

Uncertainty Assessment in Restraint System Optimization for Occupants of Tactical Vehicles

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ABSTRACT

We have recently obtained experimental data and used them to develop computational models to quantify occupant impact responses and injury risks for military vehicles during frontal crashes. The number of experimental tests and model runs are however, relatively small due to their high cost. While this is true across the auto industry, it is particularly critical for the Army and other government agencies operating under tight budget constraints. In this study we investigate through statistical simulations how the injury risk varies if a large number of experimental tests were conducted. We show that the injury risk distribution is skewed to the right implying that, although most physical tests result in a small injury risk, there are occasional physical tests for which the injury risk is extremely large. We compute the probabilities of such events and use them to identify optimum design conditions to minimize such probabilities. We also show that the results are robust to various assumptions that the statistical simulations use.

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INTRODUCTION

Advanced restraint technologies, such as seatbelt pre-tensioners, load limiters, and airbags, have the potential to provide improved occupant protection in crashes [2,3,6], but they 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 involvement, occupant characteristics, vehicle compartment geometry, and occupant seating posture. Military gear may also affect restraint system interaction and injury risk.

Recently, experimental data and computational models for quantifying occupant impact responses and injury risks in military vehicles have been developed [4]. However, the numbers of both experimental tests and model runs are small due to their high cost.

While this is true across the auto industry, it is particularly critical for the Army and other government agencies operating under tight budget constraints. This study supplements our recent findings by investigating through statistical simulation how the injury risk varies if a large number of experimental tests were conducted. Moreover, we conduct studies to assess the robustness of our results to changes in various assumptions of the statistical simulations. Such uncertainty assessment studies are necessary when the available data set is small.

The main result of this paper is that the distribution of the injury risk is skewed to the right. The practical implication of this finding is that, although most physical tests result in a small injury risk, there are occasional experimental tests (as proxies for real situations) for which the injury risk is extremely large, as reflected by the long right tail of its distribution. Consequently, it is important to know the probabilities, such as "how likely is it for each design condition to result in a physical test (or a real situation) in which the injury risk exceeds a

tolerable threshold, such as 0.15?" Then one could set the optimization objective to minimizing the occurrence of such events, incorporating both test and model data. Using only test data will result in large uncertainty due to the small sample size. Therefore, it is necessary to use model runs in order to supplement the information provided by the test data and therefore, reduce the uncertainty in the simulation study.

We show that our results are robust to changes in various assumptions related to the statistical distributions. We first considered the scalar injury risk whose components are assumed to have two different distributions: normal and lognormal. Then, we obtained statistical simulations of time-dependent responses with normal and lognormal distributions, which were subsequently summarized in order to obtain the statistical distribution of the injury risk. Regardless of the distribution and/or method used, it appears that the pretensioner and the load limiter are associated with a safer restraint system. In addition, the 5-point restraint seems to be safer than the 3-point system.

TEST, MODEL AND DESIGN DESCRIPTION

In order to achieve the design optimization goal, sled tests and accompanying computational model runs were performed. The sled tests were conducted using a custom-built sled buck which was

constructed from 3D scans of a Hummer H1 vehicle (Figure 1a). The buck (Figure 1b) was reconfigurable to represent both the driver and passenger compartments. All tests were performed in a frontal crash configuration with a 30 mph delta-V and a peak acceleration of 25 g (Figure 1c). All anthropomorphic test devices (ATDs) were outfitted with standard issue military combat boots and Advanced Combat Helmet (ACH) for every test. Tests were conducted with three additional military gear configurations (Figure 1d) - Improved Outer Tactical Vest (IOTV) only, IOTV and Squad Automatic Weapon (SAW) Gunner set with a Tactical Assault Panel (TAP), and IOTV and Rifleman set with TAP. ATDs with the SAW Gunner and Rifleman gear sets were tested in the passenger configuration, while ATDs with helmet only and IOTV only were tested in the driver configuration. Two types of seatbelts, 3-point and 5-point, with and without pretensioner(s) and load limiter(s), were also used. Pretensioners were used on the shoulder and lap belts, and were set to fire at 12ms. In tests using load limiters, a 4.9 kN load limiter was used on the shoulder of the 3-point belt, and 2×2.7 kN load limiters were used on the shoulders of the 5-point belt. While the original study was more comprehensive, here we focus on eight specific design conditions (Table 1) corresponding to a mid-size male dummy (i.e. 50th percentile male ATDs).

