I.

TABLE I
RESTRAINT SYSTEM USED IN THE SLED TESTS

Test Series	Seat belt *	Passenger airbag
Baseline	3-point belt with SLL	Baseline PAB: 110 L, 440 kPa inflator, and 2X65mm vents
Second Series	Suspender 4-point belt, Torsion bar: L12mm/R8mm	V13 PAB: 140 L, 440 kPa inflator, and 2x65mm vents
	Suspender 4-point belt, Torsion bar: L10.5mm/R8mm	
	Suspender 4-point belt, Torsion bar: L10.5mm/R8mm	Deeper PAB
Final	Suspender 4-point belt, Torsion bar: L9mm/R8mm	V13 PAB

* Suspender 4-point belts are prototype systems. The 8, 9, 10.5, and 12 mm torsion bars are approximately equivalent to 1.8, 2.7, 4.2, and 4.5 kN load limiting, and L and R indicate left and right shoulders.

Computational Model Development and Validation

A baseline model in MADYMO (TASS International, Netherlands) was developed in this study. The MADYMO

THOR-NT v2.0 model with the SD-3 shoulder has been validated against physical dummy tests at both component and whole-body level. The sled model included detailed geometry of the vehicle interior (seat, instrument panel, door interior, and windshield, etc.) and detailed restraint systems for front seat passengers (3-point seatbelt, seatbelt retractor with pretensioner and load limiting, anchor pretensioner, passenger airbag, and knee bolster). To validate the model, simulations were set up to match the baseline test as well as a test with suspender 4-point belt configurations. The model validation process followed those from previous studies, in which sensitivity analyses and optimisation techniques were used to validate ATD responses against sled tests [13-15]. THOR's responses that were used for model validation included head, chest, and pelvis accelerations, chest deflections, and neck and femur forces. To evaluate the level of correlation between the test and simulation results, statistical assessments were performed in addition to visual comparison between test and simulation results. CORA scores were calculated for each measurement of the tests to evaluate the model quality. A CORA score of 1.0 represents a precise match between the test and simulation, while CORA score of 0.0 represents no correlation between the test and simulation results.

Computational Parametric Simulations

Two sets of parametric simulations were conducted to further investigate the combined effects from passenger airbag and suspender 4-point belt designs on occupant protection in the passenger far-side impact condition. The first parametric study was conducted with a variety of suspender 4-point belts and baseline PAB designs. The design parameters that varied in this parametric study included the inflator (baseline and large), airbag depth (100% and 110% from the baseline), vent diameter (65, 75, and 85 mm), right shoulder retractor torsion bar (7.0, 7.5, and 8.0 mm), and left shoulder retractor torsion bar (9.5, 10.5, and 11.5 mm), which resulted in a total of 108 (2x2x3x3x3) simulations. Taking the results from the first parametric study, the second parametric study was conducted with a variety of prototype suspender 4-point belts and another passenger airbag (V13 PAB) designs, which is a deeper airbag with a larger inflator. The design parameters that varied in this parametric study only included the vent diameter (40, 50, 60 and 70 mm), and left shoulder retractor torsion bar (9.5, 10.5, and 11.5 mm) with the right retractor torsion bar diameter fixed (8 mm), which resulted in a total of 12 (4x3) simulations. ModeFRONTIER (ESTECO), a multi-objective optimisation software programme, was coupled with MADYMO to conduct the parametric simulations.

III. RESULTS

Baseline Sled Test

Overall, the baseline sled tests produced similar THOR kinematics to those in the NHTSA OMDB full vehicle tests; and the injury measures, especially the BrIC and maximal chest deflections, were also consistent to the OMDB tests. Fig. 3 shows THOR's kinematics in the baseline sled tests. Specifically, the torso of the THOR rotated toward the impact direction, shifted out of the shoulder seatbelt, and its head rolled laterally off the passenger airbag. These kinematics resulted in head to IP contact and an elevated BrIC value. Table II shows some of the critical injury measures along with some basic occupant kinematic characteristics for both the OMDB full vehicle tests and the baseline sled tests. The sled test generated HIC, BrIC and chest deflection within the range of those in vehicle OMDB tests.

