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Effect of Occupant Position Variations in Physical Tests on the Prediction and Validation of Computational Models

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ABSTRACT

Computational models are widely used in the prediction of occupant injury responses and vehicle structural performance of ground vehicles subjected to underbody blasts. Although these physics based computational models incorporate all the material and environment data, the classic models are typically deterministic and do not capture the potential variations in the design, testing and operating parameters. This paper investigates the effect of one such variation in physical tests, namely, variations in the position of occupant setup on the occupant injury responses. To study the effects of occupant position, a series of vertical drop tower tests were performed in a controlled setup. A vertical drop tower test involves an Anthropomorphic Test Device (ATD) dummy positioned on a seat and the setup is dropped on an energy attenuating surface, thus producing a desired shock pulse on the seat structure. The experimental data was analyzed for sensitivity of occupant position and ATD joint friction variations. Results from this work reiterate the need to include the stochastic variability of test setup and design parameters in the modeling and simulation and pre-test prediction of any physical test including live fire tests. This project work was performed under TARDEC's NTUBB (Near Term Under-Body Blast) Modeling and Simulation enhancement program.

INTRODUCTION

Developers of the military ground vehicle systems extensively utilize computational models during the design and development stages of the system. These computational models vary in their applications including protection of crew members when the vehicle is subjected to buried blasts. With the advancement in the high performance computing capabilities, analysts have developed very high fidelity computational models to simulate these blast events [1]. These models which are called end-to-end simulation models incorporate all components of the live fire event including the soil, charge, air and the vehicle structure with occupants. There are also reduced order models and sub-system models that are used to predict occupant responses under blast loading [2-5]. Although these physics based computational models incorporate all the material and environment data, the classic models do not capture the potential variations in the design, testing and operating parameters.

In additional to the deterministic nature of the computational models, these variations in the test setup, specifically, occupant positions and occupant gear are critical in the design of a vehicle system [6-7]. A successful design should be able to perform as intended through the entire range of the occupant positions since in real world situations crew positions may vary. Therefore, it is important to understand the sensitivity of these occupant positions on the injury responses for a specific system design and the associated structural responses. In addition, since deterministic computational model results are compared against physical test results in the process of verification and validation, it is important to understand and estimate the sensitivity of these test setup variations on the system performance.

Due to the importance of designing and analyzing a vehicle system performance for a range of variations in the system and environmental parameters, much work has been performed on this topic, especially in the area of soil and materials [8-10] and occupant positions [11-13]. Design of

Experiments (DOE) based sensitivity analysis as well as stochastic based simulations based on several distributions are utilized in order to understand and estimate the effects of these variation on the performance of the system. This paper investigates the effect of one such variation in physical tests of vehicle subjected to underbody blasts, variations in the position of occupant setup on the occupant injury responses.

EXPERIMENTAL SETUP

To study the effects of occupant position on the injury responses when subjected to a vertical shock load, a series of vertical drop tests (VDT) were performed in a controlled environment. A vertical drop test, a commonly used test for characterizing seats and occupant performance subjected to a vertical shock load, is basically a simple setup of an Anthropomorphic Test Device (ATD) dummy positioned on a seat and the setup is dropped from a pre-determined height on to an energy absorbing surface. By varying the drop height and the impacting surface material characteristic, a specific impact velocity and pulse characteristic can be achieved. Figure 1 shows a typical drop test setup.

Figure 1: Vertical Drop Test Setup

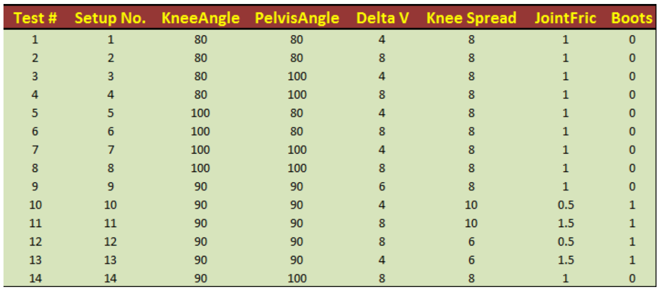
Vertical drop tests for this projects were performed at the TARDEC-GSS Vertical Drop Test facility located at Selfridge Air National Guard Base. ATD was a 50th percentile male with Personal Protective Equipment (PPE) that includes vest and helmet. The seat, referred to as a rigid Throne seat, is a non-deforming, non-stroking seat to eliminate the seat design characteristics from influencing the study of occupant positions.

