A Systematic Evaluation of Restraint System Performances for Tactical Vehicles in Frontal Crashes

Jingwen Hu, Nichole Orton, Kyle Boyle, Julie Klima, Celia Staniak, Risa Scherer, Matthew P. Reed

Abstract The objective of this study was to evaluate the effectiveness of a set of occupant restraint systems, including different types of seatbelts and airbags, in a light tactical vehicle under frontal crash conditions through sled testing. Twelve sled tests were conducted using a sled buck representing the commander compartment of a light tactical vehicle under a crash pulse within the FMVSS No. 213 testing corridor. A HIII 95th percentile male anthropometric test device wearing an advanced combat helmet, improved outer tactical vest and a SAW Gunner tactical assault panel was used for all sled tests. A set of restraint systems were tested, including 3-point, 4-point, and 5-point seatbelts with and without pre-tensioner and load limiter, different passenger airbags, and a variety of seatbelt-mounted airbags. Generally speaking, ATD kinematics were better with an airbag than without an airbag. With seatbelt only, the ATD's head tends to contact the instrument panel, while a properly designed passenger airbag can prevent a hard head contact. A properly designed seatbelt-mounted airbag can also effectively reduce the head and neck injury measures, although the improvement is not as much as those provided by a passenger airbag. The ATD chest injury risk was generally high with baseline seatbelt due to the lack of load limit and added mass from military gear. However, it can be reduced by using seatbelt pre-tensioner and load limiter. The presence of an airbag can enable a lower load limit to be used, which reduced the chest deflection indirectly. This study demonstrated the benefit of adding properly designed restraint systems, including innovative seatbelt-mounted airbag designs, to improve the occupant protection for a light tactical vehicle.

Keywords Airbag, Seatbelt, Seatbelt-mounted Airbag, Sled Test, Tactical Vehicle

I. INTRODUCTION

Non-battle injuries due to motor vehicle crashes (MVCs) are common in recent military conflicts. Reference [1] reported that MVCs were the leading cause of non-battle injury among hospitalised U.S. Army soldiers deployed to the Persian Gulf War. Reference [2] reported that 35% of soldiers in Iraq and 36% of soldiers in Afghanistan had non-battle injuries with 12%-16% of them caused by MVCs.

It has been well documented that advanced restraint systems, such as seatbelt pre-tensioners, load limiters, and airbags, can enhance the occupant protection for civilian vehicles in frontal crashes [3-7]. However, such advanced restraint systems are currently not available in tactical vehicles. Optimally implementing these technologies requires a better understanding of the occupant kinematics and injury risks in crash scenarios with tactical vehicles. Civilian vehicles and tactical vehicles may have different crash types and pulses, different vehicle compartment geometries, and different occupant seated postures. Body borne gear may also affect interaction between occupant and restraint system, and in turn affect occupant injury risks. Experimental data for quantifying occupant impact responses and injury risks in tactical vehicles are largely lacking. The research available regarding the influence of personal protection equipment is mainly focused on occupant protection in landmine blasts [8] and head protection in blast-wave situations [9], while their effects on injuries in frontal crashes are limited.

Therefore, the objective of this study was to evaluate the effectiveness of a set of occupant restraint systems, including different types of seatbelts and airbags, in a light tactical vehicle under frontal crash conditions through sled testing. The results can serve as a valuable dataset for better understanding occupant impact responses and the effects from different restraint features on occupant protection in tactical vehicle frontal crashes.

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II. METHODS

Sled Test Setup

A total of 12 sled tests were conducted using a custom-built sled buck that was based on 3D scans of a Hummer H1 vehicle (Figure 1). The buck was configured to represent the commander (right front passenger) compartments. All tests were performed in a frontal crash configuration at 30 mph using a pulse within the FMVSS No. 213 testing corridor, which is similar to that from the target tactical vehicle. A Hybrid-III (HIII) 95th percentile male ATD wearing an advanced combat helmet, improved outer tactical vest (IOTV), and a SAW Gunner tactical assault panel was used for all tests, which provided the worst-case scenarios in terms of impact energy and occupant space. The ATD was positioned based on soldier posture data from the Seated Soldier Study [10] conducted by the University of Michigan Transportation Research Institute (UMTRI), USA. The ATD posture was verified using a FaroArm digitiser. Head, neck, chest, and lower-extremity injury measurements from the ATD, 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 ATD.