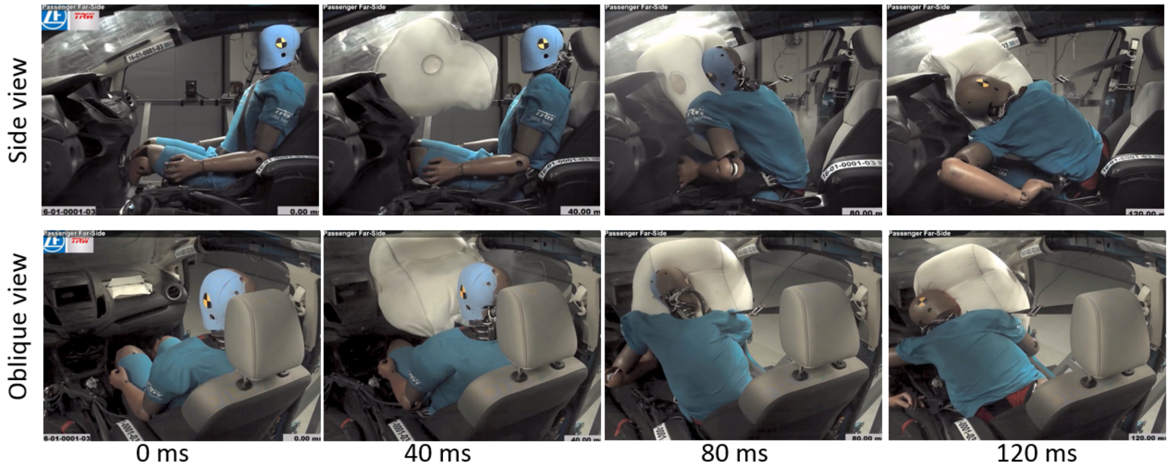


Fig. 3. Occupant kinematics in the passenger far-side baseline sled test.

TABLE II
INJURY MEASURES AND MECHANISMS IN THE PASSENGER FAR-SIDE OBLIQUE TESTS

Vehicle	HIC	BrIC	ChestD (mm)	ChestD Location	Head Contact	Belt Rollout
Mazda 3	806	1.12	38	Near Buckle	IP	Yes
Honda Accord	935	1.46	39	Near Buckle	IP	Yes
Volvo S60	223	1.46	31	Near Nothing	IP	Yes
Nissan Versa	543	1.91	41	Near Buckle	IP	Yes
Dodge Dart	113	2.21	35	Near Nothing	Header/ IP	Yes
Honda Fit	908	2.23	56	Near Buckle	IP	Yes
Honda Civic	272	2.81	42	Near Buckle	IP	Yes
Average	543	1.89	40	Near Buckle / Near Nothing	IP	Yes
Baseline Test Sled 0001-03	332	1.55	50	Near Nothing (UL)	IP	Yes

Second Series of Sled Test with Prototype Suspender 4-point Belt

By using the suspender 4-point belt, three sled tests in the second sled series generated lower BrIC and maximal chest deflection than the baseline test. Specifically, the suspender 4-point belt with higher load limit on the left shoulder and lower load limit on the right shoulder allows the torso to rotate toward the impact direction (left) without torso twist. These kinematics helped to prevent large head lateral rotation, and consequently reduced the BrIC value. The chest deflection reduction is due in-part to the loading path of the suspender belt, which used the clavicle more than the ribs.

