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OPTIMIZING OCCUPANT RESTRAINT SYSTEMS FOR TACTICAL VEHICLES IN FRONTAL CRASHES

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ABSTRACT

The objective of this study was to optimize the occupant restraint systems (including both seatbelt and airbag) in a light tactical vehicle under frontal crash conditions through a combination of sled testing and computational modeling. Two iterations of computational modeling and sled testing were performed to find the optimal restraint design solutions for protecting occupants represented by three size of ATDs (namely Hybrid-III 5th percentile female ATD, 50th percentile male ATD, and 95th male ATD) and two military gear configurations, namely improved outer tactical vest (IOTV) and SAW Gunner configuration using a tactical assault panel (TAP). The sled tests with the optimized seatbelt and airbag designs provided significant improvement on the head, neck, chest, and femur injury risks compared to the baseline tests. This study demonstrated the benefit of adding a properly designed airbag and advanced seatbelt to improve the occupant protection in frontal crashes for a light tactical vehicle.

INTRODUCTION

Although the influence of advanced restraint systems, such as seatbelt pre-tensioners, load limiters, and airbags, on civilian occupant kinematics and injury outcomes in crashes has been extensively studied (Forman et al. 2009; Hu et al. 2015a; Newberry et al. 2006), advanced restraint systems are currently not utilized in military vehicles. Optimally implementing these technologies requires a better understanding of the occupant kinematics and injury risks in crash scenarios with military vehicles. The solutions are not necessarily the same as those used in passenger vehicles because of differences in crash type and pulse, occupant characteristics, vehicle compartment geometry, and occupant seating posture. Body borne gear may also affect restraint system interaction and injury risk. Experimental data and computational models for quantifying occupant impact responses and injury risks in military vehicles are largely lacking. The research available regarding the influence of personal protection equipment is mainly focused on occupant protection in landmine blasts (Harris et al. 1999) and head protection in blast-wave situations (Grujicic et al. 2011), while their effects on injuries in frontal crashes are limited.

In the GVSETS conference last year, we presented findings from 20 sled frontal crash tests using a sled buck representing a light tactical vehicle, with three sizes of anthropomorphic test devices (ATDs), four military gear configurations, and four seatbelt designs without airbag (Hu et al. 2015b). A set of finite element (FE) models were also developed and validated against the sled test results. These tests and simulations provided improved understanding of occupant impact responses and injury risks in a crash environment representing a light tactical vehicle and how the seatbelt interacts with military gear.

The objective of the present study was to optimize the occupant restraint systems (including both seatbelt and airbag) in the frontal crash condition for military vehicles through a combination of sled testing and computational modeling, including the potential contributions of airbags.

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, in this paper we focus on the sled tests and simulations with airbag and how the optimal designs compared to the baseline tests without airbag in terms of occupant injury measures. Baseline sled tests are presented for comparison.

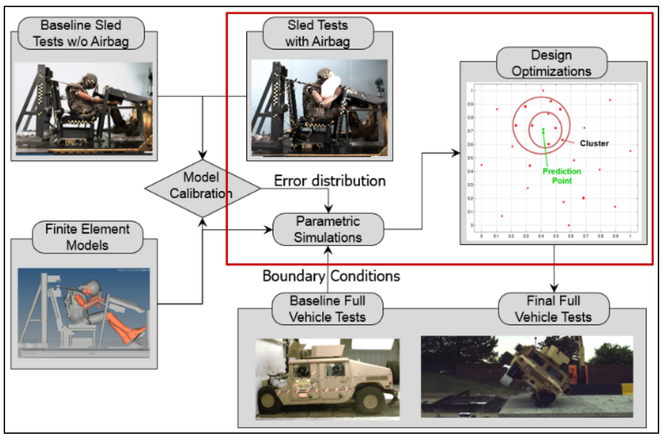

Figure 1: Method overview for the entire project Focus of this paper is highlighted in red

Two iterations of computational modeling and sled testing were performed to search the optimal restraint design solutions. Occupants were represented by the Hybrid-III 5th percentile female, 50th percentile male, and 95th 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, and rear-seat passenger seating positions. The design iterations started with the baseline sled tests and FE simulations without airbag, followed by the parametric simulations and sled tests with airbag, and ended with FE simulations and sled tests with a set of optimal restraint designs. In this study, we focused on the following four conditions:

1) **Driver:** 50th male ATD, IOTV, and 5-point belt
2) **Commander:** 95th male ATD, SAW Gunner with TAP, and 5-point belt
3) **Rear seat passenger:** 50th male ATD, IOTV, 3-point belt
4) **Rear seat passenger:** 5th female ATD, IOTV, and 3-point belt

Sled Tests

A total of over 60 frontal-impact sled tests were conducted using a custom-built sled buck that was based on 3D scans of a Hummer H1 vehicle (Figure 2). 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 UMTRI's Seated Soldier Study (Reed and Ebert 2013). 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.