EXPERIMENTAL SERIES

The following occupant positions and parameters were varied in the tests. These parameters were chosen based on discussions with occupant safety simulation subject matter experts and Live Fire Test and Evaluation (LFT&E) engineers.

1) Knee Angle (Controlling the tibia position)
2) Pelvic Angle (Controlling Upper Body Angle)
3) Knee Spread (distance between knees)
4) Joint Friction (Knee Joint Tightness)
5) Boots (Boots worn or not)
6) Delta –V (Impact Velocity), a pulse characteristic

The occupant injury responses studied are 1) Peak lower lumbar load 2) Peak tibia axial load and 3) Pelvis vertical acceleration.



Test #	Setup No.	KneeAngle	PelvisAngle	Delta V	Knee Spread	JointFric	Boots
1	1	80	80	4	8	1	0
2	2	80	80	8	8	1	0
3	3	80	100	4	8	1	0
4	4	80	100	8	8	1	0
5	5	100	80	4	8	1	0
6	6	100	80	8	8	1	0
7	7	100	100	4	8	1	0
8	8	100	100	8	8	1	0
9	9	90	90	6	8	1	0
10	10	90	90	4	10	0.5	1
11	11	90	90	8	10	1.5	1
12	12	90	90	8	6	0.5	1
13	13	90	90	4	6	1.5	1
14	14	90	100	8	8	1	0

Figure 2: Table of Experiments

Based on the design of experiments feature in LS-OPT (Design Optimization and Probabilistic Analysis software tool), a set of 14 tests, shown in Figure 2, was put together using the LS-OPT tool using Radial Basis Function Network based Meta-Model DOE. Figure 3 illustrates some of the various positions of the ATD. These 14 tests were repeated three times in different orders, resulting in a total of 42 tests, in order to remove any procedural bias as well as to address the test to test bias and repeatability issues.

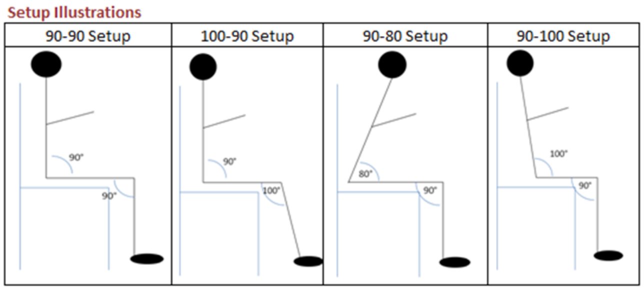


Figure 3: ATD Positions

Occupant injury values from tests were computed and entered in to the LS-OPT Design of Experiments tool to perform statistical analysis and sensitivity study of occupant positions.

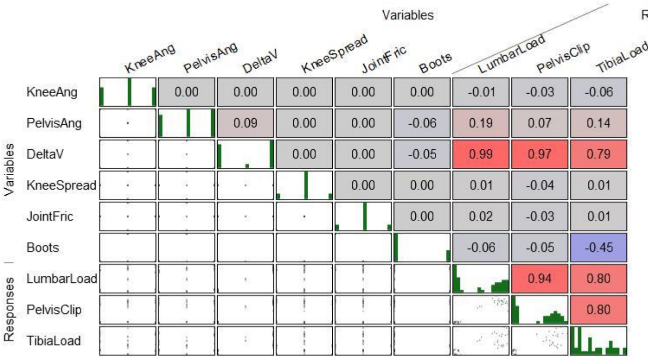
DATA ANALYSIS

The impact velocity as a Design of Experiments variable can be expected to be a dominant factor affecting the occupant responses. Hence it is possible that it would diminish or mask the effects occupant positions on the injury responses. Therefore, in order to properly analyze the effect of occupant positions, three different DOE analysis were performed:

1) All 42 tests
2) Test data involving only 4 m/s
3) Test data involving only 8 m/s

All 42 Tests (4 m/s, 6 m/s and 8 m/s)

Test data from all tests including both 4m/s and 8m/s impact velocities were compiled and analyzed. In addition to these impact velocities, it is also noted that a test for 6 m/s was also included based on the experiment matrix created by the optimization software, LS-OPT. Figure 4 shows the correlation matrix between independent variables and responses. As expected, impact velocity (Delta V) and Boots have significant effect on the occupant performance. Besides these two dominant factors, Pelvis angle seems to have a significant correlation with lumbar and tibia loads.