TABLE III
INJURY MEASURES IN THE THREE SLED TESTS WITH SUSPENDER 4-POINT BELT

Restraints	Head		Neck		Chest	Abdomen		Acetabular		Femur	
	HIC	BrIC	Old N_{IJ}	New N_{IJ}	R_{MAX}	Dmax (L)	Dmax (R)	Fmax (L)	Fmax (R)	Comp (L)	Comp (R)
Baseline, PAB	332	1.55	0.81	0.47	49	82	75	1657	4430	3010	990
L12/R8, V13	662	0.71	1.00	0.74	34	Lost	Lost	3,090	3,070	2,891	5,320
L10.5/R8, V13	548	0.64	0.92	0.69	36	Lost	Lost	2,240	2,520	3,689	2,702
L10.5/R8, Deeper PAB	898	0.76		0.90	41	42	35	2,310	2,450	3,550	2,250

Model Validation

The MADYMO model was validated against the baseline test and a test with suspender 4-point belt (L10.5mm/R8mm). Fig. 4 and Fig. 5 show the validation results. Generally speaking, the MADYMO provided reasonable validity. The suspender 4-point belt model shows better validation than the baseline 3-point belt.

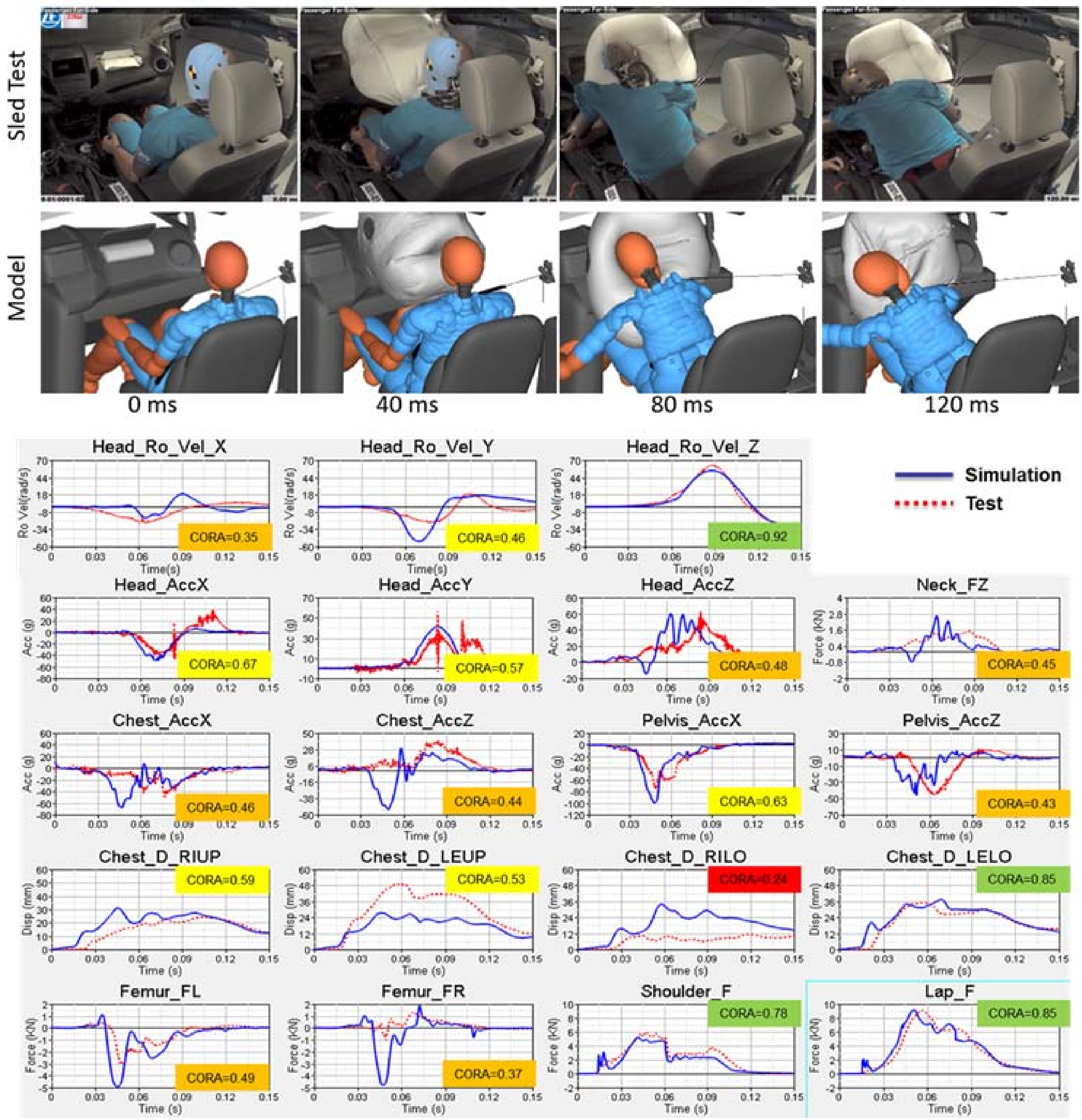


Fig. 4. Model-predicted occupant kinematics and injury measures compared with baseline test.