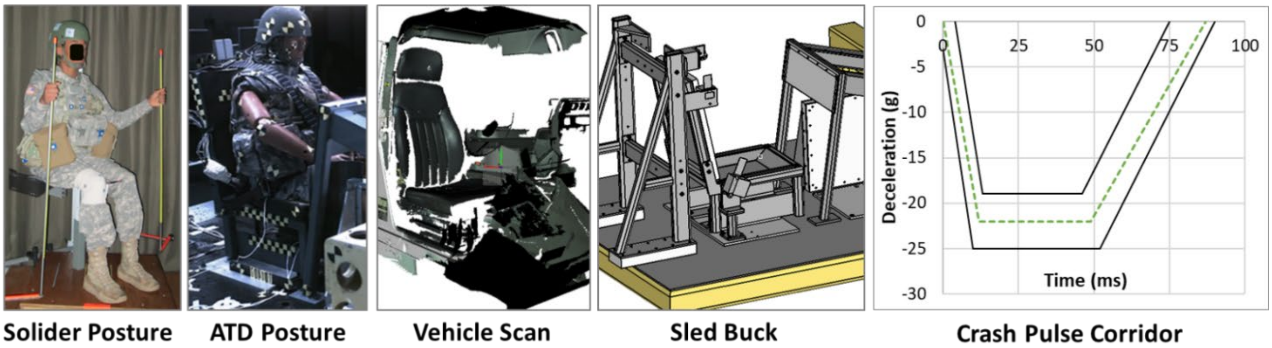

Fig. 1. Sled test setup to mimic real soldier seating and body borne gear conditions in tactical vehicle.

Restraint systems and Test Matrix

Three types of seatbelt systems were used in this study, including a 3-point belt, 4-point belt (two shoulder belts and two lap belts), and a 5-point belt (two shoulder belts, two lap belts, and a crotch belt). Advanced seatbelt features included pre-tensioner (PT) and load limiter (LL). Pre-tensioners were used to engage the occupant early. A retractor pre-tensioner was used to help reduce the slack in the shoulder portion of the belt system. An anchor pre-tensioner was used to help reduce the slack in the lap portion. Constant load limiters in the retractor with various load limits were used to manage the load on the shoulder belts and help reduce the loads to the occupant's chest.

Two types of airbag systems were used in this study, including a generic passenger airbag (PAB) and a seatbelt-mounted airbag (SAB). Seatbelt-mounted airbags are a new type of airbag system, in which the airbag is integrated into either the shoulder belt or lap belt. In this study, we used tubular airbags mounted on the shoulder belts both with and without a face airbag (FAB). Compared to the traditional airbag designs, which are installed in the steering wheel, instrument panel, or the roof rail, seatbelt-mounted airbag design combines the seatbelt and airbag together, hence can be easily and quickly implemented into the current tactical vehicles, without changing the existing vehicle interior designs.

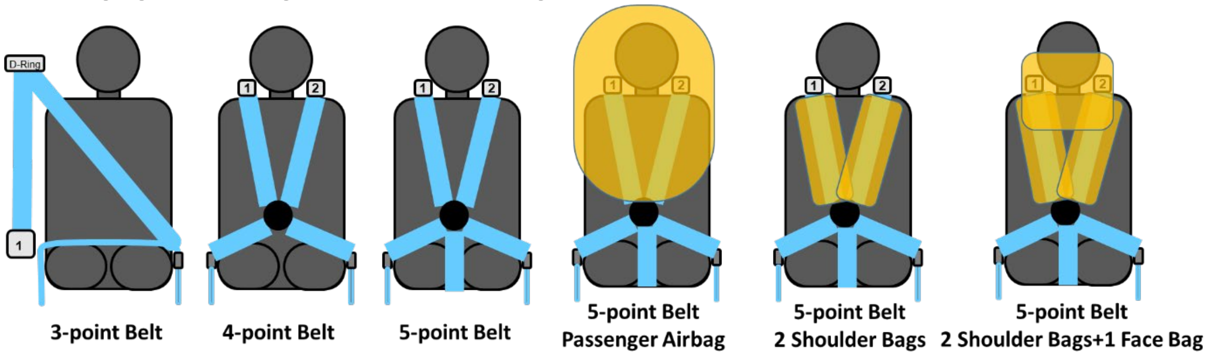

Fig. 2. Illustration of various types of seatbelt and airbag systems used in this study.