	KneeAng	PelvisAng	DeltaV	KneeSpread	JointFric	Boots	LumbarLoad	PelvisClip	TibiaLoad
KneeAng		0.00	0.00	0.00	0.00	0.00	-0.01	-0.03	-0.06
PelvisAng			0.09	0.00	0.00	-0.06	0.19	0.07	0.14
DeltaV				0.00	0.00	-0.05	0.99	0.97	0.79
KneeSpread					0.00	0.00	0.01	-0.04	0.01
JointFric						0.00	0.02	-0.03	0.01
Boots							-0.06	-0.05	-0.45
LumbarLoad								0.94	0.80
PelvisClip									0.80
TibiaLoad									

Figure 4: Correlation Matrix for All Test Data

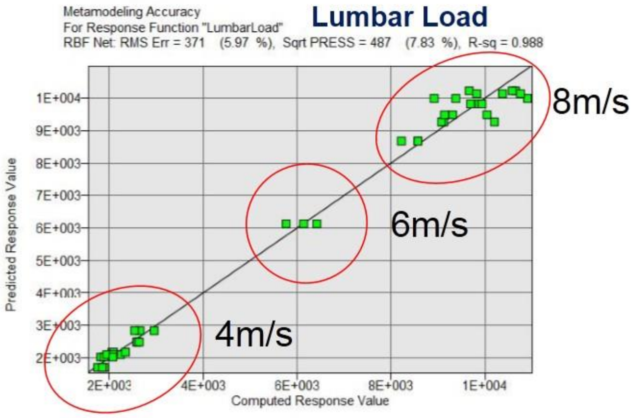


Figure 5: Meta Model Accuracy for Lumbar Load

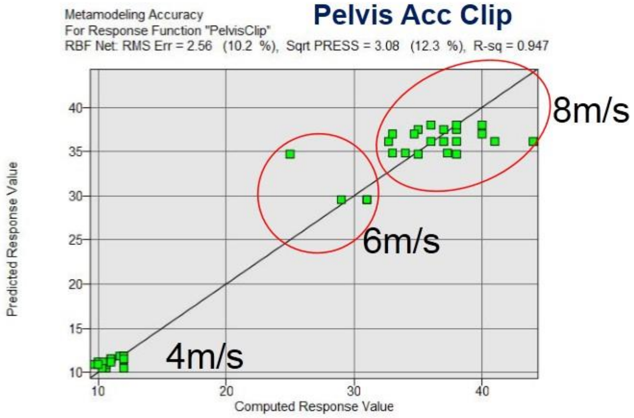


Figure 6: Meta Model Accuracy for Pelvis Acceleration

Figures 5 and 6 illustrate the accuracy of meta-models in terms of predicting the injury responses based on the independent variables. This clearly demonstrates the dominant effect of Delta-V on the injury values as test points are grouped in islands each representing a Delta-V test condition. High Correlation Coefficients (R-SQ) of 0.99 and 0.95 are primarily due to the correlation with Delta-V. This is further illustrated using the Sensitivities Plot for Lumbar load shown in figure 7. Hence, the data analysis was performed for each Delta V test data to identify the occupant position variable that affects the injuries.

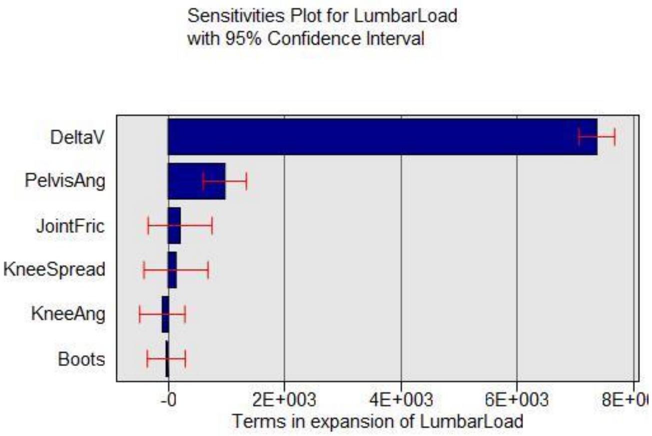
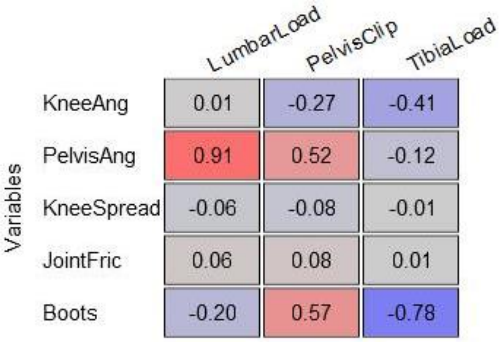