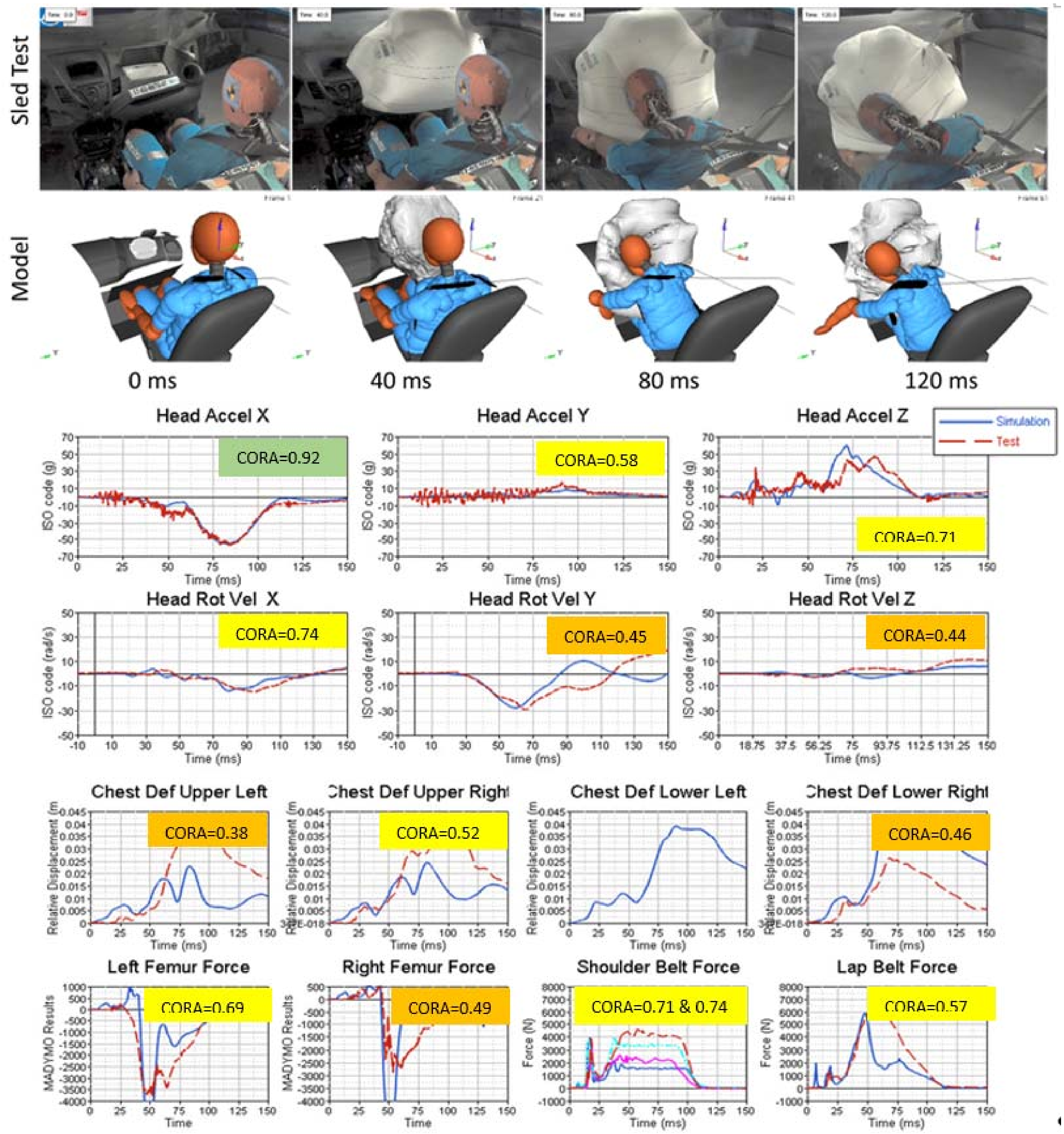


Fig. 5. Model-predicted occupant kinematics and injury measures compared with test using suspender 4-point belt.

Parametric Simulations

Fig. 6 shows the design parameter effects on THOR head and neck injury measures, which were reported as the percentage of injury measures in the baseline restraint model shown in Table III. Overall, the prototype suspender 4-point belt resulted in lower injury values than the baseline 3-point belt design, as the majority of the injury measures were below the baseline model (<100%). There were large variations in HIC values, due to some soft restraint designs, which caused the THOR to contact the IP. Some general trends were worth noting, including potential injury reductions by having a larger inflator with a deeper airbag, and using an 8-mm torsion bar on the right shoulder. The effects of the airbag vent diameter and the left shoulder torsion bar had on the head and neck injury measures are nonlinear.

