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SEATBELT-MOUNTED AIRBAG DESIGN FOR OCCUPANT PROTECTION IN TACTICAL VEHICLES DURING FRONTAL CRASHES

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ABSTRACT

Seatbelt-mounted airbag *is a new type of occupant restraint system, in which the airbag is integrated into the seatbelt and hence can be easily and quickly implemented into the current tactical vehicles without significant vehicle structure or interior changes. The objective of this study was to develop, optimize, and demonstrate seatbelt-mounted airbag designs for reducing occupant injury risks in a light tactical vehicle under frontal crashes. A total of 19 sled tests and over 30 FE simulations were performed to find the optimal seatbelt-mounted airbag designs for protecting occupants represented by three sizes of ATDs and two military gear configurations. Various lap-belt-mounted airbag and shoulder-belt-mounted airbag designs were evaluated for driver, front-seat passenger, and rear-seat passenger locations in a tactical vehicle. The test and simulation results showed that the optimized designs substantially reduced the occupant injury risks to the head, neck, and chest compared to the baseline tests. This study demonstrated the benefit of adding a properly designed seatbelt-mounted airbag to improve the occupant protection in frontal crashes under an environment representing a light tactical vehicle.*

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1. INTRODUCTION

Motor vehicle crashes (MVCs) accounted for a significant proportion of non-battle injuries in recent military conflicts. Writer et al. [1] reported that MVCs were the leading cause of non-battle injury among hospitalized U.S. Army soldiers deployed to the Persian Gulf War. Hauret et al. [2] also reported that 35% of soldiers in Iraq and 36% of soldiers in Afghanistan had non-battle injuries, and 12%-16% of them were caused by MVCs.

Although the influence of advanced restraint systems, such as seatbelt pre-tensioners, load limiters, and airbags, on civilian occupant kinematics and injury outcomes in MVCs has

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been extensively studied and demonstrated [3-7], advanced restraint systems are currently not available in tactical vehicles. In our previous studies published in GVESTS [8] and SAE [9], the benefit of driver and passenger airbags in improving the occupant protection in tactical vehicles has been clearly demonstrated in frontal impact conditions through crash tests and finite element (FE) simulations. Specifically, the driver airbag and passenger airbag can effectively reduce the head contact to the interior and/or head whipping motion during frontal crashes, and in turn reduce the head and neck injury measures. These airbags can also allow a lower load limit to be used in the seatbelt, which leads to lower chest injury measures. However, installation of these airbags requires major changes in the current vehicle designs. In particular, the steering column and steering wheel have to be replaced by a new system to accommodate the driver airbag, and some components in the right front passenger interior have to be modified and removed to install the passenger airbag. Such modifications are rather time-consuming and very difficult to be implemented into the vehicle production process.

To solve this problem, in the current study, seatbelt-mounted airbag designs were proposed. A seatbelt-mounted airbag is a new type of airbag system, in which the airbag is integrated into a seatbelt. Because no vehicle interior modifications are needed and only replacement of the seatbelts is required, such systems can be easily and quickly implemented into the current military vehicles. Therefore, the objectives of this proposed study were to develop and optimize seatbelt-mounted airbag designs, and demonstrate their benefit in reducing occupant injury risks in frontal crashes.

2. METHODS

An overview of the methods being used during the entire study is shown in Figure 1, which included several series of sled tests, computational model development and validation, baseline full vehicle crash test, parametric simulations, design optimizations, and final full vehicle crash test. Because the sled tests without airbag and model development and validation against those sled tests have been presented previously [8], in this paper we focus on the sled tests and simulations with the seatbelt-mounted airbag only and how the optimized designs compared to the baseline design without airbag in terms of occupant injury measures. Baseline sled tests are presented for comparison purpose.

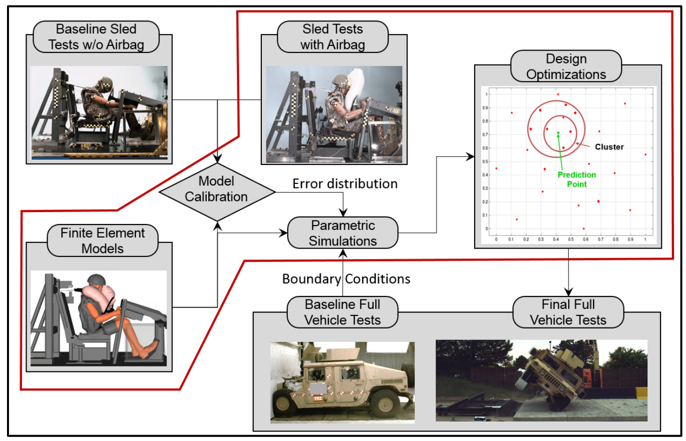

Figure 1: Method overview for the entire project (Focus of this paper is highlighted in red)