Figure 7: Sensitivities Plot for Lumbar Load

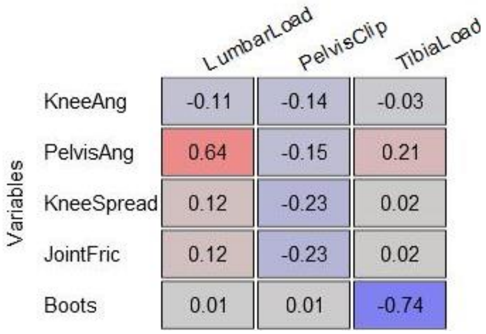
Independent Analysis for 4m/s and 8m/s Delta-V

Data from tests with impact velocity of 4m/s and 8m/s were compiled and analyzed independently so that the Delta-V is not considered as a DOE variable in the analysis. Figures 8 and 9 show the correlation matrix between independent variables and responses for 4m/s and 8m/s dataset respectively.



	LumbarLoad	PelvisClip	TibiaLoad
KneeAng	0.01	-0.27	-0.41
PelvisAng	0.91	0.52	-0.12
KneeSpread	-0.06	-0.08	-0.01
JointFric	0.06	0.08	0.01
Boots	-0.20	0.57	-0.78

Figure 8: Correlation Matrix for 4 m/s Drop Tests



	LumbarLoad	PelvisClip	TibiaLoad
KneeAng	-0.11	-0.14	-0.03
PelvisAng	0.64	-0.15	0.21
KneeSpread	0.12	-0.23	0.02
JointFric	0.12	-0.23	0.02
Boots	0.01	0.01	-0.74

Figure 9: Correlation Matrix for 8 m/s Drop Tests

The correlation matrix indicates that the lumbar loads correlate well with pelvis angle. Pelvis acceleration clip correlates with pelvis angle and presence of boots only at lower impact speeds and surprisingly none at higher impact speeds. Similarly tibia loads correlate reasonably well with knee angle at lower impact speeds only. However, the tibia loads are influenced by the presence of boots on the ATD. The negative value of correlation indicates the inverse effect, meaning the presence of boots lowers the tibia loads.

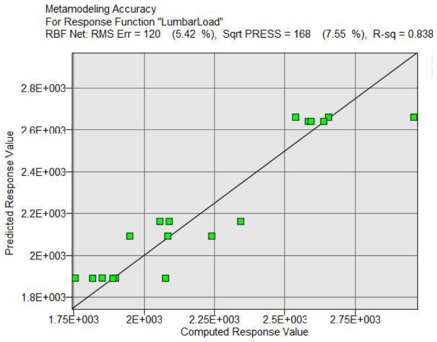


Figure 10: Meta-Model for Lumbar Loads (at 4 m/s)

In general, occupant responses show higher level of correlation to position variables at lower impact speed. In particular Pelvis Angle showed correlation with both Lower lumbar loads as well as Pelvic Acceleration Clip. Knee Angle also indicates a reasonable level of correlation with tibia loads.

However, at higher impact velocity of 8m/s, pelvis clip indicates no correlation to any of the occupant position. The meta-model also indicates lack of correlation for Pelvic Angle and Tibia load especially at 8m/s as seen in figures 11 and 12.

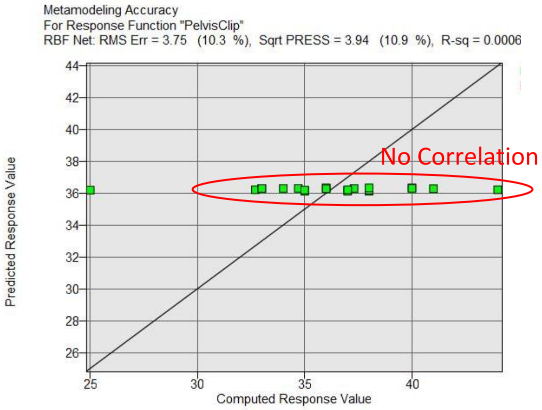


Figure 11: Meta-Model for Pelvis Clip (at 8 m/s)

The dominant effect of Boots on the tibia loads can be observed from figure 12 based on the grouping of responses with and without boots. Especially on cases with boots on, it can be seen that there is not much variation in the tibia loads.

