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AUGUST 12-14, 2014 - NOVI, MICHIGAN

A MULTIDISCIPLINARY OPTIMIZATION FRAMEWORK FOR OCCUPANT CENTRIC GROUND VEHICLE SYSTEM DESIGN
- Part I: Vehicle Design Parameter Screening Study

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ABSTRACT

This paper presents a vehicle design parameter screening, the first portion of our MDO efforts on occupant-centric vehicle design. The study uses a full simplified vehicle by considering occupant centric survivability performance under underbody mine blast loading. The top 10 design variables have been identified by TARDEC SMEs and analyzed systematically. 32 finite element models were built to represent fractional factorial combinations of these design parameters and used to determine the main contributors to vehicle structure response and occupant injury potentials. Four preferred design parameter selections have been found in this effort to achieve improved occupant survivability performance and structural response under underbody blast loadings. They are: optimized seat energy absorption system, higher standoff distance and vehicle mass, double-V underbody shape without structural reinforcement, and smaller vehicle width. The study found and confirmed that an optimized seat energy absorption system can lower occupant injury indices significantly. The efforts presented in this paper pave a road to a full system multidisciplinary design optimization.

INTRODUCTION

In recent years, underbody vehicle mine blast events have become the greatest threat to military personnel. Underbody blast events were estimated to be responsible for 60% of coalition deaths in Iraq [1, 2] and 75% of casualties in Afghanistan [3]. However, other threats exist against crew survivability, such as rollover and slam down. Traditionally, Ground vehicles are designed first without consideration of the occupant safety, rather than designing vehicles around soldiers with a focus on occupant centric survivability. Increasing protection levels of the platforms impacts interior volumes, space claims and reduces mobility, maneuverability, leading to heavier platforms.

In response, TARDEC has initiated a S&T program to make improvements to the existing platforms or develop new platforms. These platforms provide appropriately increased protection from current and emerging threats, as well as optimal space allocation for soldiers and their gear. This can be achieved by decreasing platform weight and maintaining or increasing maneuverability during a full spectrum of operations. The goals are to reduce the overall platform weight by 25%, the fatalities and wounded in actions (WIAs) by 50% across each mission role, within scalable protection levels, to defeat a wide range of threats, and return mobility performance back to baseline, as well as maintain freedom of action during full spectrum operations.

Increasing protection has historically driven up gross vehicle weight; a new design paradigm is required to balance the “iron triangle” and increase vehicle efficiency, dynamic performance and payload. These efforts are faced with many challenges. For example, to attain the needed level of survivability to the increasing threat sizes experienced in theater, current tactical vehicles have reached weights that exceeded 30 tons with a standoff distance greater than 36 inches. However, to meet better mobility requirements, the vehicle needs to lower its standoff distance. Hence, it is very important to introduce Multidisciplinary Design Optimization (MDO) to balance these requirements in the design & product development process.

BACKGROUND

Ground vehicle occupant safety is a top priority for designers, and in recent years the greatest threat to soldiers is

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This paper presents a vehicle design parameter screening, the first portion of our MDO efforts on occupant-centric vehicle design. The study uses a full simplified vehicle by considering occupant centric survivability performance under underbody mine blast loading. The top 10 design variables have been identified by TARDEC SMEs and analyzed systematically. 32 finite element models were built to represent fractional factorial combinations of these design parameters and used to determine the main contributors to vehicle structure response and occupant injury potentials. Four preferred design parameter selections have been found in this effort to achieve improved occupant survivability performance and structural response under underbody blast loadings. They are: optimized seat energy absorption system, higher standoff distance and vehicle mass, double-V underbody shape without structural reinforcement, and smaller vehicle width. The study found and confirmed that an optimized seat energy absorption system can lower occupant injury indices significantly. The efforts presented in this paper pave a road to a full system multidisciplinary design optimization.

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the improvised explosive devices (IED). Ground vehicle designers and engineers make choices that affect occupant safety, including the weight and structural design of the underbody and the design of seating systems. The latter carry energy to occupants of rapid accelerations caused by blast wave and vehicle mobility. This study uses computational tools to evaluate the vehicle performance requirements. It also combines them into a single-objective design optimization formulation that minimizes personnel casualties and increases vehicle integrity. In military vehicle design and product development, there are various disciplines (survivability, mobility, dynamics, power train & thermal etc.,) with their own set of performance requirements that need to be satisfied in order to get a successful product for the war fighter. Traditionally, computational simulations were performed for different disciplines. But at the time of optimization, a single discipline optimization was usually performed. Later confirmatory runs were done for the other disciplines. This process was very time consuming, with a loop of running multiple iterations, and with different disciplines, and engaged people from each discipline to meet the optimized design performance targets. Quite often, these approaches led to tradeoffs made for design requirements or significant deviations from the optimized design obtained by running single discipline optimization.

Multidisciplinary optimization addresses this shortcoming and takes into account different disciplines for optimization, thus reducing the need to iteratively evolve the design. Though this process has its benefits, those benefits are often overridden with the setup time required for MDO. The major proportion of the setup time is consumed in defining shape variables on full vehicle Finite Element (FE) models that have all types of connections, as the process needs to be repeated for different disciplines. As a result, an alternate methodology is sometimes pursued to create concept models based on the full vehicle FE models, thereby reducing the complexities of a full vehicle FE model. This approach introduces not only the approximation in the entire process by idealizing the detailed FE model, but also requires this definition of shape variables separately for each discipline.

A military ground vehicle is a very complex system that has hundreds of design variables, if not thousands. In order to develop an MDO framework for designing a vehicle system, a simplified vehicle system with the major features of a real system is utilized for the methodological development. Still, there are many design variables in such a simplified system. The number of simulations to take into account all these design variables is huge, which can exceed the existing resources for multidisciplinary design optimization. In order to make it more realistic to conduct a full system MDO analysis, it is necessary to select those major design parameters using a scientific method. This paper describes the screening DOE studies conducted to select the most important design variables used in the multidisciplinary design optimization framework for a ground vehicle system design.

UNDERBODY BLAST MODELING AND SIMULATION

The simulation of a blast event underneath a ground vehicle is a challenging task due to the nature of the multi-physics involved. Energetic material explosion transmits energy to its surroundings, i.e., to the ground, the air and nearby structures, such as a ground vehicle. This energy release takes many forms, including heat, air and soil kinetic energy, soil deformation and work done by the expanding gaseous products. Many factors affect the distribution of the released energy. Our objective of this project is to study the energy transmitted to a nearby ground vehicle, the response of a vehicle, and the potential crew injury.