Computational modeling and sled testing were performed to identify the optimal restraint design solutions. Occupants were represented by the Hybrid-III 5th percentile female, 50th and 95th percentile male ATDs. Two military gear configurations were used: improved outer tactical vest (IOTV) and a SAW Gunner configuration using a tactical assault panel (TAP). Testing and simulations were conducted for driver, commander (front passenger), and rear-seat passenger seating positions. In this study, we only focused on the following four conditions:

1) **Driver:** 50th male ATD, IOTV only
2) **Commander:** 95th male ATD, SAW Gunner with IOTV, TAP and Camelbak
3) **Rear seat passenger:** 50th male ATD, IOTV and Camelbak

4) **Rear seat passenger:** 5th female ATD, IOTV and Camelbak

2.1. Seatbelt-mounted Airbag Designs

Seatbelt-mounted airbags are a new type of airbag system, in which the airbag is integrated into either the shoulder belt or lap belt. Compared to the traditional airbag designs, which are installed in the steering wheel, instrument panel, or the seat, seatbelt-mounted airbag design combines the seatbelt and airbag together, and hence can be easily and quickly implemented into the current tactical vehicles, without changing the existing vehicle interior designs. As shown in Figure 2, the seatbelt-mounted airbag design concept can be applied to different types of seatbelt designs. In this study, a variety of seatbelt-mounted airbag designs were evaluated, including:

1) 2-point belt with lap-belt-mounted airbag
2) 3-point belt with lap-belt-mounted airbag
3) 3-point belt with shoulder-belt-mounted airbag
4) 4-point belt with 2 shoulder-belt-mounted airbags
5) 5-point belt with 2 shoulder-belt-mounted airbags
6) 5-point belt with 2 shoulder-belt-mounted airbags and an additional hybrid bag

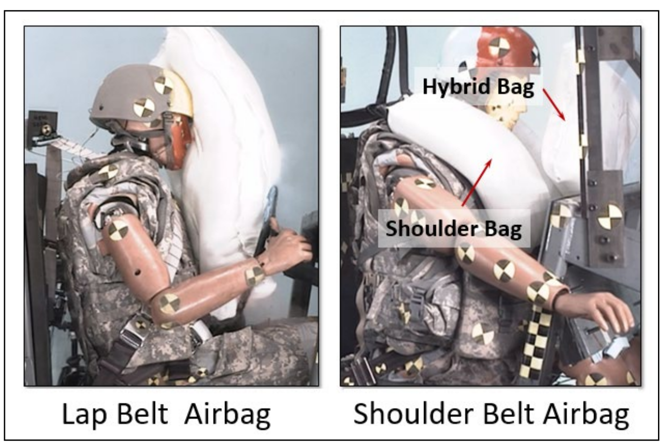

Figure 2: Seatbelt-mounted airbag design examples (Three-point lap belt airbag on the left, and five-point shoulder belt airbag with a hybrid airbag on the right)

2.2. Sled Tests

A total of 19 frontal-impact sled tests were conducted using a custom-built sled buck that was based on 3D scans of a Hummer H1 vehicle (Figure 3). The buck was reconfigurable to represent the driver, commander, and rear-seat compartments. All tests were performed in a frontal crash configuration with a 30-mph delta-V and a peak acceleration of 25 g. All ATDs in the sled tests were outfitted with standard issue military combat boots, Advanced Combat Helmet (ACH) and one of the military gear configurations (IOTV or SAW Gunner) for every test. Each ATD was positioned based on soldier posture data from the Seated Soldier Study [10] conducted by the University of Michigan Transportation Research Institute. The ATD posture was verified using a FaroArm digitizer. Head, neck, chest, and lower-extremity injury measurements from the ATDs, as well as the belt loads, were collected in each test. Multiple high-speed video cameras were also used in each test to record the kinematics of the ATDs.