The sled test matrix is shown in Table I. Among the 12 sled tests, TD1518, TD1703 and TD1519 are the tests with baseline 3-point, 4-point, and 5-point belt system without advanced seatbelt and airbag technologies, respectively. All other tests are with advanced belt feature(s) and airbag. The seatbelt and passenger airbags were provided by Takata and the seatbelt-mounted airbags were provided by AmSafe.

TABLE I
SLED TEST MATRIX

Test No.	Belt type	Pre-tensioner	Load limit	Airbag Type	Airbag Details
TD1518	3-point	None	None	None	-
TD1517	3-point	Lap+Shoulder	2.8 kN	Passenger	Baseline passenger airbag
TD1703	4-point	None	None	None	-
TD1704	4-point	Lap	None	Belt-mounted	Two large-diameter shoulder bags
TD1706	4-point	Lap	None	Belt-mounted	Two small-diameter shoulder bags
TD1519	5-point	None	None	None	-
TD1516	5-point	Lap+Shoulder	1.75 kN	Passenger	Baseline passenger airbag
TD1603	5-point	Lap+Shoulder	1.75 kN	Passenger	Passenger airbag with larger vents
TD1604	5-point	Lap+Shoulder	1.5 kN	Passenger	Baseline passenger airbag
TD1705	5-point	Lap	None	Belt-mounted	Two small-diameter shoulder bags + Face bag
TD1719	5-point	Lap	None	Belt-mounted	Two small-diameter shoulder bags
TD1803	5-point	Lap	4.0 kN	Belt-mounted	Two small-diameter shoulder bags + Face bag

Injury Measures

The injury outcomes for each test were determined using the HIII 95th percentile male ATD's Injury Assessment Reference Values (IARVs) as shown in Table II, which are based on reference [11], which is consistent to 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).

TABLE II
IARVS USED IN THIS STUDY [11]

Body Region	Injury Measure	95M ATD
Head	HIC-15	700
Neck	Nij	1.00
	Critical Intercept Values	
	Ten and Comp (kN)	5.44
	Flexion (Nm)	415
	Extension (Nm)	166
	Neck axial tension (kN)	5.44
	Neck compression (kN)	5.44
Chest	Chest acceleration (g)	55
	Chest deflection (mm)	70
Leg	Femur axial force (kN)	12.7

RESULTS

Figure 3 shows the ATD kinematics at the time with peak head excursion and Table III shows the injury measures reported as ratios to the IARVs.

In all three baseline tests with only seatbelt and no airbag, the ATD head contacted the instrument panel (IP), causing HIC values over the IARV. In all other tests with the airbag, there is no clear head to IP contact. However, in the tests with the 5-point belt and belt-mounted airbags (TD1705, TD1719 and TD1803), the ATD head likely struke through the airbag, indicated by the relatively high HIC values. Overall, the passenger airbags provided the best protection to the head based on the HIC values, and the belt-mounted airbag also provided better protection for the head compared to the baseline tests.

The restraint effects on neck injury measures (Nij, NeckT, and NeckC) are generally consistent to those on the head injury measures, but none of the neck injury measures exceeded the IARVs. Specifically, the baseline tests sustained the highest neck injury risks; passenger airbags provided the lowest neck injury risks; and belt-mounted airbags provided decent neck injury risk reduction from the baseline tests but are not as significant as passenger airbags.

The chest deflection measured in the test with baseline 3-point belt was much lower than any other tests. We suspect that this low value might be due to the belt location being away from the chest pot (chestD measurement location) or some other reasons that do not necessarily reflect the true condition of chest injury risk. Nevertheless, based on the results with 4-point and 5-point belt systems, adding advanced belt features (pre-tensioner and load limiters) along with the airbags can effectively reduce the chest injury measures (ChestG and ChestD). There is no significant difference between passenger airbag and belt-mounted airbag in terms of chest injury measures.

The restraint effects on lower extremity injury measures (LFF and RFF) are not as significant as those on other body regions. Slight femur force reduction was generally achieved with advanced belt and airbag likely due to the lap pre-tensioner.