There are two extreme cases of mine explosions in relation to a ground vehicle. If the mine is buried too deep into the ground, the explosion energy is not enough to remove the overburden of the ground material. The blast energy is totally absorbed by soil compression and deformation. The detonation products are contained underground and no air shock is generated above ground. Vehicles above ground may experience vibration, but no major vehicle damage or crew injury will occur. This case is not in the interest of this study. On the other extreme, if the blast occurs above ground and ground is similar to hard rock, very little explosive energy is transmitted into the ground, and instead the chemical energy is converted to heat, air compression and shock wave formation, which damages vehicle structure and could cause severe injury or even fatality of crew members. In between these two extreme cases, there exists a broad range of conditions where a substantial portion of the available energy is transmitted to soil kinetic energy, thereby generating ejecta. At the same time, another portion of blast energy will also be converted to a shock wave which propagates and impacts the vehicle. Under certain conditions, the ejecta could carry considerable momentum and impact load onto the vehicle. In addition, the crater created during blast will focus the explosion energy to the ground vehicle above it, which causes more localized damage to a ground vehicle.

The explosive part of a land mine is simulated using the Eulerian method. In this case, it does not include the mine casing. The empirical JWL equation of state (EOS) was used in the modeling of the ignition and growth of the products of the explosive reaction. The soil material surrounding the charge is also modeled using the Eulerian formulation. The Gruneisen equation of state model is applied to the soil material.

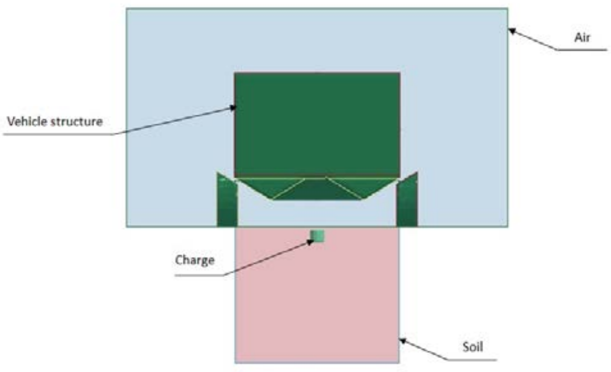


Figure 1: Lagrangian-Eulerian structure

The air surrounding a vehicle is modeled to represent the medium in which the blast wave propagates using the Eulerian algorithm and three dimensional 8-node solid (brick) elements (one point ALE multi-material element). In LS-DYNA, an operator split method is used to integrate the governing equations in Eulerian formulation. A linear polynomial equation of state (*MAT_NULL material and *EOS_LINEAR_POLYNOMIAL in LS-DYNA) is used to simulate the air behavior during a mine blast event.

The Euler and Lagrangian elements at the air and vehicle structure interface are coupled using penalty method. This method is a contact algorithm rather than a true fluid and structure wall coupling. It has the advantage of giving freedom to create an optimal mesh for both the Lagrangian and Eulerian domains. The disadvantage of the methodology is that leakage will occur if it is not controlled properly.

MODEL ASSUMPTIONS

The ground vehicle structures studied in this MDO are simplified vehicles like structural boxes represented with exterior shapes. The underbody kit is made of RHA steel. The remaining vehicle components are made of aluminum. The complicated ground vehicle wheel assembly in this study is simplified by using rigid shell components. The effects of suspension components on blast loading to a vehicle structure are assumed to be minimal. Therefore, the vehicle suspension system is not included in this study. The eight wheels are then rigidly attached directly to the vehicle hull. The crew seat pan and seat back are all assumed to be rigid and there is no seat foam included in the model. When a seat energy absorption option is selected, the seat energy absorption is simulated by using discrete spring and damper elements. If the energy absorption is not activated, the rigid seat is attached to the seating mount position rigidly. There is no foot rest included in the model. In the underbody blast modeling and simulation, the cylindrical charge is placed underneath the center of the underbody structure kit. Therefore, the maximum deformation of an underbody kit under blast loading is assumed to be at the center of the kit.

MODEL DESCRIPTION

The vehicle model is composed of a crew cabin, underbelly kit, wheel assembly, crew seat assembly and reinforcement structure. The crew cabin is a hull of a box shape with four side walls, a roof attached to the top of the box, and a crew floor attached to the lower end of the side walls. The hull is made of aluminum and modeled with MAT24 in LS-Dyna. There two types of underbelly kits. One is a box shape with flat bottom, named as flat hull. The other has a double-V shape at the bottom called double-V hull. An underbelly kit is attached to the bottom of the crew cabin by using four short sections of side walls. The height of these side walls is called the floor gap, which is the gap between the crew floor and the top edge of an underbelly kit as illustrated in Figure 2. The underbelly kit is made of RHA steel and modeled by using Johnson-Cooks material model in LS-Dyna. When the structural reinforcement option is chosen in the design of experiments (DOE), there are four pillars mounted to the roof and the crew floor along the center line of the crew cabin to increase the vertical stiffness of the cabin structure, as shown in Figure 3.

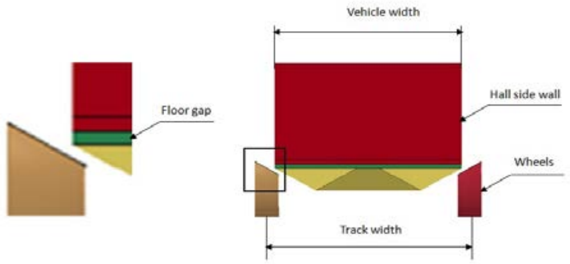


Figure 2: Vehicle structure

Seats are modeled as rigid components; they are either attached to the floor or the side walls by using either rigid mount or springs and dampers, depending on the selected seat mount and energy absorption options. Figure 4 shows that four seats are mounted on crew floor with an energy absorption system. The springs and dampers used in these models are discrete energy absorbing (EA) elements. They are used to reduce the acceleration induced blast injury of crew members. The vehicle wheels are modeled as rigid bodies which are attached to the underbelly kit without using axles or suspension components. One typical vehicle model with double-V underbelly kit is shown in Figures 2 through 4.