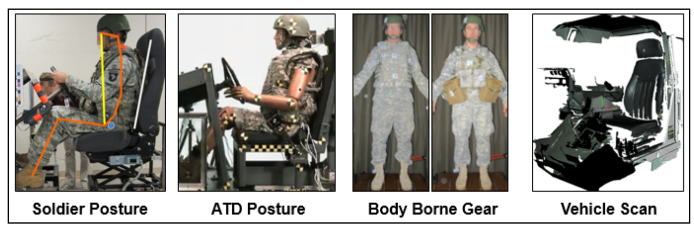

Figure 3: Sled test setup to mimic real soldier seating and body borne gear conditions in a tactical vehicle

Various lap-belt-mounted airbag and shoulder-belt-mounted airbag designs were evaluated for driver, commander, and rear-seat passenger locations in a tactical vehicle. The testing matrix is attached in the Appendix.

The injury outcomes for each test were determined using each respective ATD's Injury Assessment Reference Values (IARVs) as shown in Table 1, which are based on the Federal Motor Vehicle Safety Standards (FMVSS) No. 208. The injury measures examined in the present study include the head injury criterion (HIC), neck tension (NeckT), neck compression (NeckC), neck injury criteria (Nij), chest acceleration (ChestG), chest deflection (ChestD), and left and right femur force (LFF, RFF).

The HIC is a measure of the likelihood of head injury resulting from an impact, and is defined as

$$HIC_{15} = max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1) \quad [1]$$

where a(t) is head acceleration as a function of time, and t_1 and t_2 represent a 15-ms time interval over the acceleration pulse.

The Nij measures the likelihood of neck injury using measured neck forces and moments normalized to critical injury tolerance levels determined from experimental testing. Nij is defined as

$$Nij = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \quad [2]$$

where F_z is the axial load on the neck, M_y is the flexion/extension bending moment of the neck, and F_{int} and M_{int} are the corresponding critical intercept values of load and moment, respectively, used for normalization. Nij is computed at all-time instances, and the maximum value from all combination of loading modes (tension, compression, flexion, extension) is reported.

Table 1: IARVs from FMVSS No. 208 [11]

Body Region	Injury Measure	95M ATD	50M ATD	5F ATD
Head	HIC-15	700	700	700
Neck	Nij Critical Intercept Values Ten and Comp (N) Flexion (Nm) Extension (Nm)	1.00 5440 415 166	1.00 4500 310 125	1.00 3370 155 62
	Neck axial tension (kN)	5.44	4.17	2.62
	Neck compression (kN)	5.44	4.0	2.52
Chest	Chest acceleration (g)	55	60	60
	Chest deflection (mm)	70	63	52
Leg	Femur axial force (kN)	12.7	10	6.805

2.3. Computational Models

A set of FE models developed previously, including the test buck, three ATDs (HIII 5th, 50th, and 95th), and military gear configurations (helmets, IOTVs at different sizes, and SAW Gunner) were used in this study. The test buck model was developed based on the design CAD data. The LSTC public models were used for the ATDs. The geometry of the models for military gear was based on the Seated Soldier Study with simplification and modification [8]. The seatbelt-mounted airbag models were developed in this study with the airbag models provided by AMSafe and validated against airbag component tests.

The validation of this set of FE models without airbags was presented previously [8]. In the current study, we focus on the results of integrating the seatbelt-mounted airbag models into the simulations, validating the integrated model against a subset of the sled test results, and running parametric simulations to improve the restraint performance in reducing occupant injury risks.

Figure 4 shows an example of positioning the ATD, adding IOTV, helmet, and Saw Gunner onto the ATD body, and integrating the ATD, military gear, and seatbelt models into the sled buck. The ATD model was positioned and postured based on the FaroArm data measured in the sled tests.

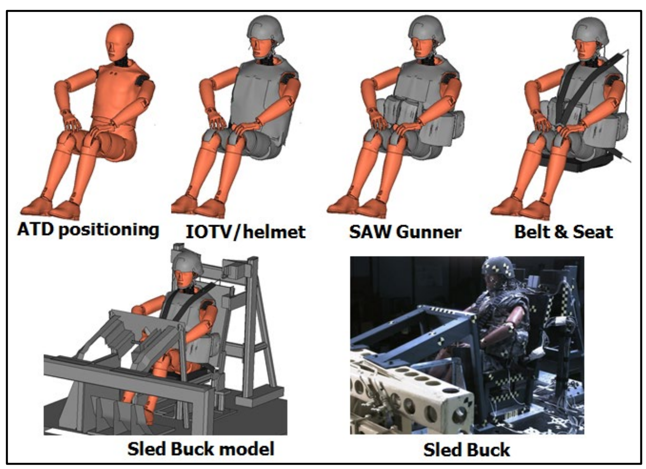

Figure 4: An example of building FE models to simulate the crash condition

2.4. Restraint Design Optimizations

Based on the tests and simulations with the baseline restraint systems from our previous studies [8], the major safety concerns in a frontal crash with the baseline restraint system (without an airbag) are the potential head contact to the vehicle interior, high neck tension force and Nij, and sometimes high chest deflections and femur forces. In theory, a properly designed airbag should be able to prevent the hard head contact to any stiff interior, reduce the whipping motion of the head and thus reducing the neck force and Nij, and potentially allow the occupant to pitch more forward by using a lower load limit to reduce chest deflection.