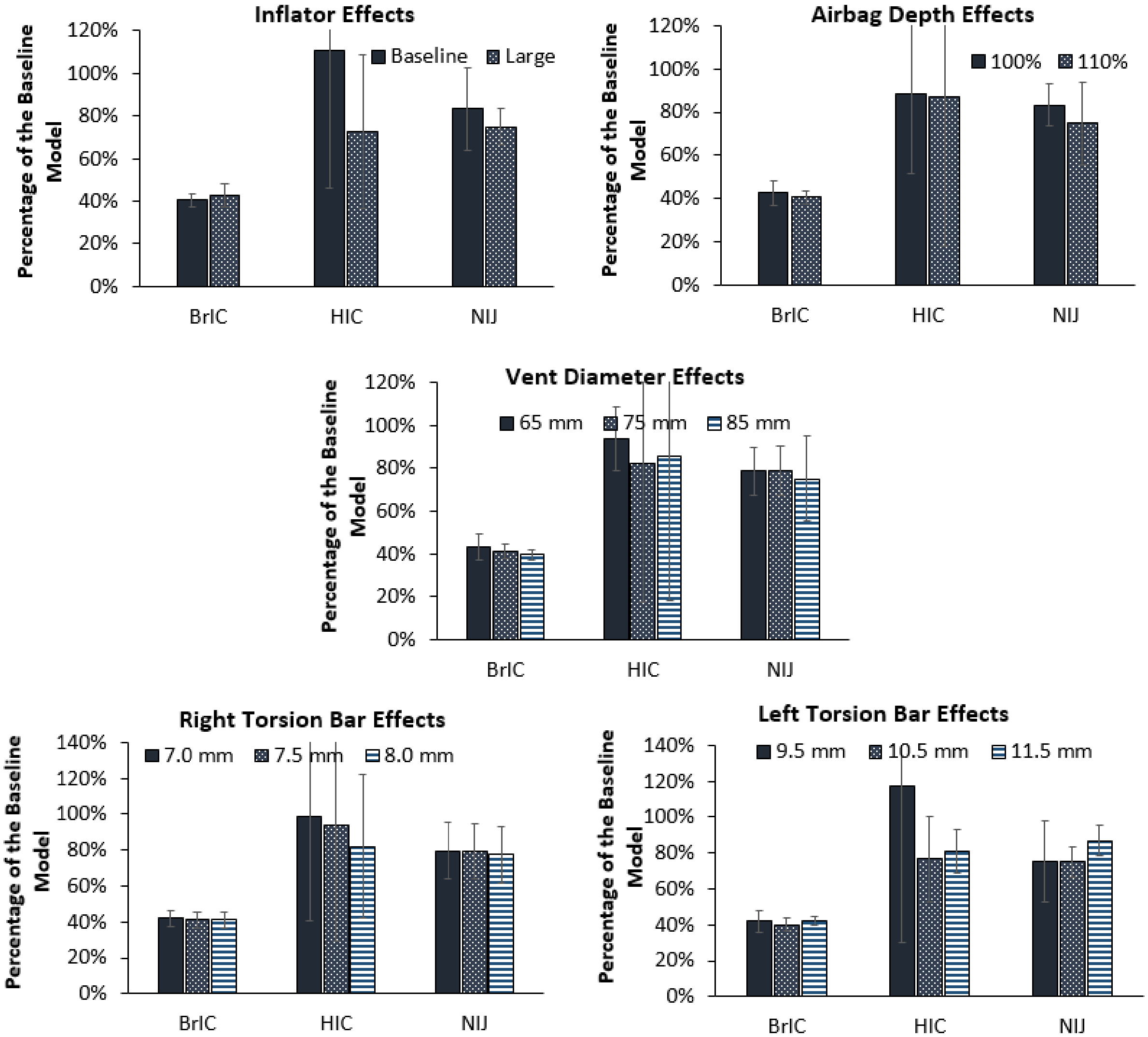


Fig. 6. Airbag and seatbelt effects on ATD injury measures in passenger far-side impacts.

Table IV shows the head and neck injury measures for all the 12 simulations in the second set of parametric simulations. Simulation No. 4 provided the lowest HIC and BrIC values. There were conflicting effects between BrIC and Nij, but many designs provided lower head and neck injury measures than the baseline design.

TABLE IV
HEAD AND NECK INJURY MEASURES IN THE PARAMETRIC STUDY WITH SUSPENDER 4-POINT BELT AND V13 PAB

ID	Vent Size (mm)	Belt	HIC	BrIC	Old Nij	New Nij
1	40	Suspender (R8L9.5)	997	1.20	0.59	0.35
2	50	Suspender (R8L9.5)	799	0.76	0.68	0.40
3	60	Suspender (R8L9.5)	639	0.57	0.79	0.47
4	70	Suspender (R8L9.5)	520	0.54	0.87	0.52
5	40	Suspender (R8L10.5)	959	0.81	0.68	0.41
6	50	Suspender (R8L10.5)	798	0.58	0.71	0.43
7	60	Suspender (R8L10.5)	642	0.56	0.90	0.54
8	70	Suspender (R8L10.5)	536	0.55	1.02	0.61
9	40	Suspender (R8L11.5)	932	0.73	0.85	0.51
10	50	Suspender (R8L11.5)	764	0.70	0.97	0.58
11	60	Suspender (R8L11.5)	644	0.66	1.11	0.66
12	70	Suspender (R8L11.5)	542	0.67	1.18	0.71

Fig. 7 shows a comparison on THOR kinematics between the simulated baseline restraint, one of the alternate restraints in the first sets of parametric simulations, and one of the alternate restraints in the second sets of parametric simulations. The prototype suspender 4-point belt and the alternate airbag helped to achieve reduced lateral head rotation and in turn a reduction in BrIC values by holding the left (inboard) shoulder tighter than the right (outboard) shoulder. The deeper airbag and larger inflator helped to achieve earlier engagement between the airbag and the THOR's head, which reduced the HIC and Nij.