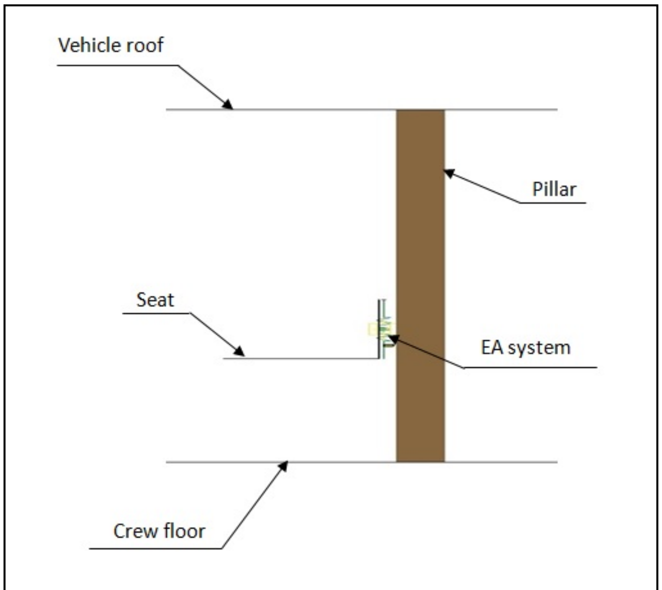


Figure 3: Model with reinforcement (rigid pillar)

In these vehicle models, accelerometers were placed at different locations of a vehicle to monitor the responses of the vehicle structure to an underbody blast loading. An accelerometer was placed at the center of the underbody kit to measure the maximum deformation. Since the charge is placed underneath the center of an underbody kit, it is anticipated that the maximum underbody deformation is at the center of the kit. Accelerometers are also placed on the crew floor at a location between dummy feet to monitor feet accelerations of occupants. Accelerometers are also placed at the center of a seat pan, the side walls and the roof to measure structural acceleration and displacements. The structural accelerations at these locations are believed to be crucial to occupant safety.

Figures 3 and 4 show various components of the simplified vehicle structure used for this study, including seat mounting options, and vehicle interior arrangements. In this study, the arrangement of these components is varied according to the DOE plan described in Design of Experiments section to investigate their influence on the occupant's injury metrics.

A rigid and fast running hybrid 50th percentile LS-Dyna dummy is placed on the central crew seat. A three-point seat belt is fit around the dummy surface. The purpose of the seat belt is to restrain the crew on their seats during a mine blast event and to prevent or reduce potential injuries that may occur during a blast, crash or rollover. Acceleration responses at different locations of the dummy were measured, such as at the pelvis location. Tibia vertical forces and lower lumbar spine forces were also measured and used as the responses to an underbody blast (UBB) loading.

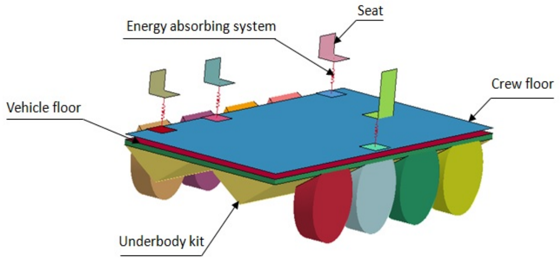


Figure 4: Interior components: seat mounting

In this study, underbody mine explosive, soil, and air around a vehicle are modeled by using Arbitrary Lagrangian Eulerian (ALE) formulation. Both a constitutive model and an equation of state (EOS) are used to describe these materials in ALE formulation. While a constitutive model defines the stress-strain relationship and failure criteria, the EOS formulation relates the pressure to the specific volume, and temperature of a material at a physical state. The mine explosive properties are modeled by using *MAT_HIGH _EXPLOSIVE_BURN and *EOS_JWL [4]. The material constitutive model and equation of state of air used in this study are *MAT_NULL and *EOS_LINEAR_ POLYNOMIAL [4,5,7] respectively. The material model of Elastic Plastic Hydro (EPH) Spall in LS-Dyna, along with Gruneisen equation of state are used to simulate the double-sifted (DS) ITOP soil behavior during a mine blast. The shock wave pressure created by explosive detonation as well as soil ejecta impacting loads are coupled to the vehicle structure above the charge by using *CONSTRAINED _LAGRANGE_IN_SOLID in LS-Dyna. This modeling approach is commonly employed in an End-to-End underbody mine blast computational modeling and simulation [4-11].

The overall model setup is illustrated in Figure 1. The vehicle is placed inside the air medium, so that the charge lies under the underbody center with a given standoff distance (Figure 1). The charge is buried in the soil with a depth of 0.05 m., which is called Depth Of Burial (DOB). The majority element size of the overall vehicle structural finite element model is 20 mm. The same element size is used for charge, soil and air domain.

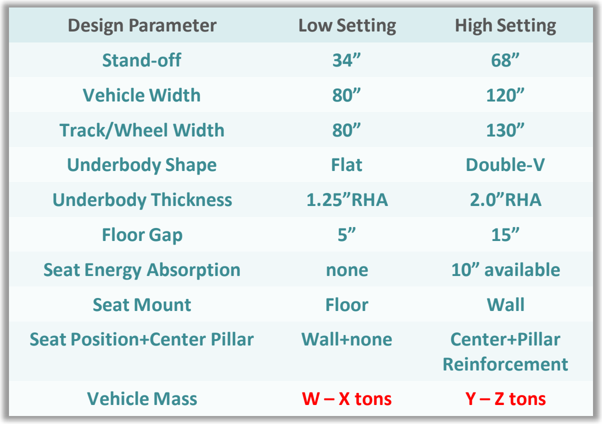
DESIGN PARAMETERS AND SPACES

Military ground vehicles are very complicated systems with hundreds of design parameters. After many discussions with subject matter experts (SME) of ground vehicle systems, the top 10 design parameters were selected for design of experiment (DOE) screening. They are listed as follows:

1) Vehicle standoff distance

2) Vehicle width
3) Track/wheel width
4) Underbody shape
5) Underbody armor thickness
6) Floor gap
7) Seat energy absorption device
8) Seat mount
9) Seat position + center pillar structural reinforcement
10) Vehicle mass

Upon the decision of the main vehicle design variables, SME's expertise and experiences were consulted to obtain the potential maximum ranges of these design parameters, as listed in Table 1. In addition, regulations and transportation limitations were taken into account while selecting the design spaces.