In this study, the injury measures for the head, neck, chest and lower extremities were considered as the objective functions to be minimized, while the IARVs associated with the injury measures were considered as the design constraints. In other words, the optimal restraint design should have the lowest injury measures and at the same time all the injury measures should be below the IARVs.

Due to the nature of FE simulations, a systematic optimization with hundreds of simulations is too time-consuming and not possible for each crash scenario. Therefore, in this study, simulated designs as well as the final recommended systems were manually selected based on the testing and simulation results and engineering judgement from experienced injury biomechanists.

3. RESULTS

3.1. General ATD Kinematics with and without Seatbelt-mounted Airbag

Figures 5 and 6 show exemplar kinematics of the 95th ATD (with SAW Gunner TAP) on the commander location and the 50th ATD (with IOTV) on the rear seat using a 5-point seat belt with and without shoulder-belt-mounted airbags and a hybrid bag. Seatbelt retractor load limiters and lap belt pre-tensioners were used for cases with the airbag but not for cases without airbag.

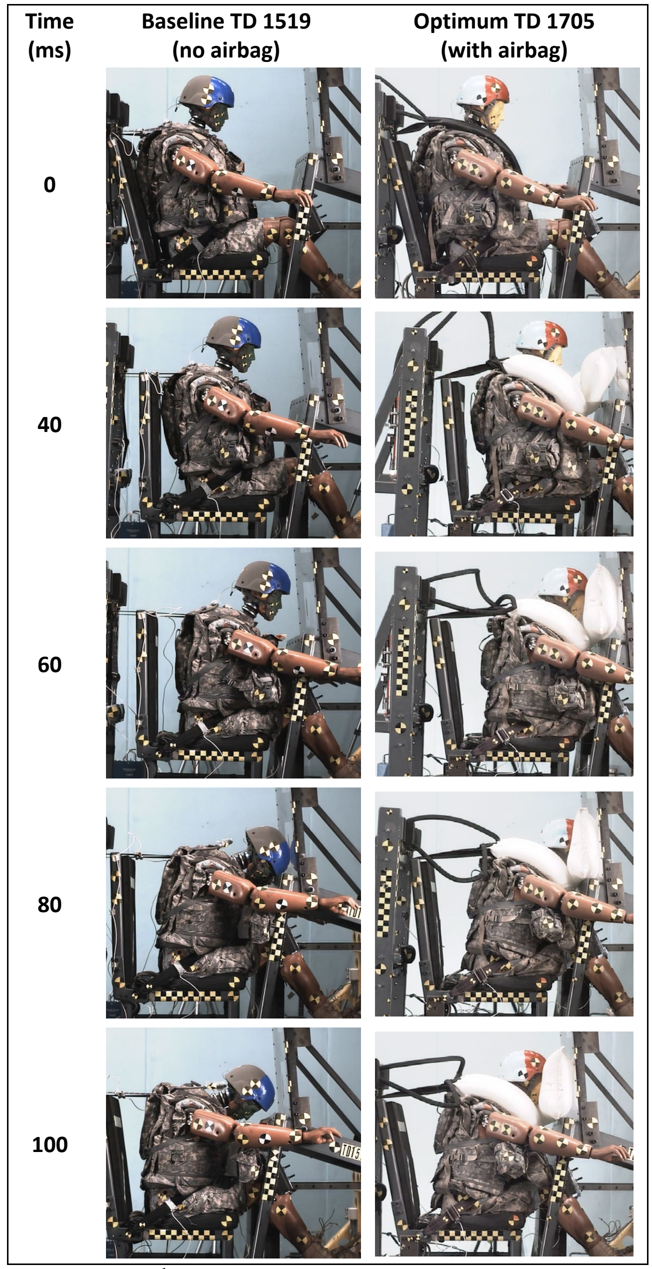

Figure 1: 95th ATD (with SAW Gunner) kinematics in the commander location with and without airbag

Although the performance of the seatbelt-mounted airbags varied from test to test, generally speaking, ATD kinematics were better with a properly functioning seatbelt-mounted airbag than without an airbag. In particular, the airbag significantly improved torso and head kinematics. As a result, neck injury measures were reduced and the head was prevented from impacting the the instrument panel for the commander. In addition, the torso of the 50th ATD with IOTV pitched much more forward when using an airbag along with a belt load limiter. This kinematics can effectively reduce the chest deflection, as the belt forces were added more on the shoulders than the ribs.