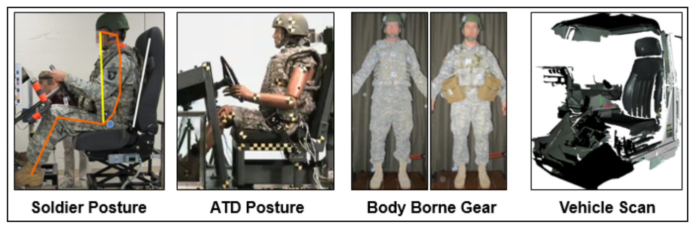

Figure 2: Sled test setup to mimic real soldier seating and body borne gear conditions in tactical vehicle frontal crashes

The injury outcomes for each test were determined using each respective ATD's Injury Assessment Reference Values (IARVs) as shown in Table 1. 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

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

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

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

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. In this paper, the results for each test are reported as a percentage of the ATD's respective IARVs.

Table 1: IARVs (Mertz et al. 2003)

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

Computational Models

A set of FE models, including the test buck, three ATDs (HIII 5th, 50th, and 95th), military gear configurations (helmets, IOTVs at different sizes, and SAW Gunner), and different seatbelts and airbags were developed and integrated together. 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 (Hu et al. 2015b). The seatbelt models were developed based on the seatbelt component tests on the webbing, retractor, pre-tensioner, and load limiter. The airbag models were provided by Takata and validated against airbag component tests.

The validation of this set of FE models without airbags was presented previously (Hu et al. 2015b). In the current paper, we focus on the results of integrating airbag models into the simulations, running parametric simulations, and comparing the simulation results with airbags to the sled tests.

Figure 3 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.

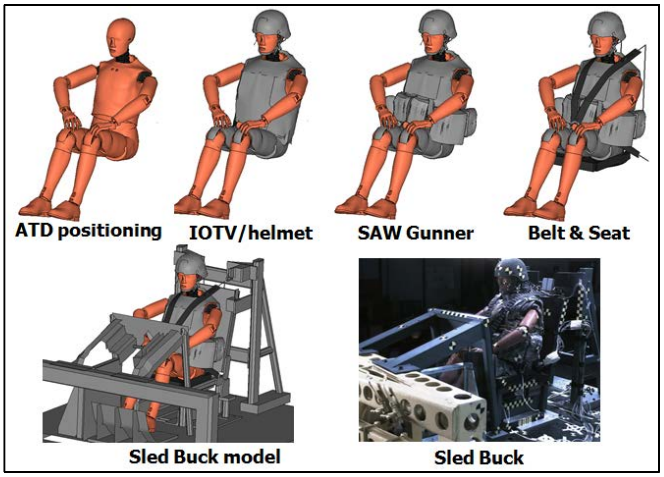

Figure 3: An example of building FE models to simulate the crash condition

Design Optimizations

For front seat occupants (driver and commander), 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 ensure all the injury measures to be below the IARVs.

For rear seat occupants, the head excursion was considered as an additional design constraint. Because in sled tests and FE simulations for rear-seat occupants a front seat was not presented, the head excursion was constrained to prevent a potential head-to-front-seat contact.

Two iterations of FE simulations and sled tests were conducted to ensure the model accuracy and tune the seatbelt and airbag designs for providing the best protection to the occupants. The design parameters optimized in the simulations included the seatbelt load limit, airbag size/shape, airbag stiffness (by changing the vent size), and knee bolster thickness and stiffness (for commander only).

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 tested systems were selected based on the engineering judgement from experienced injury biomechanists.

Adding a properly designed airbag into the restraint system can potentially help to control head kinematics, which will result in lower head/neck injury risks. Reducing the seatbelt load limits can potentially reduce the chest injury risks, but may also increase the occupant head excursions. Increased head excursion is considered to increase injury risk even if no head contact occurred during testing, because in a vehicle crash head contact would be increasingly likely with greater excursion.