Design Parameter	Low Setting	High Setting
Stand-off	34"	68"
Vehicle Width	80"	120"
Track/Wheel Width	80"	130"
Underbody Shape	Flat	Double-V
Underbody Thickness	1.25"RHA	2.0"RHA
Floor Gap	5"	15"
Seat Energy Absorption	none	10" available
Seat Mount	Floor	Wall
Seat Position+Center Pillar	Wall+none	Center+Pillar Reinforcement
Vehicle Mass	W – X tons	Y – Z tons

Table 1: Ground vehicle design spaces

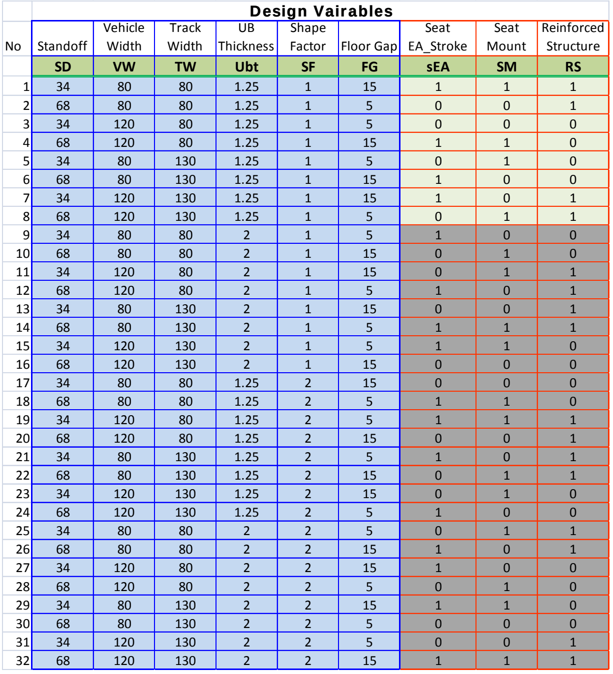
The vehicle width is varied between 80 in. and 120 in. and the track width is varied between 80 in. and 130 in.; the latter factor can influence blast mitigation. The blast wave can be funneled out by increasing the track width, and hence the energy transferred to vehicle can be reduced. However, by increasing the track width, the dynamic stability of the vehicle can be compromised. An optimal value has to be found. The underbody shape was varied by comparing a flat shape and a double-V hull.

The underbody shape is very important, as different shapes funnel the blast wave differently, affecting blast mitigation. The thickness of the underbody kit was varied in this study between 1.25 in. and 2 in., the floor gap was varied between 5 in. and 15 in.. The stand-off, which is the distance between the charge and the bottom of the underbody kit, was varied between 34 in. and 68 in.. The mass of the vehicle used in this study was W-X tons for the low standoff, and Y-Z tons for the high standoff. The seat mounts were connected to either the floor or the wall. Energy absorption mechanisms were used (springs and dampers) were used between the seat mounts and the floor or the wall; some models do not have energy absorption mechanisms. Some models have reinforcements (rigid pillars represented in Figure 4) connected between the vehicle roof and the crew floor, and also the seat location variable was investigated. Responses were determined at different seat locations: driver seat, crew front seat, crew rear seat, and crew center seat.

DESIGN OF EXPERIMENTS (DOE)

In the design parameter screening DOE investigation, the first 9 design variables are considered. A resolution IV DOE is used to develop a design of experiment plan. For each level of vehicle mass, the resolution IV fractional factorial DOE is illustrated in Table 2.

Table 2: Resolution IV DOE



	Design Vairables								
No	Standoff	Vehicle Width	Track Width	UB Thickness	Shape Factor	Floor Gap	Seat EA_Stroke	Seat Mount	Reinforced Structure
	SD	VW	TW	Ubt	SF	FG	sEA	SM	RS
1	34	80	80	1.25	1	15	1	1	1
2	68	80	80	1.25	1	5	0	0	1
3	34	120	80	1.25	1	5	0	0	0
4	68	120	80	1.25	1	15	1	1	0
5	34	80	130	1.25	1	5	0	1	0
6	68	80	130	1.25	1	15	1	0	0
7	34	120	130	1.25	1	15	1	0	1
8	68	120	130	1.25	1	5	0	1	1
9	34	80	80	2	1	5	1	0	0
10	68	80	80	2	1	15	0	1	0
11	34	120	80	2	1	15	0	1	1
12	68	120	80	2	1	5	1	0	1
13	34	80	130	2	1	15	0	0	1
14	68	80	130	2	1	5	1	1	1
15	34	120	130	2	1	5	1	1	0
16	68	120	130	2	1	15	0	0	0
17	34	80	80	1.25	2	15	0	0	0
18	68	80	80	1.25	2	5	1	1	0
19	34	120	80	1.25	2	5	1	1	1
20	68	120	80	1.25	2	15	0	0	1
21	34	80	130	1.25	2	5	1	0	1
22	68	80	130	1.25	2	15	0	1	1
23	34	120	130	1.25	2	15	0	1	0
24	68	120	130	1.25	2	5	1	0	0
25	34	80	80	2	2	5	0	1	1
26	68	80	80	2	2	15	1	0	1
27	34	120	80	2	2	15	1	0	0
28	68	120	80	2	2	5	0	1	0
29	34	80	130	2	2	15	1	1	0
30	68	80	130	2	2	5	0	0	0
31	34	120	130	2	2	5	0	0	1
32	68	120	130	2	2	15	1	1	1

In order to study the effects of gross vehicle mass, and charge sizes, the above DOE will be repeated.

There are many performance considerations during a ground vehicle system design and development. In this study, there are two major categories of performances considered: occupant injury indices and vehicle structural responses. The objective of the MDO analysis in a ground vehicle system design and development process is to minimize the injury indices of an occupant and maintain structural integrity. The occupant injuries associated with underbody blast considered in this study include lower tibia loads, lower lumbar loads, and pelvis accelerations. The vehicle structural Delta-V, or the maximum vertical vehicle jump velocity is selected as the structural response, which is analogous to vehicle impulse metric usage.

VEHICLE MODELS FOR THE DOE

The screening DOE uses various design variables, including different underbody shapes, and structural reinforcement. With different combination of vehicle width, standoff distance, and track/wheel width, a vehicle will need to be designed with different wheel wells. Since the study described in this paper is a simplified vehicle, there is no wheel well used in these models. Instead, a portion of wheel is trimmed off to avoid structural interference, as illustrated in Figure 5.

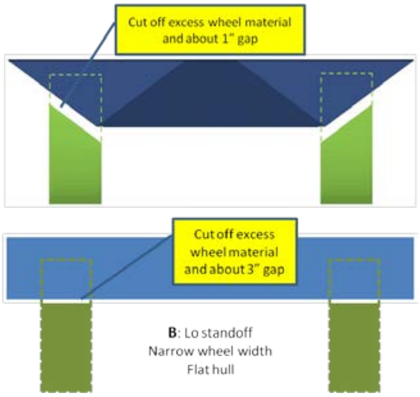


Figure 5: Wheel treatment when interfere with vehicle hull

This series of simplified vehicle models supports the CAMEL concept demonstrator clean sheet approach. It enables a fast turnaround model creation. It also isolates factors of interest. Finally it enables automating the DOE FEA analysis. Different vehicle features of this study defined in the DOE Table 2 are illustrated in Figure 6. 32 models have been created individually and manually for this DOE analysis.