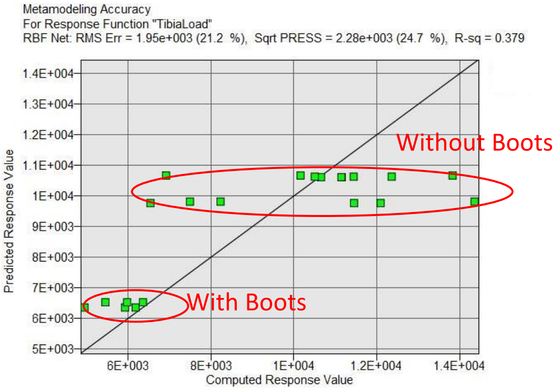


Figure 12: Meta Model for Tibia Load (at 8 m/s)

Sensitivities plot with 95% confidence interval line for lumbar load is shown in figures 13 and 14 at impact speeds of 4 m/s and 8 m/s respectively. Even with a wider range for 95% confidence interval, the lumbar load is shown to be sensitive to pelvis angle variations. However, other occupant positions and setup parameters are not significant in influencing the lumbar load. Knee-spread has no effect on lumbar load at all.

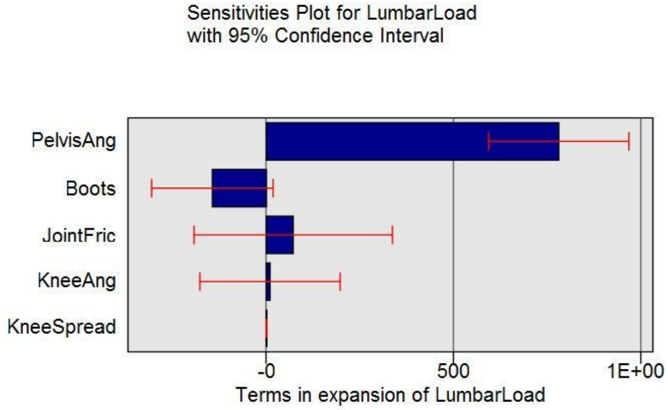


Figure 13: Sensitivities Plot for Lumbar Load at 4 m/s

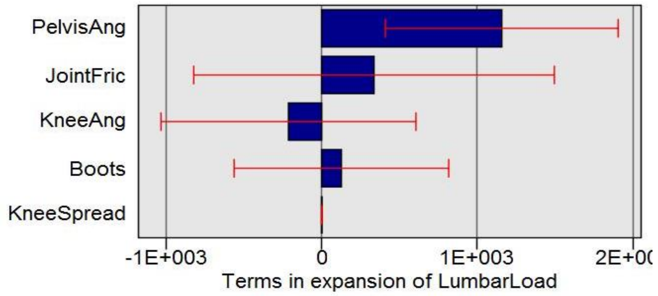


Figure 14: Sensitivities Plot for Lumbar Load at 8 m/s

Sensitivities plot shown in figures 15 and 16 indicate the significant effect of boots on tibia loads. Boots are especially sensitive at higher impact velocity resulting in a difference of 4000N in tibia loads. This high amount of sensitivity shows the importance of boot characteristics as any variations in boots could affect the tibia loads. Next to boots, as expected, knee angle affects the tibia loads. However, at higher impact speed, none of the occupant positions have any effect on the tibia loads.