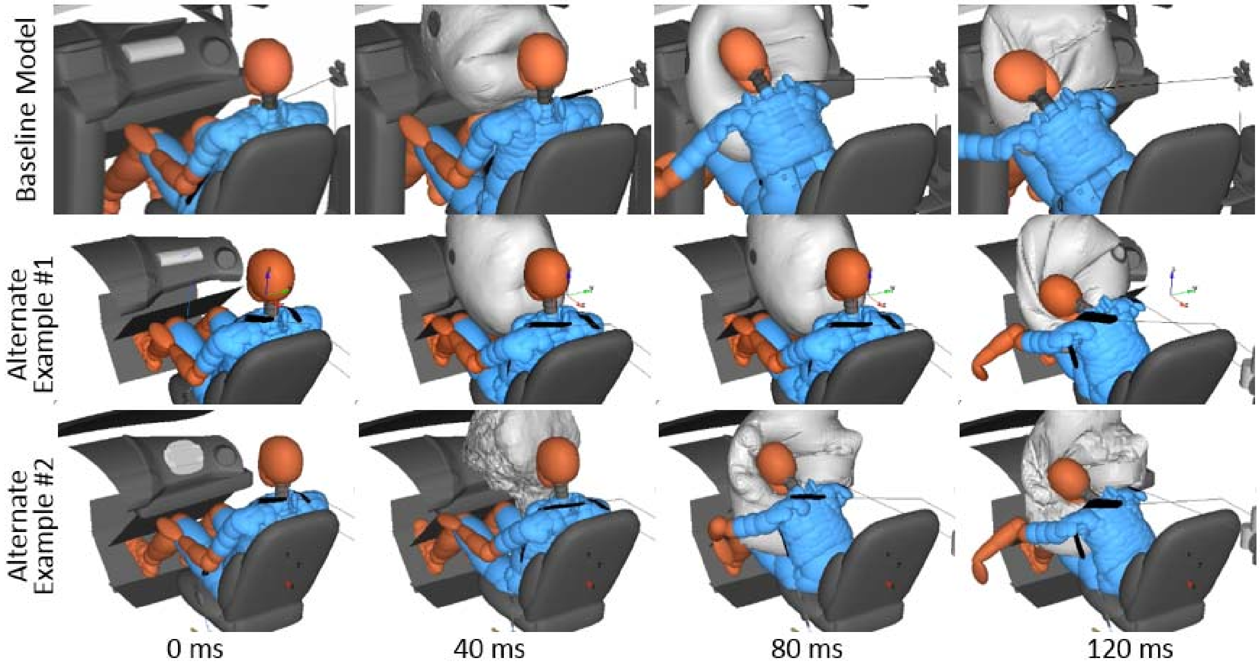


Fig. 7. THOR kinematics with the baseline restraint and two alternate PAB and prototype suspender 4-point belt designs.

Final Sled Test

The THOR kinematics in the baseline test and the test with the advanced prototype suspender 4-point belt and slightly changed airbag are shown in Fig. 8. The associated injury measures are shown in Table IV. The test with the suspender 4-point belt design showed reduced BrIC and chest deflection values, which are two concerns in the baseline test. The HIC and Nij with the suspender 4-point belt increased slightly from the baseline test potentially due to a larger head whipping motion, but such motion helped reduce the lateral head rotation and BrIC. This tradeoff between BrIC and Nij with the suspender belt existed.