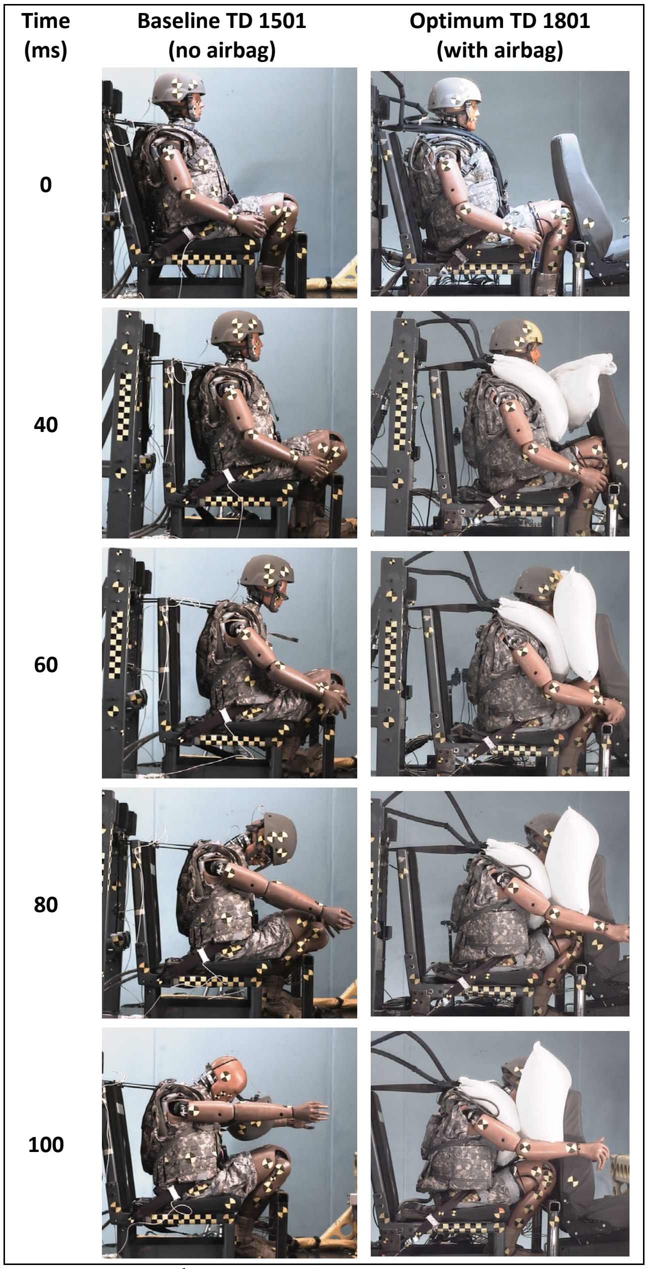

Figure 6: 50th ATD (with IOTV) kinematics in the rear-seat location with and without airbag

3.2. Model Validations with Seatbelt-mounted Airbag

Model validations against a subset of the sled tests with the seatbelt-mounted airbag were conducted to assess the model accuracy. Figures 7 and 8 showed two examples of the comparisons between the tests and the simulations with shoulder-belt-mounted airbags. Overall, reasonable model and test correlations were achieved across crash conditions. More specifically there is a good match of occupant kinematics, but the chest deflection and belt forces did not correlate well with the test data. This is likely due to the complicated belt-vest-chest interactions, which may require additional investigations.