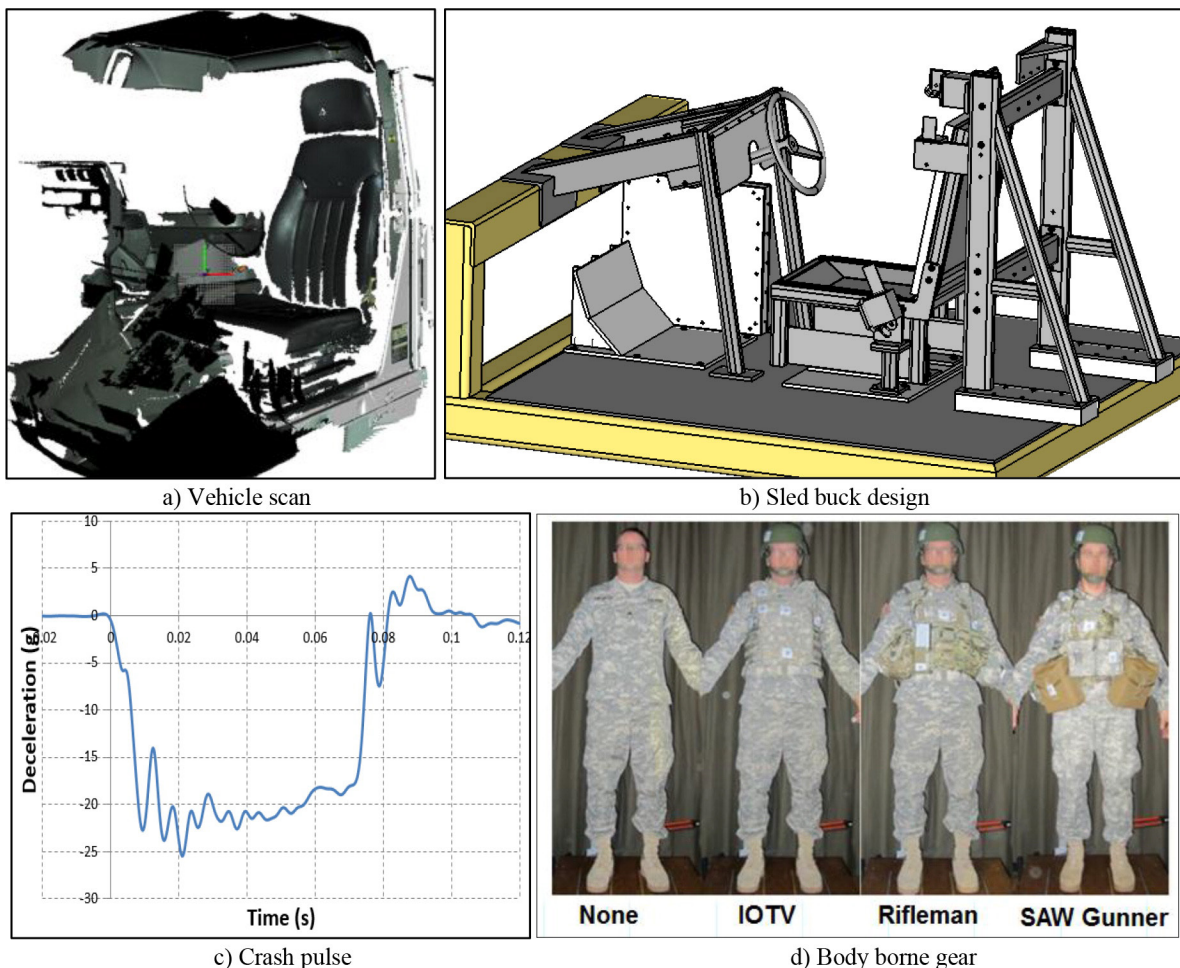


Figure 1. Sled test conditions

Table 1. Analyzed test conditions

PT: Pre-tensioner, LL: Load limiter

Test ID	Abbreviation	Side	IOTV	Gear	Seat belt	
					Type	PT+LL
TD1403	5pt_base	Driver	N	N	5-pt	N
TD1404	5pt_iotv	Driver	Y	N	5-pt	N
TD1405	3pt_base	Driver	N	N	3-pt	N
TD1407	5pt_sawgunner	Passenger	Y	SAW Gunner	5-pt	N
TD1408	3pt_sawgunner	Passenger	Y	SAW Gunner	3-pt	N
TD1409	5pt_sawgunner_ptll	Passenger	Y	SAW Gunner	5-pt	Y
TD1417	3pt_iotv_ptll	Driver	Y	N	3-pt	Y
TD1418	5pt_iotv_ptll	Driver	Y	N	5-pt	Y

A set of finite element (FE) models, including the test buck, ATDs, military gear configurations, and different seatbelts were developed and integrated together. The test buck model was developed based on the design CAD data. The geometries of the models for military gears were based on the seated soldier study ([7]) with simplification and modification. The seatbelt models were developed based on the seatbelt component tests on the webbing, retractor, pre-tensioner, and load limiter.

A sequence of the crash tests were used to validate the FE models. For each model, the ATD model was positioned and postured based on the FaroArm data measured in the tests. The time histories of the ATD head, chest, and pelvis accelerations, chest deflection, femur forces, seatbelt forces, as well as the head and hip excursions were used to tune the models, so that occupant kinematics and injury risks can be accurately modeled. The parameters that were calibrated in the models included the seatbelt slack, material properties of the vest and other military gears, seatbelt to vest/gear contact, seatbelt routing, friction, etc.

For each design condition, injury measures, including the head injury criterion (*HIC*), chest deflection (*D*), and left and right femur values (*LF*, *RF*), were calculated based on the time histories of the ATD output, and were used to compute the injury risks of the head, chest, and lower extremities. The *HIC* is a measure of the likelihood of head injury resulting from an impact, and is defined as