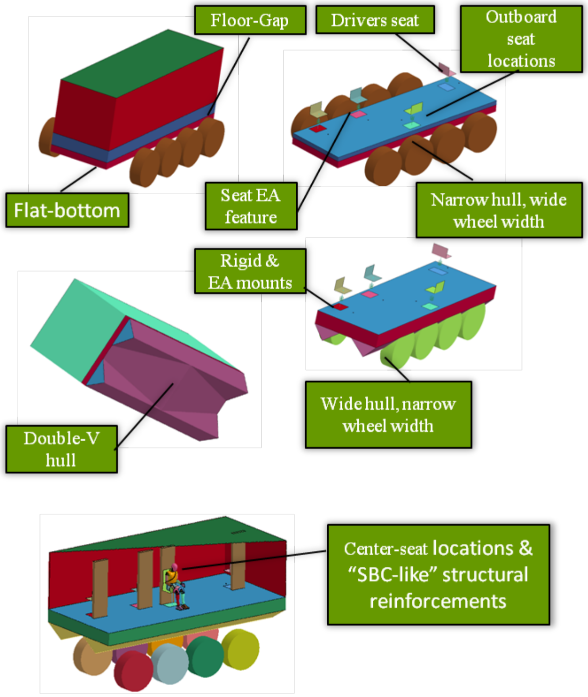


Figure 6: DOE Model Features

DOE ANALYSIS

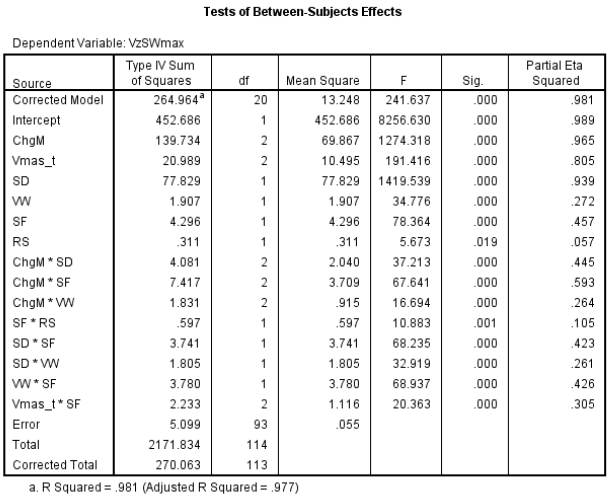
The significant main effects and interactions of vehicle design parameters are determined by using Analysis Of Variance (ANOVA). ANOVA is a simultaneous multiple effect hypothesis test. It is used as a tool to establish statistical significance and effect. Effect in this context means contribution to the total variation. ANOVA uses a mathematical technique known as the sum of squares to study the deviation of a control variable average effect from the total experimental mean response. Significance of a controllable factor response is determined by comparing the variance between the control factor effects against the experimental error. The F Ratio is a test statistic that determines the variable significance beyond variation due to random error. The calculated F statistic should be greater than the critical F value to reject the Null Hypothesis. So if significance of a factor in the ANOVA Table is less than 0.05 we would reject the Null Hypothesis that the given factor has no effect at a 95% confidence level.

The sizes of the significant factor effect are ranked by using Partial-Eta Squared (PES). The PES statistic reports the "practical" significance of each factor. It is the ratio of the sum of squares accounted for by the factor divided by the sum of squares accounted for by the factor plus the sum of squares left to error. Larger values of PES indicate a greater amount of variation accounted for by the model term, to a maximum of 1. Here the individual factors, while statistically significant, do not have same effect on the dependent variable. Also, any variation explained by other factors is removed. This allows us to compare the effect of the same factor in two different studies which contain different factors. Thus, we have a metric to judge the effect of each factor individually with effect of the other factors removed. The residual analysis is used to validate the adequacy of the underlying statistical model [12].

A. The Main Effects on Vehicle Delta-V

The ANOVA table for the response of vehicle Delta-V is shown in Table 3. The Partial-Eta Squared of peak vehicle structural Delta-V is listed in the same table. The PES Perato charts of the vehicle design variables are shown in Figure 7

Table 3: ANOVA Table of Vehicle Delta-V



Tests of Between-Subjects Effects

Dependent Variable: VzSWmax

Source	Type IV Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	264.964[a]	20	13.248	241.637	.000	.981
Intercept	452.686	1	452.686	8256.630	.000	.989
ChgM	139.734	2	69.867	1274.318	.000	.965
Vmas_t	20.989	2	10.495	191.416	.000	.805
SD	77.829	1	77.829	1419.539	.000	.939
VW	1.907	1	1.907	34.776	.000	.272
SF	4.296	1	4.296	78.364	.000	.457
RS	.311	1	.311	5.673	.019	.057
ChgM * SD	4.081	2	2.040	37.213	.000	.445
ChgM * SF	7.417	2	3.709	67.641	.000	.593
ChgM * VW	1.831	2	.915	16.694	.000	.264
SF * RS	.597	1	.597	10.883	.001	.105
SD * SF	3.741	1	3.741	68.235	.000	.423
SD * VW	1.805	1	1.805	32.919	.000	.261
VW * SF	3.780	1	3.780	68.937	.000	.426
Vmas_t * SF	2.233	2	1.116	20.363	.000	.305
Error	5.099	93	.055			
Total	2171.834	114				
Corrected Total	270.063	113				

a. R Squared = .981 (Adjusted R Squared = .977)

The R-Squared value of the ANOVA fitted model is 0.981, indicating the correlation is very high. Based on the estimated PES values, the main effects on the vehicle Delta-V are contributed by the following design variables:

- Standoff distance
- Vehicle mass
- Underbody shape
- Vehicle width
- Structure reinforcement

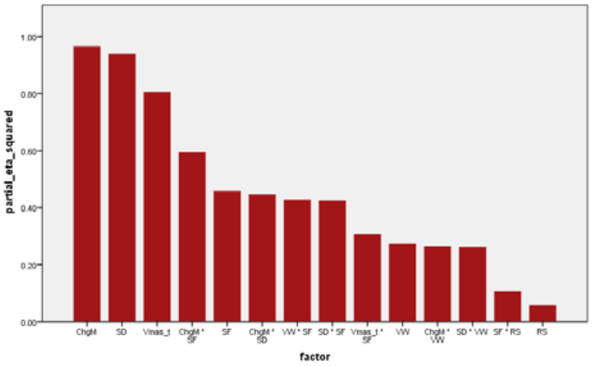


Figure 7: Perato Charts of PES vs. Design Variables

The following interactions also contribute significantly to the vehicle Delta-V:

- Charge sizes- Underbody shape
- Charge sizes- Standoff
- Vehicle Width - Underbody shape
- Standoff – Underbody shape
- Vehicle mass – Underbody shape
- Charge mass – Vehicle width
- Standoff - Vehicle width

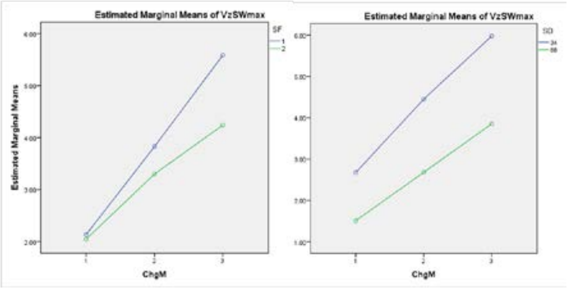


Figure 8: Interactions: Charge mass vs. underbody shape and standoff distance.