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RESULTS

General ATD Kinematics with and without Airbag

Figures 4 and 5 show kinematics of the 50th ATD (with IOTV) on the driver location and the 95th ATD (with SAW Gunner) on the commander location using a 5-point seat belt with and without airbag. Seatbelt retractor pre-tensioners and load limiters as well as lap belt pre-tensioners were used for cases with airbag but not for cases without airbag.

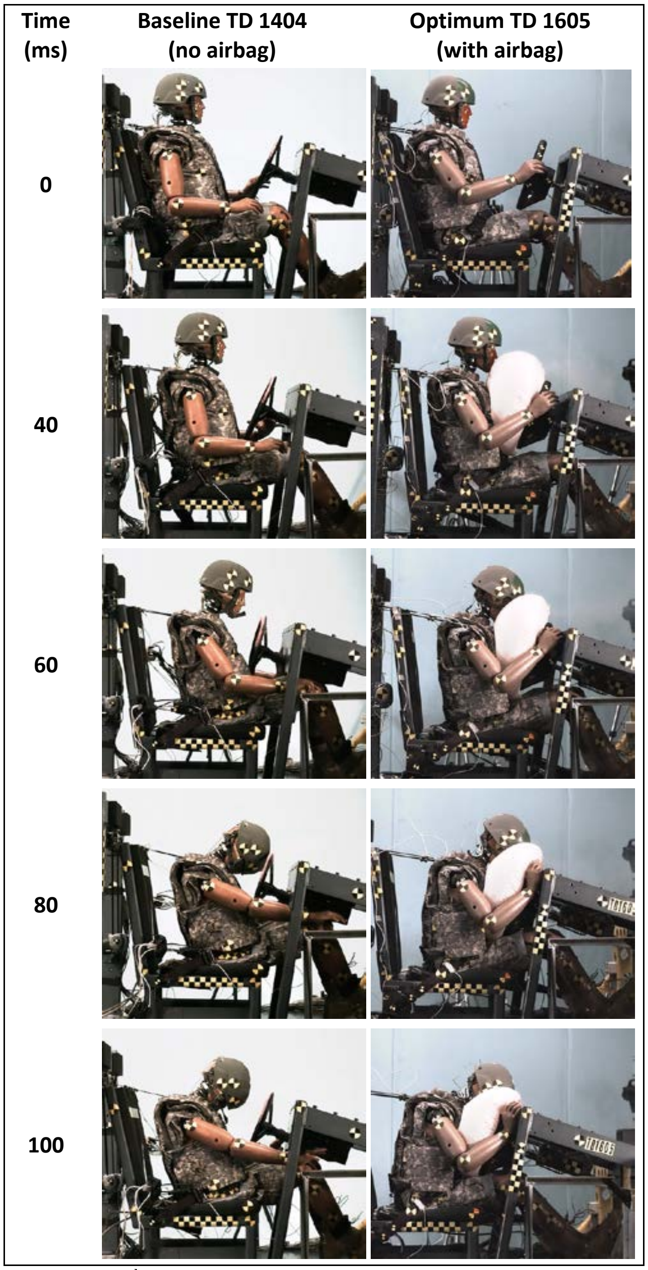

Figure 4: 50th ATD (with IOTV) kinematics in the driver location with and without airbag