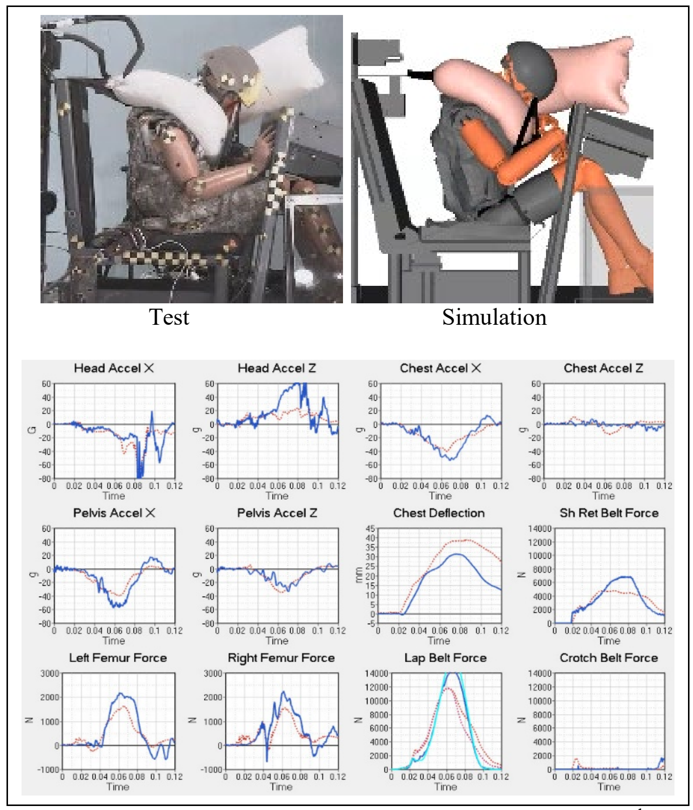

Figure 7: Model injury measure validation for 50th ATD with IOTV, 5-point belt, and two shoulder-belt-mounted airbags with a hybrid bag in the driver location (Red: test / Blue: simulation)
Note that the hybrid bag did not get to the proper location in this test.

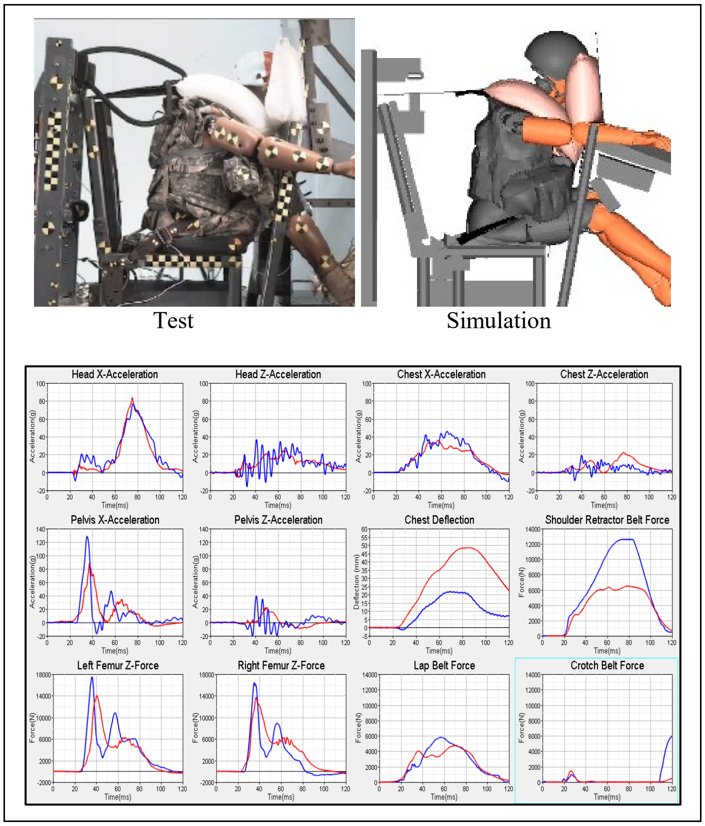

Figure 8: Model injury measure validation for 95th ATD with SAW Gunner, 5-point belt, and two shoulder-belt-mounted airbags with a hybrid bag in the commander location
(Red: test / Blue: simulation)

3.3. Design Optimization and Injury Measure Reduction with Seatbelt-mounted Airbags

FE simulations were conducted in a case-by-case manner for the 50th ATD in the driver location, 95th ATD in the commander location, and 5th and 50th ATD in the rear-seat location. Although the lap-belt-mounted airbag works reasonably well for the driver, it does not work for the commander with the SAW Gunner TAP. The SAW Gunner TAP will sit on top of the lap belt, which will likely prevent a proper airbag deployment. We also found that the hybrid airbag is highly beneficial in reducing the head injury measures. For these reasons, we focused on the simulations and design optimization for the 5-point belt with 2 shoulder airbags and a hybrid bag. The design parameters included airbag shape, mounting location, inflation, jet angle, and vent size, as well as seatbelt load limit and the presence of lap belt pre-tensioner(s).