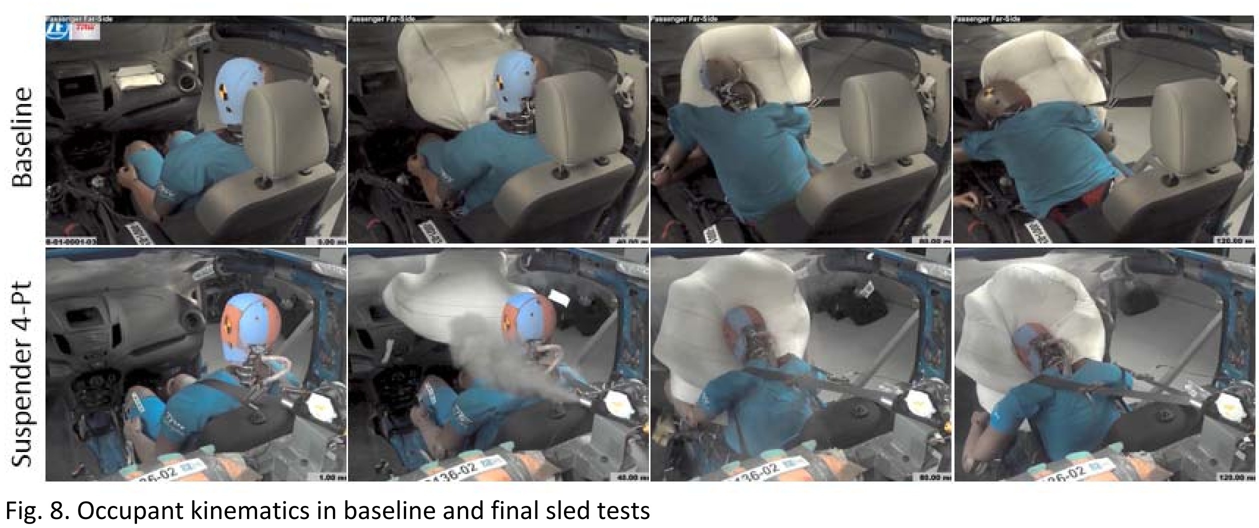


Fig. 8. Occupant kinematics in baseline and final sled tests

TABLE IV
INJURY MEASURES IN BASELINE AND FINAL SLED TESTS

Test	Head		Neck		Chest	Abdomen		Acetabular		Femur	
	HIC	BrIC	Old N_{IJ}	New N_{IJ}	R_{MAX}	Dmax (L)	Dmax (R)	Fmax (L)	Fmax (R)	Comp (L)	Comp (R)
Baseline	332	1.55	0.81	0.47	50	82	75	1657	4430	3010	990
Final	543	0.53	0.96	0.58	38	39	-	2310	2450	3550	2250

IV. DISCUSSION

The NHTSA OMDB crash condition is a new and different crash condition and can pose unique challenges for occupant protection. First, in an oblique impact, the ATD has the potential to contact the edge/side of the driver or passenger airbag, inducing lateral head rotation and potential contact between the ATD's head and vehicle interior, e.g., door and IP. Such kinematics could result in increased HIC and/or BrIC values. Regarding the head injury measures, typically far-side oblique impacts are more challenging than near-side impacts, because in near-side impacts the vehicle front door may limit the ATD torso's lateral movement and curtain airbags may provide lateral support to the ATD's head. In a far-side oblique impact, an occupant can shift out of the shoulder belt of a typical 3-point belt, which may reduce the seatbelt effectiveness and potentially limit the possibility of reducing the chest deflection by lowering the shoulder belt load limiting.

The advantages of the prototype suspender 4-point belt were: 1) two shoulder belts apply loading on the clavicles, which helped reduce the chest deflection; 2) different load limiting could be assigned to the two shoulder belts, which helped control the torso rotation during the oblique impact and consequently prevented a large lateral head rotation; 3) with a proper sensing system, the shoulder belt load limiting could adapt to the impact direction (higher load limiting on the shoulder close to the impact direction), which provided an opportunity to better protect the occupant equally between near-side and far-side impacts. The results show that the prototype suspender 4-point belt did not require airbag changes to help improve occupant protection in oblique crash conditions, and generally provided lower injury potential than the restraint systems with 3-point belts from a safety point of view. However, we did not evaluate consumer acceptance or the feasibility for original equipment manufacturers to integrate a 4-point belt system into a particular vehicle environment.

In this study, only a single vehicle right front seat passenger compartment based on a compact vehicle was investigated with the midsize male THOR. Therefore, the findings from this study cannot be generalised for all vehicles or occupants with significantly different size from the midsize male. Additional simulations could determine whether the compartment size, crash pulse, crash angle, occupant size could affect the advanced prototype restraint design solutions. Finite element human models with varied size and shape may also be applied in the future to evaluate the effectiveness of this new restraint system [16].

V. CONCLUSIONS

This study investigated a new prototype 4-point belt design and its effects on front seat passengers in far-side oblique crash conditions through five sled tests and hundreds of computational simulations. The results demonstrated that a suspender 4-point belt has the potential to improve passenger protection, including measured reductions in the head and chest injury values, in the tested oblique crash condition. The results also indicated that a suspender 4-point belt design can potentially improve occupant protection in other oblique frontal crash conditions.

VI. ACKNOWLEDGEMENT

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