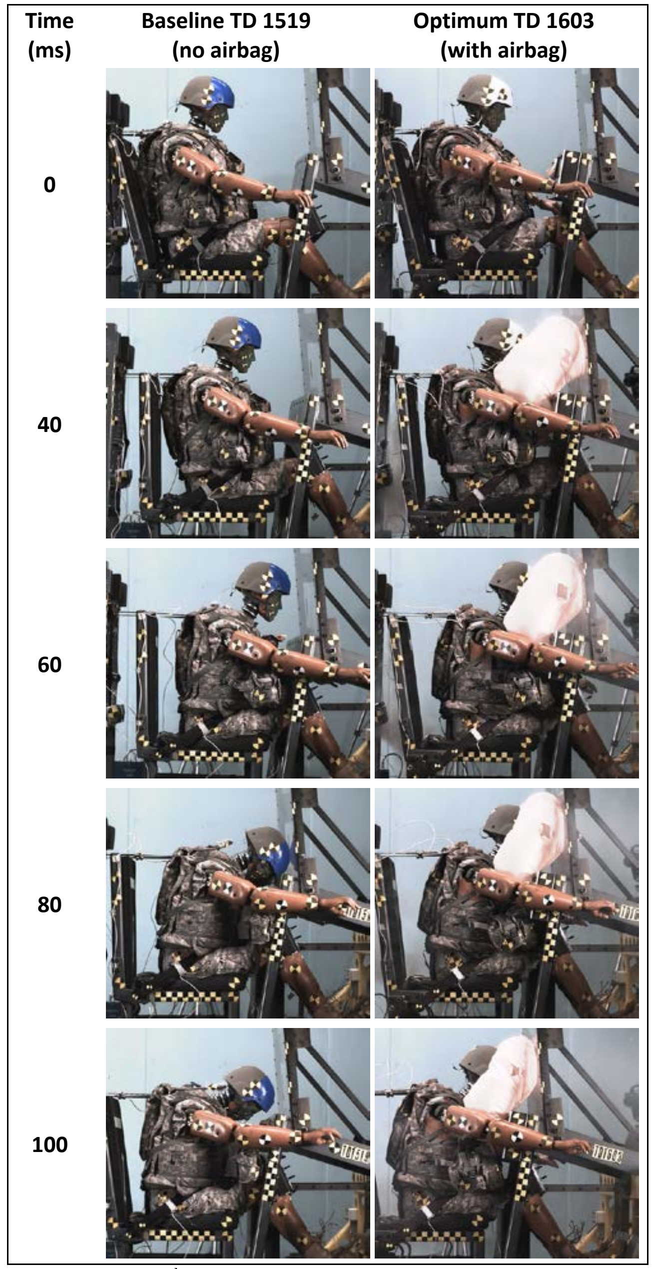

Figure 5: 95th ATD (with SAW Gunner) kinematics in the commander location with and without airbag

Generally speaking, ATD kinematics were better with an airbag than without an airbag. In particular, the airbag significantly improved head kinematics. As a result, neck injury measures were reduced and the head was prevented from impacting the steering wheel for the driver or the instrument panel for the commander. In addition, the 50th ATD with IOTV produced submarining-type of kinematics without an airbag due to the lack of knee bolster, while better kinematics were achieved (ATD torso pitching forward) when

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using an airbag along with belt pre-tensioners and load limiters.

Model Validations with Airbag

The advanced seat belt and airbag FE models were developed based on physical component tests, therefore their characteristics were believed to be fairly accurate. However, integrating the airbag models into the sled/occupant model may lead to possible errors caused by the interaction between the occupants and the airbag. Therefore, model validations against sled tests with airbag were conducted to assess the model accuracy. Figures 6 and 7 showed two examples of the comparisons between the tests and the simulations with airbags. Overall, reasonable model and test correlations were achieved across crash conditions.

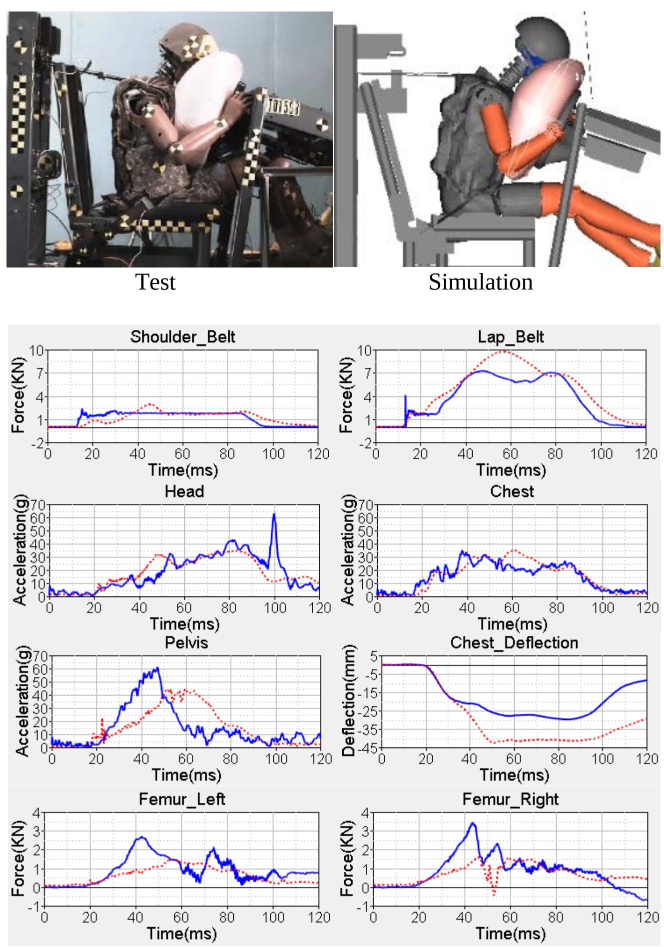

Figure 6: Model injury measure validation for 50th ATD with IOTV, 5-point belt, 1.5 kN load limiter, and driver airbag (Red: test / Blue: simulation)