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

where $a_H(t)$ is the head acceleration as a function of time, and t_1 and t_2 represent a (15-ms) time interval over the acceleration pulse. The chest deflection *D* is obtained as the maximum of the chest deflection time-dependent curve $C_D(t)$, while the femur scalar values *LF* and *RF* are the maximal values of femur compression forces (i.e. minimum of the corresponding femur force time history), respectively. The injury risks are defined as

$$P_{head} = \Phi \left(\frac{\ln(HIC) - 7.45231}{0.73998} \right) \quad (2)$$

where Φ is the cumulative standard normal distribution,

$$P_{chest} = \frac{1}{1 + \exp(10.5456 - 1.568 \cdot D^{0.4612})} \quad (3)$$

$$P_{femur\ left} = \frac{1}{1 + \exp(5.795 - 0.5196 \cdot LF)} \quad (4)$$

and

$$P_{femur\ right} = \frac{1}{1 + \exp(5.795 - 0.5196 \cdot RF)} \quad (5)$$

The last two injury risks are combined into

$$P_{femur} = \max(P_{femur\ left}, P_{femur\ right}) \quad (6)$$

and the overall injury risk is calculated as

$$P_{joint} = 1 - (1 - P_{head})(1 - P_{chest})(1 - P_{femur}). \quad (7)$$

It is important to emphasize that each crash test and each model run produce an overall injury risk as in (7). Therefore, we distinguish between test injury risk and model injury risk. Equations (1, 2, 3, 4, 5, 6, 7) were based on those used in [5], the current US New Car Assessment Program (US-NCAP), although neck injury measures were not considered in this study.

Generally speaking, good agreements between the tests and simulations were achieved. Examples of model kinematic validation are shown in Figure 2. Examples of model injury measure validation are shown in Figures 3 and 4.