There is no clear trend in terms of belt type. However, the test using a 5-point belt with lap and shoulder pre-tensioners and 1.75kN load limiter and a passenger airbag (TD1603) provided the overall best protection, and all injury measures were below 80% of the IARV. It is worth noting that the forces of the crotch belt of the 5-point belt system were all less than 0.5 kN except in one test; while the combined lap belt forces and femur forces were consistently high. These results indicated that the lap belts and knee bolster played much more important role in controlling the pelvis and leg kinematics than the crotch belt.

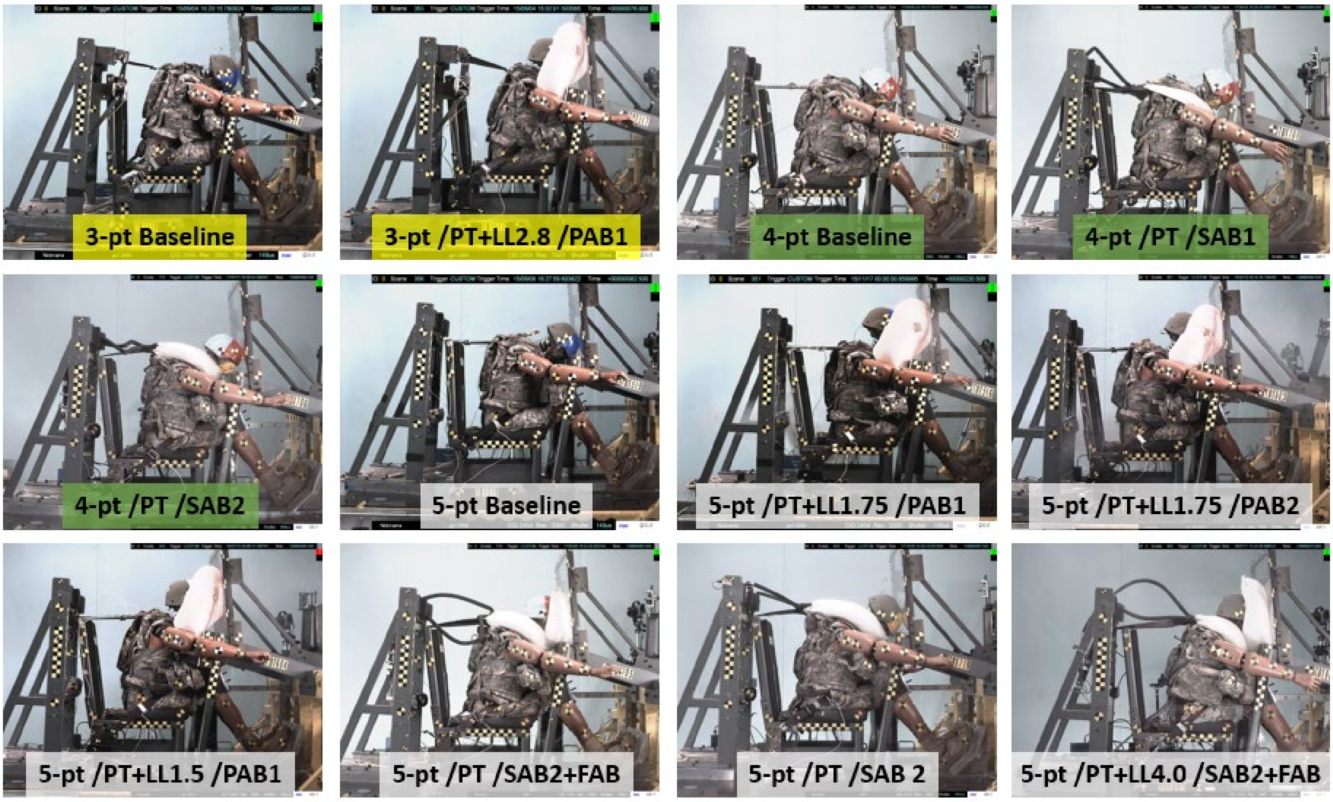

Fig. 3. ATD kinematics at the peak head excursion time.