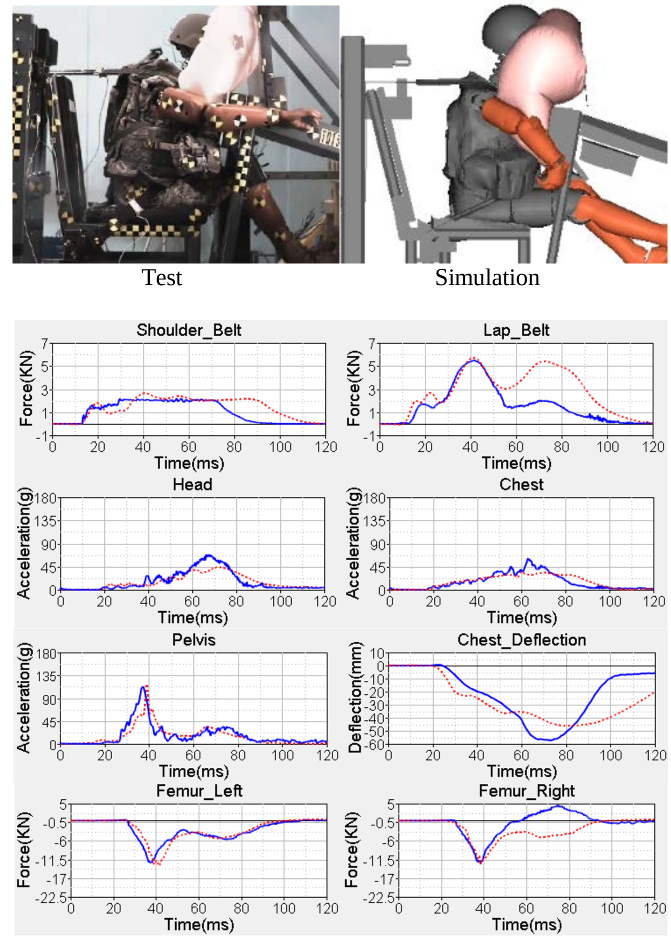

Figure 7: Model injury measure validation for 95th ATD with SAW Gunner, 5-point belt, 1.75 kN load limiter, and passenger airbag (Red: test / Blue: simulation)

Design Optimization and Injury Measure Reduction under Two Design Iterations

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. In the first iteration, optimal designs developed based on the FE model were used in a sled test series. The sled test results were further used to fine tune the FE models. In the 2nd iteration, the final optimal designed were selected, and final sled tests were conducted with those designs.

Tables 2 to 5 show the injury measures and head excursions for rear-seat passengers in the baseline tests, tests with optimal restraint design after iteration 1, and the tests with the final optimal restraint designs. Generally speaking, the injury measures in the optimal restraint designs are much lower

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(better) than those in the baseline tests, especially for the head and neck.

Table 2: Injury measures for 50th ATD in the driver location

	Driver, 50th ATD, IOTV, 5-point Belt		
	Baseline	**Iteration 1**	**Final**
Seatbelt	No PT No LL	2 shoulder PT 2 lap PT 2 1.5kN LL	2 shoulder PT 2 lap PT 2 1.5kN LL
Airbag	None	driver AB	driver AB with 10% larger vent area
HIC	100%	22%	16%
Neck T	100%	29%	31%
Nij	100%	33%	29%
Chest D	100%	124%	101%
Femur F	100%	39%	21%

PT: pre-tensioner, LL: load limiter, AB: airbag
The driver airbag is originally designed for a passenger car.
A crushable steering column was used for tests with airbag.
Injury measures were presented as the percentages of the baseline performance.