The interactions of charge mass vs. underbody shape, as well as standoff distance are illustrated in Figure 8. At the smaller charge mass, underbody shape has negligible effects on vehicle Delta velocity. As charge mass increases, underbody shape plays a more important role in reducing vehicle Delta velocity. Standoff distance plays a significant role in reducing vehicle delta velocity in all charge mass cases.

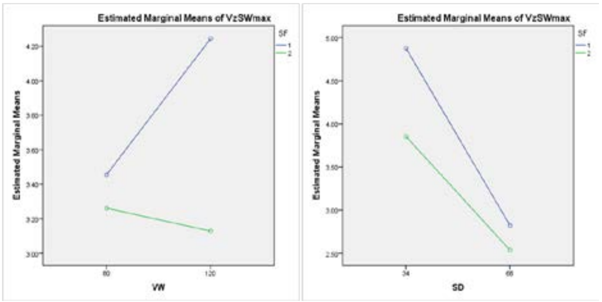


Figure 9: Interactions: Underbody shape vs. vehicle width, and standoff distance.

Figure 9 shows the interactions of underbody shape vs. vehicle width, and standoff distance. For flat underbody shape, vehicle delta velocity increases significantly as vehicle width increases. For double-V shape underbody, vehicle width has limited effect on Delta-V. At lower standoff distance, underbody shape has significant effects on Delta-V. As stand-off distance increases, underbody shape has less effect on vehicle Delta velocity.

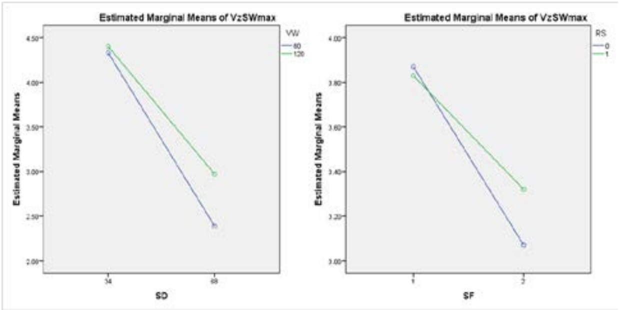


Figure 10: Interactions: Standoff vs. vehicle width, and Underbody shape vs. Reinforcement.

The interactions of standoff vs. vehicle width, and underbody shape vs. structure reinforcement are shown in Figure 10. With a lower standoff distance, vehicle width has no significant effects on vehicle Delta velocity. As standoff distance increases, vehicle width increase results in higher Delta velocity. For flat bottom, the structural reinforcement has no effects on vehicle Delta velocity. But with a double-V underbody shape, the structural reinforcement will increase vehicle Delta velocity. It is therefore concluded that underbody shape has significant effects on vehicle Delta velocity either with or without structural reinforcement.

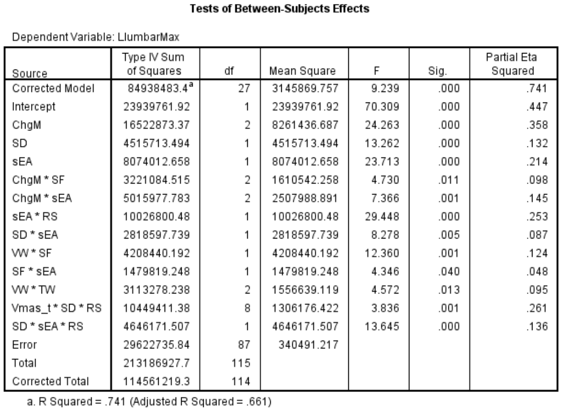
B. The Main Effects on Occupant Lumbar Loads

For the response of occupant lumbar loads, the ANOVA table and the PES of the analysis are listed in Table 4. The partial Eta squared values of the main effect variables are shown in Figure 11. The R-Squared value of the ANOVA fitted model is 0.741, indicating the analysis fitting model is reasonably good. Based on the estimated PES value, the main effects on the occupant lumbar loads are contributed by the following design variables:

- Seat energy absorption
- Standoff distance

In addition to the vehicle design variables, charge size is of course another major effect on the occupant lumbar loads.

Table 4: Main Effect for Peak Lower Lumbar Load



Tests of Between-Subjects Effects

Dependent Variable: LlumbarMax

Source	Type IV Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	84938483.4[a]	27	3145869.757	9.239	.000	.741
Intercept	23939761.92	1	23939761.92	70.309	.000	.447
ChgM	16522873.37	2	8261436.687	24.263	.000	.358
SD	4515713.494	1	4515713.494	13.262	.000	.132
sEA	8074012.658	1	8074012.658	23.713	.000	.214
ChgM * SF	3221084.515	2	1610542.258	4.730	.011	.098
ChgM * sEA	5015977.783	2	2507988.891	7.366	.001	.145
sEA * RS	10026800.48	1	10026800.48	29.448	.000	.253
SD * sEA	2818597.739	1	2818597.739	8.278	.005	.087
VW * SF	4208440.192	1	4208440.192	12.360	.001	.124
SF * sEA	1479819.248	1	1479819.248	4.346	.040	.048
VW * TW	3113278.238	2	1556639.119	4.572	.013	.095
Vmas_t * SD * RS	10449411.38	8	1306176.422	3.836	.001	.261
SD * sEA * RS	4646171.507	1	4646171.507	13.645	.000	.136
Error	29622735.84	87	340491.217			
Total	213186927.7	115				
Corrected Total	114561219.3	114				

a. R Squared = .741 (Adjusted R Squared = .661)

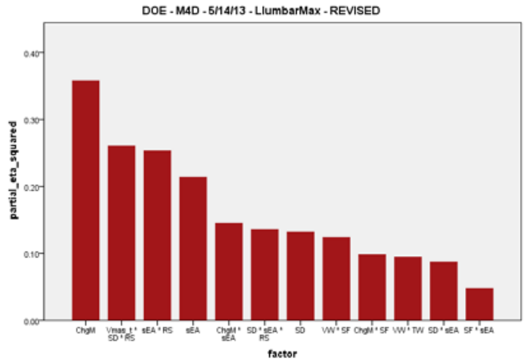


Figure 11: Main Effects for Peak Lower Lumbar Load

The following interactions also contribute significantly to the occupant lumbar loads:

- Vehicle mass – Standoff – Structural reinforcement
- Seat EA – Structural reinforcement
- Charge size – Seat energy absorption
- Standoff – Seat EA – Structural reinforcement
- Standoff – Seat energy absorption
- Vehicle width – Underbody shape
- Charge mass – Underbody shape

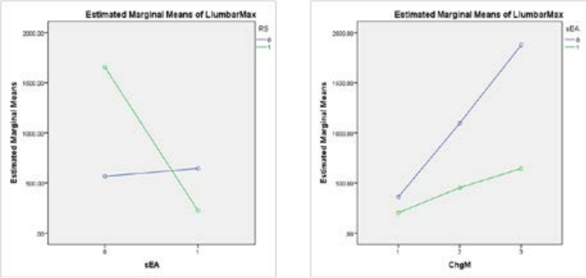


Figure 12: Interactions for Peak Lower Lumbar Load

Figure 12 shows the interactions of seat energy absorption system and structural reinforcement, as well as the charge sizes and seat energy absorption system on the peak occupant lumbar load. With vehicle structural reinforcement, seat EA system has significant effects on peak lower lumbar load. However, without structural reinforcement, the effect of seat EA system on peak lower lumbar load is insignificant. With the optimized seat EA system, charge mass (up to the larger charge case studies here) has limited effects on peak lower lumbar load. Without EA system, peak lower lumbar load increases linearly with the charge mass increases.

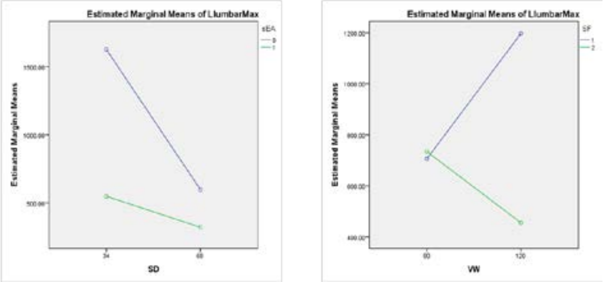


Figure 13: Interactions for Peak Lower Lumbar Load

The interactions of the vehicle standoff distance and seat energy absorption system option, as well as the vehicle width and underbody shape on the peak occupant lumbar load are illustrated in Figure 13. With the optimized seat EA systems, stand-off distance has limited effects on peak lower lumbar load. Without EA system, peak lower lumbar load decreases as the standoff distance increases. With the smaller vehicle width, underbody shapes doesn't have significant effects on peak lower lumbar load.

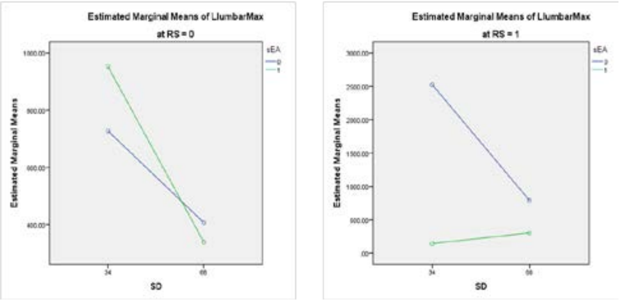


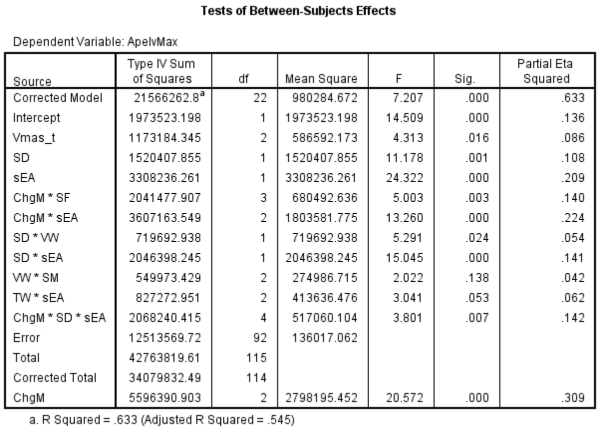
Figure 14: 3 Way Interactions for Peak Lower Lumbar Load

The three way interactions of vehicle standoff distance, seat energy absorption option, and structural reinforcement on the peak lower lumbar load are shown in Figure 14. Without structural reinforcement (RS), both seat EA option and standoff distance have significant effects on peak lower lumbar load. With structural reinforcement and seat EA system, standoff distance will have insignificant effects on peak lower lumbar load.

C. *The Main Effects on Occupant Pelvis Acceleration*

The ANOVA table for the response of occupant peak pelvis acceleration is shown in Table 5. The partial-Eta

Table 5: Main Effect for Peak Pelvis Acceleration



Tests of Between-Subjects Effects

Dependent Variable: ApelvMax

Source	Type IV Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	21566262.8[a]	22	980284.672	7.207	.000	.633
Intercept	1973523.198	1	1973523.198	14.509	.000	.136
Vmas_t	1173184.345	2	586592.173	4.313	.016	.086
SD	1520407.855	1	1520407.855	11.178	.001	.108
sEA	3308236.261	1	3308236.261	24.322	.000	.209
ChgM * SF	2041477.907	3	680492.636	5.003	.003	.140
ChgM * sEA	3607163.549	2	1803581.775	13.260	.000	.224
SD * VW	719692.938	1	719692.938	5.291	.024	.054
SD * sEA	2046398.245	1	2046398.245	15.045	.000	.141
VW * SM	549973.429	2	274986.715	2.022	.138	.042
TW * sEA	827272.951	2	413636.476	3.041	.053	.062
ChgM * SD * sEA	2068240.415	4	517060.104	3.801	.007	.142
Error	12513569.72	92	136017.062			
Total	42763819.61	115				
Corrected Total	34079832.49	114				
ChgM	5596390.903	2	2798195.452	20.572	.000	.309

a. R Squared = .633 (Adjusted R Squared = .545) squared values of peak occupant pelvis acceleration are listed in the same table. The PES Perato charts of the vehicle design variables are shown in Figure 15.