Generally speaking, it is challenging to get the hybrid bag deployed to the designed location. Therefore, the bag location and jet angle have to be carefully tuned to ensure a proper deployment. We also found that increasing the airbag inflation (+30% from the initial design), adding two anchor pre-tensioners to the lap belt and using a shoulder belt load limit in the range of 3 to 4 kN can benefit the restraint system performance in reducing the ATD injury measures.

Table 2 shows the injury measures in the tests with optimal restraint designs, reported as percentages of those in the baseline tests in four investigated conditions. The majority of the injury measures with the optimal restraint designs are much lower (better) than those in the baseline tests, especially for the head and neck.

Table 2: Injury measures with the improved seatbelt-mounted airbag designs as percentages of those in the baseline tests

Condition	Improved seatbelt-mounted airbag*			
	Driver	Commander	Rear-seat	Rear-seat
ATD	50th	95th	5th	50th
HIC	68%	36%	92%	60%
Nij	44%	68%	72%	34%
Neck T	40%	101%	46%	42%
Chest D	117%	81%	65%	83%
Femur F		79%**	99%	101%

*All values of baseline injury measures in different conditions are different, but they were all set as 100%.
**All the injury measures with the improved seatbelt-mounted airbags are below the IARVs, except for the femur force for the commander.

4. DISCUSSION

This study demonstrated the feasibility and benefit of adding a properly designed seatbelt-mounted airbag with advanced seatbelt features to improve occupant protection in frontal crashes in an environment representing a light tactical vehicle. Through sled tests and computational simulations, the head, neck, chest, and femur injury measures of the ATDs were reduced significantly with improved restraint designs.

The baseline sled tests and simulations demonstrated that Hybrid III ATDs in an environment similar to light tactical vehicles exhibit significantly different occupant kinematics than are typically seen in passenger vehicles. The lack of a knee bolster in the driver location allowed for large lower extremity excursions resulting in submarining kinematics using a baseline 5-point belt without pre-tensioner and load limiter. Without an airbag in the driver or the commander locations, head and chest excursions were also elevated, leading to a high probability of contact with the steering wheel or the instrument panel. This was especially true for the 95th ATD with the SAW Gunner gear configuration at the commander location due to the added mass. The high neck injury measures seen in the baseline tests were generally due to inertial loading due to head kinematics and not to direct force applied to the head.

By integrating a properly designed seatbelt-mounted airbag into the restraint system, it allowed a lower load limit to be used for the seatbelt, which resulted in lower chest deflections in most conditions. However, the chest deflection was not reduced for the 50th ATD in the driver location. This may be associated with the fact that IOTV can distribute the chest load, which makes the airbag less effective for reducing the chest deflection. It should be mentioned that the chest deflection was always below the IARV in the baseline tests, thus it is not the major concern in the design optimization. On the other hand, the effectiveness of the airbag for reducing the head and neck injury measures was clearly demonstrated in this study.

The performance of the seatbelt-mount airbags varied with seating location and body borne gear configuration. In some of the initial sled tests, the airbag did not performed well. For example, in the first two sled tests with 4-point belt and shoulder-belt-mounted airbags, the shoulder airbags tend to slip off the ATD's shoulders. This problem was resolved by packaging the shoulder airbag into smaller tubes and connecting the two shoulder belts around the retractor location to make the belt into a "Y" shape. In some of the tests, the lap-belt-mounted airbag or the hybrid bag was blocked by the steering wheel or the front seat, and consequently they did not deploy into the desired location. This problem was resolved by better controlling the airbag installation location and jet angle. Additional design changes may be required in real vehicle applications under a wide range of crash conditions.

Comparing to the traditional driver and passenger airbags that are installed in the steering wheel or instrument panel, the seatbelt-mounted airbag has a clear advantage of easy installation, and their performances are fairly comparable for front-seat occupants. The seatbelt-mounted airbag is especially beneficial to rear-seat occupants, in which a traditional airbag for frontal crashes is typically not available.

5. CONCLUSIONS

This study demonstrated the benefit of adding a properly designed seatbelt-mounted airbag to improve the occupant protection in frontal crashes under an environment representing a light tactical vehicle. Through the iterations of computational simulations and sled tests, the head, neck, and chest injury measures of the ATDs can be reduced substantially.

ACKNOWLEDGEMENT

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REFERENCES

[1] J. V. Writer, *et al.*, "Non-battle injury casualties during the Persian Gulf War and other deployments," *American journal of preventive medicine,* vol. 18, pp. 64-70, Apr 2000.