TABLE III
INJURY MEASURES REPORTED AS RATIOS TO THE IARVS*

Test No.	Restraint System	HIC	Nij**	NeckT	NeckC	ChestG	ChestD	LFF	RFF
TD1518	3-pt Baseline	1.03	0.80	0.58	0.34	0.97	0.32	1.25	1.29
TD1517	3-pt /PT+LL2.8 /PAB1	0.31	0.32	0.36	0.06	0.71	0.61	1.00	1.06
TD1703	4-pt Baseline	1.84	0.61	0.59	0.74	0.97	0.93	1.01	1.03
TD1704	4-pt /PT /SAB1	0.57	0.48	0.67	0.01	0.68	0.84	0.95	0.93
TD1706	4-pt /PT /SAB2	0.77	0.59	0.57	0.37	0.90	0.86	0.93	0.96
TD1519	5-pt Baseline	2.52	0.91	0.57	0.02	0.84	0.88	1.22	1.33
TD1516	5-pt /PT+LL1.75 /PAB1	0.21	0.31	0.30	0.07	0.63	0.66	1.05	1.02
TD1603	5-pt /PT+LL1.75 /PAB2	0.14	0.25	0.27	0.05	0.53	0.64	0.76	0.76
TD1604	5-pt /PT+LL1.5 /PAB1	0.14	0.26	0.21	0.04	0.61	0.71	0.88	0.83
TD1705	5-pt /PT /SAB2+FAB	0.91	0.51	0.34	0.07	0.66	0.69	1.11	1.08
TD1719	5-pt /PT /SAB 2	0.92	0.64	0.57	0.06	0.73	0.71	-	1.27
TD1803	5-pt /PT+LL4.0 /SAB2+FAB	1.08	0.28	0.32	0.17	0.71	0.96	0.85	0.85

*Injury measures over 100% IARV are highlighted in red, values between 80% and 100% IARV are highlighted in yellow, and values below 80% IARV are in green.
**Nte is the highest Nij for all tests, except TD1604, in which Ntf is the highest Nij.

III. DISCUSSION

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

The baseline sled tests demonstrated that Hybrid III 95th male ATD, in an environment similar to light tactical vehicles, exhibit significantly different occupant kinematics than are typically seen in passenger vehicles. Without an airbag in the commander location, head and chest excursions were elevated by the added mass from the SAW Gunner gear, leading to a high probability of contact with the instrument panel. Based on the timing of Nij, the relatively high neck injury measures seen in the baseline tests were due to inertial loading due to head whipping kinematics and not to direct force applied to the head.

By integrating a properly designed passenger airbag into the restraint system, the head was protected and the head whipping motion was mitigated, which led to significantly lower head and neck injury risks. The passenger airbag also 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 as much as we expected. This may be associated with the fact that IOTV can distribute the chest load, which makes the lower load limit 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 when introducing the new restraint features. On the other hand, the effectiveness of the airbag for reducing the head and neck injury measures was clearly demonstrated in this study. These results are widely consistent to previous studies on restraint design optimisations for civilian vehicles [7] and tactical vehicles [12].

The performance of the seatbelt-mounted airbags is better than the baseline belt-only system, but not as good as those with a passenger airbag. Further improvement is necessary, but this study showed the potential of this innovative design. This design concept may be especially valuable for rear-seat occupants, in which a traditional airbag for frontal crashes is typically not available. Furthermore, comparing to the traditional passenger airbags that are installed in the instrument panel, the seatbelt-mounted airbag has a clear advantage of easy installation without any change of the vehicle interior. Based on our previous study [12] with different sizes of ATDs, we expect that the findings presented in this study could be transferred to smaller sizes of ATDs. The currently study used the largest HIII ATD with the heaviest military gear configuration, which represents the worst case scenario in terms of the impact energy.

There are several important design problems associated with the seatbelt-mounted airbags that should be paid attention. For example, the shoulder airbags may slip off the ATD's shoulders with two shoulder retractors. This problem was resolved by packaging two retractors into a single retractor and connecting the two shoulder belts around the retractor location to make the belt into a *Y* shape. Because the face bag is deployed from one of the shoulder bags, it is critical to ensure that the face bag deploys toward 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.

IV. CONCLUSIONS

This study demonstrates the benefit of adding properly designed restraint systems, including advanced belt systems, passenger airbags, and innovative seatbelt-mounted airbag designs, to improve the occupant protection in frontal crashes under an environment representing the commander compartment in a light tactical vehicle. The results presented here can serve as a valuable dataset for better understanding the impact responses of occupants with military gear and the effects from different restraint features on occupant protection in tactical vehicle frontal crashes.

V. ACKNOWLEDGEMENT

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