Based on the estimated PES values, the main effects on the occupant peak pelvis accelerations are contributed by the following design variables:

- Seat energy absorption option
- Vehicle standoff distance
- Vehicle mass

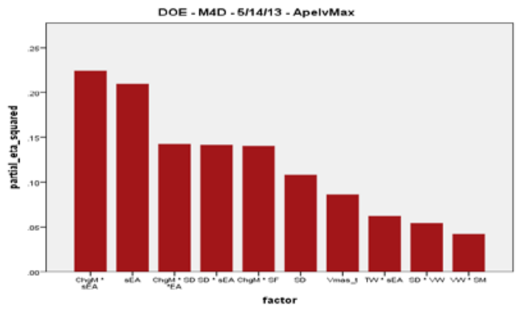


Figure 15: Interactions: Standoff vs. vehicle width, and underbody shape vs. reinforcement.

In addition, the following interactions also contribute significantly to the occupant peak pelvis acceleration:

- Charge mass – Seat EA
- Charge mass - Standoff – Seat EA
- Standoff – Seat EA
- Charge mass- Underbody shape
- Wheel width – Seat EA
- Standoff – Vehicle width

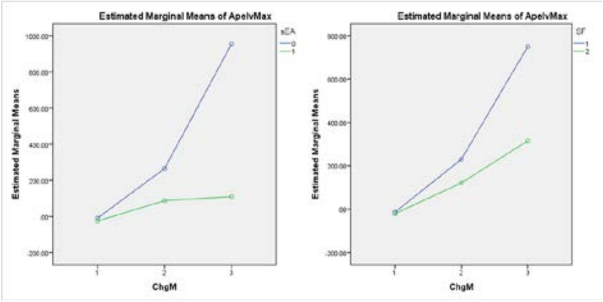


Figure 16: Interactions: Charge mass vs. seat EA, and underbody shape.

Figure 16 shows the interaction of charge mass and seat energy absorption option, as well as vehicle underbody shape. With a smaller charge, seat EA system has negligible effects on peak pelvis acceleration. The seat EA was already optimized for the baseline model which is used a basis for all vehicle models creation, such that occupant pelvis acceleration doesn't change significantly from lower to higher charge sizes. With the lower charge, vehicle underbody shapes of flat and double-V have about the same peak pelvis acceleration.

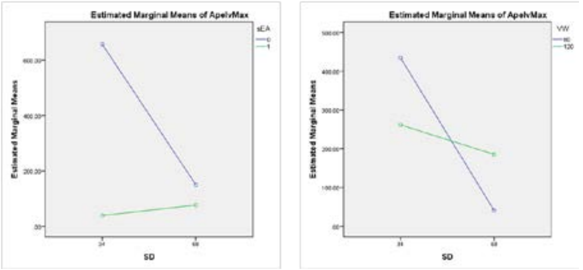


Figure 17: Interactions: Peak Pelvis Acceleration

The interactions of standoff distance and seat EA options as well as vehicle width are shown in Figure 17. With the optimized seat EA system, standoff distance has negligible effects on peak pelvis acceleration. Without the EA system, standoff distance plays an important role in reducing peak pelvis acceleration. With larger vehicle width value, vehicle standoff distance has insignificant effects on peak pelvis acceleration. As vehicle width reduces, the effects of standoff distance increases.

CONCLUSIONS

In this screening design of experiment study, the top ten important vehicle design variables have been selected based on subject matter experts' past knowledge and experience. A systematic investigation was conducted to analyze effects of these identified vehicle design parameters on vehicle structure responses as well as occupant injury indices. 32 finite element (FE) models representing fractional factorial combinations of these parameters were created and analyzed systematically by using the high fidelity of the underbody blast (UBB) models. A 50th percentile Hybrid III dummy is also included in the analysis to assess the potential occupant injury indices. The analysis has confirmed and validated the SME intuitions.

For the vehicle Delta-V, the main effects are vehicle standoff distance, vehicle mass, underbody shape, and vehicle width. If occupant injury indices are considered, the main effects of a ground vehicle system are: seat energy absorption system option, standoff distances, and underbody shapes.

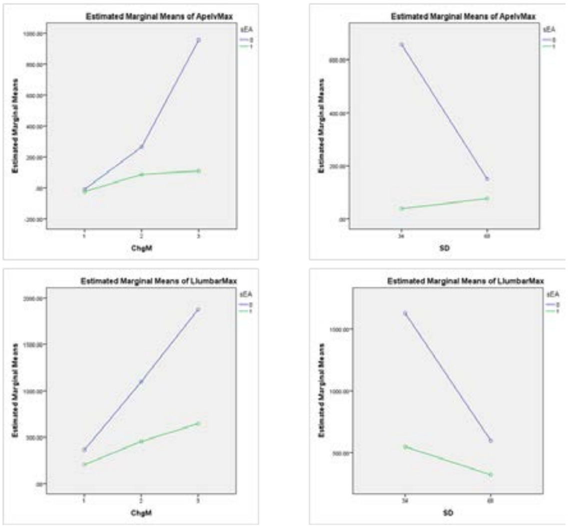


Figure 18: Optimized energy absorption system impact on occupant injury indices

To effectively protect an occupant in a ground vehicle system in an underbody blast event, the preferred vehicle design combinations based on this study are:

- Optimized seat energy absorption system
- Higher standoff distance and vehicle mass
- Double-V underbody without structural reinforcement
- Smaller vehicle width

The presented study has also found and confirmed that an optimized seat energy absorption system has significant impact on occupant injury, as illustrated in Figure 18. This study has paved a road to a full system multidisciplinary design optimization effort.

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This analysis was initiated at the early stages of the Occupant-Centric Platform Technology-Enabled Demonstrator (OCP-TECD) program, and many TARDEC business units helped to select the vehicle design parameters and determine the design spaces. The authors would like to thank the following individuals who contributed in the research efforts associated with the published work here:

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ACRONYMS

ALE	Arbitrary Lagrangian Eulerian
ANOVA	ANalysis Of VAriance
DOB	Depth Of Burial
DOE	Design Of Experiments
DOTE	Director of Operational Test and Evaluation
DS	Double-Sifted
EA	Energy Absorption
EOS	Equation Of State
FSI	Fluid Structure Interaction
GSS	Ground System Survivability
IED	Improvised Explosive Device
ITOP	International Test Operations Procedure
JWL	Jones-Wilkins-Lee (Eq. of state for explosives)
MDO	Multidisciplinary Design Optimization
M&S	Modeling & Simulation
NTUBB	Near-Term Under Body Blast modeling and simulation enhancement program
OCP-TECD	Occupant-Centric Platform Technology-Enabled Capability Demonstrator
PEO	Program Executive Office
PES	Partial Eta Squared
PM	Program Manager
RS	Reinforced Structure or structural reinforcement option
SD	Standoff Distance
SME	Subject Matter Expert
S&T	Science and Technology
TARDEC	Tank Automotive Research, Development and Engineering Center
UB	Under Body
UBB	Under-Body Blast
WIA	Wounded In Action

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