[2] K. G. Hauret, *et al.*, "Frequency and causes of nonbattle injuries air evacuated from operations iraqi freedom and enduring freedom, U.S. Army, 2001-2006," *American journal of preventive medicine,* vol. 38, pp. S94-107, Jan 2010.

[3] J. Forman, *et al.*, "Rear seat occupant safety: an investigation of the progressive force-limiting, pretensioning 3-point belt system using adult PMHS in frontal sled tests," *Stapp Car Crash J,* vol. 53, pp. 49-74, 2009.

[4] W. Newberry, *et al.*, "Modeling the effects of seat belt pretensioners on occupant kinematics during rollover," *SAE Technical Paper,* vol. 2006-01-0246, 2006.

[5] J. Hu, *et al.*, "Effects of Crash Pulse, Impact Angle, Occupant Size, Front Seat Location, and Restraint System on Rear Seat Occupant Protection," *SAE Technical Paper,* vol. 2015-01-1453, 2015.

[6] J. Hu, *et al.*, "Optimizing Seat Belt and Airbag Designs for Rear Seat Occupant Protection in Frontal Crashes," *Stapp car crash journal,* vol. 61, pp. 67-100, Nov 2017.

[7] J. Hu, *et al.*, "Does unbelted safety requirement affect protection for belted occupants?," *Traffic injury prevention,* vol. 18, pp. S85-S95, May 29 2017.

[8] J. Hu, *et al.*, "Effects Of Occupant Size, Military Gear, Seatbelt Type, And Advanced Seatbelt Features On Occupant Kinematics In Tactical Vehicles During Frontal Crashes," presented at the 2015 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM, NOVI, MICHIGAN, 2015.

[9] J. Hu, *et al.*, "Optimizing Occupant Restraint Systems for Tactical Vehicles in Frontal Crashes," presented at the SAE World Congress, Detroit, MI. SAE 2018-01-0621, 2018.

[10] M. P. Reed and S. M. Ebert, "The Seated Soldier Study: Posture and Body Shape in Vehicle Seats," *UMTRI-2013-13,* 2013.

[11] H. J. Mertz, *et al.*, "Biomechanical and scaling bases for frontal and side impact injury assessment reference values," *Stapp Car Crash J,* vol. 47, pp. 155-88, Oct 2003.

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Appendix: Testing Matrix

Test ID	Occupant side	ATD	Gear	Seatbelt			
				Type	Airbag	Pre-tensioner	Load Limit
TD1702	Driver	50th	IOTV	4-point	large tubes, 2 shoulder	Lap	N/A
TD1704	Commander	95th	SAWGunner	4-point	small tubes, 2 shoulder	Lap	N/A
TD1705	Commander	95th	SAWGunner	5-point	hybrid, small tubes (Y)	N/A	N/A
TD1706	Commander	95th	SAWGunner	4-point	small tubes (Y)	Lap	N/A
TD1707	Driver	50th	IOTV	5-point	hybrid, small tubes (Y)	N/A	N/A
TD1708	Driver	50th	IOTV	4-point	small tubes (Y)	Lap	N/A
TD1709	Driver	50th	IOTV	2-point	lap belt bag	N/A	N/A
TD1710	Driver	50th	IOTV	3-point	shoulder/chest bag	N/A	N/A
TD1711	Driver	50th	IOTV	3-point	lap belt bag	N/A	3.5kN
TD1712	Rear	5th	IOTV/CB	3-point	lap belt bag	N/A	3.5kN
TD1713	Rear	5th	IOTV/CB	5-point	hybrid, small tubes (Y)	N/A	N/A
TD1716	Rear	5th	IOTV/CB	3-point	shoulder/chest bag	N/A	N/A
TD1717	Driver	50th	IOTV	4-point	small tubes (Y)	N/A	N/A
TD1718	Driver	50th	IOTV	5-point	small tubes (Y)	N/A	N/A
TD1719	Commander	95th	SAWGunner	5-point	small tubes (Y)	N/A	N/A
TD1801	Rear	50th	IOTV/CB	5-point	hybrid, small tubes (Y)	Lap	3.5kN
TD1802	Driver	50th	IOTV	5-point	hybrid, small tubes (Y)	Lap	3.0kN
TD1803	Commander	95th	SAWGunner	5-point	hybrid, small tubes (Y)	Lap	4.0kN
TD1804	Rear	5th	IOTV/CB	5-point	hybrid, small tubes (Y)	Lap	3.0kN