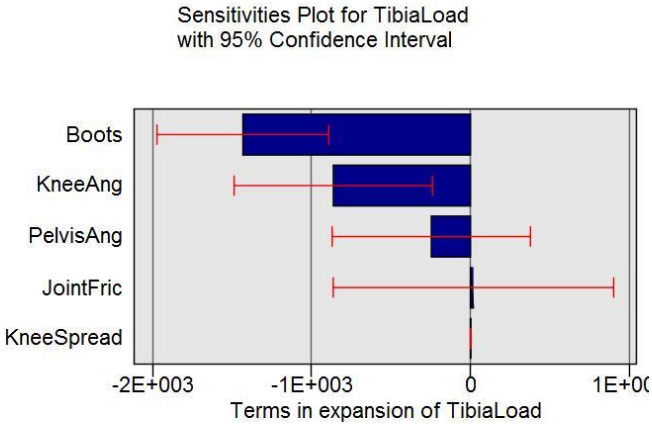


Figure 15: Sensitivities Plot for Tibia Load at 4 m/s

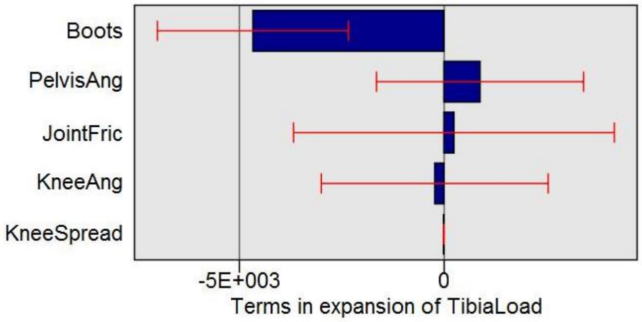
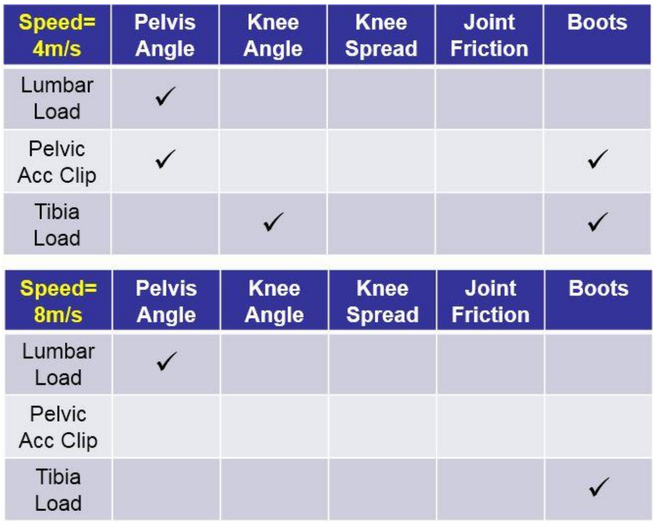


Figure 16: Sensitivities Plot for Tibia at 8 m/s

Sensitivities plots of pelvis acceleration (figures not shown) indicate that the pelvis angle and boots have marginal effect at 4 m/s impact speed. However, there is no effect at higher impact speed.

SUMMARY AND DISCUSSIONS

Analysis of these 42 vertical drop tower experiments have been conducted with varying occupant position parameters for 4 m/s and 8 m/s drop velocities and with/without boots. Impact velocity proved to be a dominant factor and hence data from each impact velocity was analyzed independently. Pelvis angle, knee angle and boots have shown to have significant effect on the occupant responses as seen in figure 17.



Speed= 4m/s	Pelvis Angle	Knee Angle	Knee Spread	Joint Friction	Boots
Lumbar Load	✓				
Pelvic Acc Clip	✓				✓
Tibia Load		✓			✓

Speed= 8m/s	Pelvis Angle	Knee Angle	Knee Spread	Joint Friction	Boots
Lumbar Load	✓				
Pelvic Acc Clip					
Tibia Load					✓

Figure 17: Effects of Occupant Positions

Analysis of test data shows that any variations in pelvis angle or knee angle will result in significant changes in the occupant responses, lumbar load, pelvis acceleration and tibia load. As the computational models are deterministic in nature, the predicted occupant responses from these simulations need to be considered along with these variations in pre-test predictions. Similarly, when deterministic computational models are validated using physical test data, it is important to address the potential variations in the test setup.

Another aspect to consider in the computational modeling and simulation is to include the variations in parameters as statistical distributions and estimate the end responses as a distribution or a range.

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GLOSSARY

ATD	Anthropomorphic Test Device
DOE	Design of Experiments
NTUBB	Near Term Under-Body Blast
VDT	Vertical Drop Test
GSS	Ground Systems Survivability
LFT&E	Live Fire Test & Evaluation
Delta-V	Impact Velocity
R-SQ	Correlation Coefficient
LS-OPT	Optimization Software Tool

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