Table 3: Injury measures for 95th ATD in the commander location

	Commander, 95th ATD, SAW, 5-point Belt		
	Baseline	**Iteration 1**	**Final**
Seatbelt	No PT No LL	2 shoulder PT 2 lap PT 2 1.75kN LL	2 shoulder PT 2 lap PT 2 1.75kN LL
Airbag	None	Passenger AB	Passenger AB with 10% larger vent area
HIC	100%	8%	5%
Neck T	100%	52%	47%
Nij	100%	40%	36%
Chest D	100%	75%	73%
Femur F	100%	79%	57%

The passenger airbag is originally designed for an SUV, but in the tests the airbag was installed upside down to get better performance.
A piece of 1-inch foam was added to the knee reaction surface for tests with airbag.
Injury measures were presented as the percentages of the baseline performance.

Table 4: Injury measures for 50th ATD in the rear-seat location

	Rear-seat, 50th ATD, IOTV, 3-point Belt		
	Baseline	**Iteration 1**	**Final**
Seatbelt	No PT No LL	1 shoulder PT 1 lap PT 1 3.5kN LL	1 shoulder PT 1 lap PT 1 4.0kN LL
Airbag	None	None	None
Head Excursion	391 mm	534 mm	503 mm
HIC	100%	53%	67%
Neck T	100%	75%	96%
Nij	100%	56%	76%
Chest D	100%	97%	82%
Femur F	100%	94%	79%

The head excursion should be less than 505 mm to prevent head to front seat contact.
Injury measures were presented as the percentages of the baseline performance.

Table 5: Injury measures for 5th ATD in the rear-seat location

	Rear-seat, 5th ATD, IOTV, 3-point Belt		
	Baseline	**Iteration 1**	**Final**
Seatbelt	No PT No LL	1 shoulder PT 1 lap PT 1 3.5kN LL	1 shoulder PT 1 lap PT 1 2.8kN LL
Airbag	None	None	None
Head Excursion	319 mm	370 mm	468 mm
HIC	100%	21%	23%
Neck T	100%	70%	59%
Nij	100%	66%	56%
Chest D	100%	131%	111%
Femur F	100%	53%	57%

The head excursion should be less than 505 mm to prevent head to front seat contact.
Injury measures were presented as the percentages of the baseline performance.

DISCUSSION

This study demonstrated the benefit of adding a properly designed airbag and advanced seatbelt to improve occupant protection in frontal crashes in an environment representing a light tactical vehicle. Through an iterative sequence of computational simulations and sled tests, the head, neck, chest, and lower extremity injury measures of the ATDs were reduced significantly with the optimal 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 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 airbag into the restraint system, it allowed a lower load limit to be used for the seatbelt, which will typically result in lower chest deflections. However, in the sled tests and simulations, the head whipping

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motion was removed by adding the airbag, but 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 design optimization for rear seat occupants is slightly different from those for front seat occupants due to the lack of airbag. The main philosophy for optimizing the rear seat belt is to reduce the load limit as much as possible and at the same time to avoid the head-to-front-seat contact. By doing that, the seat belt allows the maximal head excursions without head contact, which will improve head/neck kinematics while also reducing chest deflection. In the current study, we found that adding the load limiter or reducing the load limit for a 3-point belt did not always lead to reduced chest deflection for rear seat passengers. This is likely due to the seatbelt routing or location differences with different load limits. The Hybrid III ATD only has one chest deflection measurement at the mid sternum location, thus seatbelt loading away from that location may result in less chest deflection measurement. For example, the 5th ATD sustained relatively small chest deflection with the baseline belt. A review of the test video revealed that the seatbelt was very close to the upper sternum and neck region due to the small stature of the ATD, which will likely lead to smaller chest deflection measures. Further studies using computational human models (Holmqvist et al. 2014; Kimpara et al. 2006; Wang et al. 2015) may help us evaluate the chest deflections better.

CONCLUSIONS

In this study, the occupant restraint systems in a light tactical vehicle under frontal crash conditions was optimized through a combination of sled testing and computational modeling. Two iterations of computational modeling and sled testing were performed to find the optimal seatbelt and airbag design solutions for protecting occupants represented by three size of ATDs and two military gear configurations. The sled tests with the optimized seatbelt and airbag designs provided significant improvement on the head, neck, chest, and femur injury risks compared to the baseline tests. This study demonstrated the benefit of adding a properly designed airbag and advanced seatbelt to improve the occupant protection in frontal crashes for a light tactical vehicle.

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