Quantification of the design relationship between ground vehicle weight and occupant safety under blast loading

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Abstract: Military ground vehicle design must consider the threat posed by underbody blasts to new vehicles and their occupants, while also accounting for weight reduction goals for improving fuel economy,

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UNCLASSIFIED: Dist A. Approved for public release

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **01 APR 2011**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Quantification of the design relationship between ground vehicle weight and occupant safety under blast loading (PREPRINT)**		5a. CONTRACT NUMBER **W56HZV-04-2-0001**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Steven Hoffenson; Sudhakar Arepally; Michael Kokkolaras**		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA University of Michigan Ann Arbor, MI 48109 USA**		8. PERFORMING ORGANIZATION REPORT NUMBER **21661RC**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA**		10. SPONSOR/MONITOR'S ACRONYM(S) **TACOM/TARDEC/RDECOM**
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) **21661RC**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Submitted for publication ia a special issue of Int'l Journal of Vehicle Design, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**15**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

mobility, and cost. A two-stage process is presented to model the blast event for simulating the vehicle response and for the occupant response. Issues including computational expense, objective function formulation, and multi-objective seating system design optimization are addressed in detail, and three different blastworthiness optimization formulations are presented and evaluated.

Keywords: Military ground vehicle design; Occupant safety; Blastworthiness; Vertical drop tower, Design optimization.

Reference to this paper should be made as follows: Hoffenson, S.; Arepally, S.; Kokkolaras, M.; and Papalambros, P.Y. (2011) 'Quantification of the design relationship between ground vehicle weight and occupant safety under blast loading', *Int. J. Vehicle Design*, Vol. x, No. x, pp.xxx–xxx.

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1 Introduction

Improvised explosive devices (IEDs), often referred to as "roadside bombs," pose one of the greatest threats to U.S. ground troops in overseas operations, accounting for over sixty percent of combat fatalities and injuries in Afghanistan and Iraq (Anonymous, 2010). Injuries and fatalities to ground vehicle occupants occur due to the rapid accelerations and hard contact experienced when an explosive such as an IED detonates beneath the vehicle. Ground vehicle designers must consider this threat when designing new vehicles and restraint systems; however, single-objective optimization for occupant survivability might compromise other objectives such as performance and range. Specifically, while increasing vehicle mass will decrease the accleration pulse from a given explosive and improve occupant safety, it hinders the accleration, fuel consumption, and range of the vehicle.

While many argue that safety is the top priority in vehicle design, it must be noted that acceleration, fuel consumption, and range are all inextricably linked to personnel safety. The ability of soldiers to rapidly move in and out of combat areas decreases their exposure to hostile situations, thereby making a case for improving acceleration and top speed. The need for additional fuel to be transported to military bases exposes additional convoys of vehicles to danger, pressing the need for improved fuel economy. Lastly, longer driving range of ground vehicles allows bases to be safely located farther away from hostile environments. Thus, even if safety is the sole priority in vehicle design, designers must simultaneously consider all of the aforementioned performance objectives along with direct safety objectives such as missile protection and blastworthiness.

The relationship between these design objectives is evident when comparing the High Mobility Multipurpose Wheeled Vehicle (HMMWV) and the Mine Resistant Ambush Protected vehicle (MRAP), two ground vehicles used extensively by the United States Army. The HMMWV, which has been the primary light tactical vehicle in the U.S. Army since 1985, is a 4-ton vehicle with a 75 mile-per-hour top speed, 275 mile range, and a fuel economy of 11 miles per gallon (Lardner, 2010; U.S. Army, 2010). In response to high casualty rates for HMMWV occupants under IED attacks, the U.S. Army introduced the MRAP, which weighs 17 tons, has a 65 mile-per-hour top speed, 420 mile range (due to a fuel tank three times the size of the HMMWV), and can travel approximately 6 miles per gallon of fuel. The MRAP has been successful in protecting occupants from underbody blast events due to its greater mass, higher ground clearance, and v-shaped hull; however, its size prohibits maneuvering over difficult terrain and bridges, and it consumes twice as much fuel as the HMMWV. This apparent trade-off motivates a need to study the relationship between vehicle weight and blastworthiness.

Blast and crash testing procedures vary greatly within the research and design community, though a common trend is the extensive use of virtual modeling and testing to reduce time, cost, and equipment requirements. Computational modeling has its own considerable trade-off when choosing between a high-fidelity model that may take days to simulate and a less sophisticated model that runs in minutes. Regardless of whether the modeling is done physically or computationally, researchers typically study the vehicle response to the crash or blast event separately from the occupant's response to the vehicle motion. This serves to break down the problem into managable subproblems, allowing for specialized

testing and software for the structural response of the vehicle as well as for the biomechanical response of the occupant or dummy.

The first procedure evaluates the vehicle response to a crash or blast event, where the outputs of interest are the resulting motion and deformation of the vehicle at the position of the occupant's seat. The second procedure inputs that motion to the occupant and vehicle interior, resulting in profiles of the forces and accelerations experienced by different parts of the occupant's body. The latter test often takes the form of a "sled test," in which the occupant, seat, floor, and restraint system are positioned on rails that allow them to move together in a prescribed manner in the upward (z) direction for blast events and in the fore-aft (x) direction for frontal crash. From the occupant data, scientists make predictions regarding the probability of different injury modes. In vehicle occupant safety optimization, the objective is typically to minimize these probabilities.

This paper presents the general modeling approach used in the optimization tradeoff studies in Section 2, including the development of surrogate models for the vehicle's structural response and occupant compartment. Section 3 presents three optimization formulations with different design objectives. Section 4 presents and discusses the results obtained from solving the optimization problems, and Section 5 offers conclusions.

2 Modeling Approach

This study models underbody vehicle blast events as the two-stage process outlined in the previous section. In particular, we examine the opportunity to tune the seating system design parameters with a prescribed vehicle mass and blast pulse to minimize the occupant's overall probability of injury. With this in mind, a computational model for the seating system test is used, which was developed to replicate the behavior of the physical vertical drop tower tests used to study aircraft seat ejection and ground vehicle blast events. This model was created and evaluated using a mathematical dynamic modeling program that integrates multibody dynamics with finite element analysis to replicate the behavior of physical systems (TNO, 2010; Arepally et al., 2008). The vertical drop tower sled shown in Figure 1 includes a floor, seat, seat-back, seat cushions, energy-absorbing (EA) system that allows limited travel between the seat bottom and floor, lap belt, shoulder belt, and Hybrid III dummy; this system travels along rigid vertical (z-direction) rails. Analysis software reports the forces and accelerations experienced at different locations within the occupant model.

To obtain the blast pulse, a less sophisticated model of the vehicle and blast charge is employed, which simulates the acceleration response of a vehicle-sized box to a mine blast. While this simplifies the vehicle to a rigid body, not allowing for underbody deformation, it evaluates quickly, is non-proprietary and unclassified, and adequately demonstrates the relative impact of vehicle mass and charge parameters on the acceleration pulse. The vehicle mass varies with prescribed changes to the material density properties, and the mine blast load is estimated using the CONWEP engineering model built in the software (Randers-Pehrson & Bannister, 1997; LSTC, 2007), where the charge intensity (in TNT mass-equivalent) and charge location (longitudinal/x- and lateral/y-

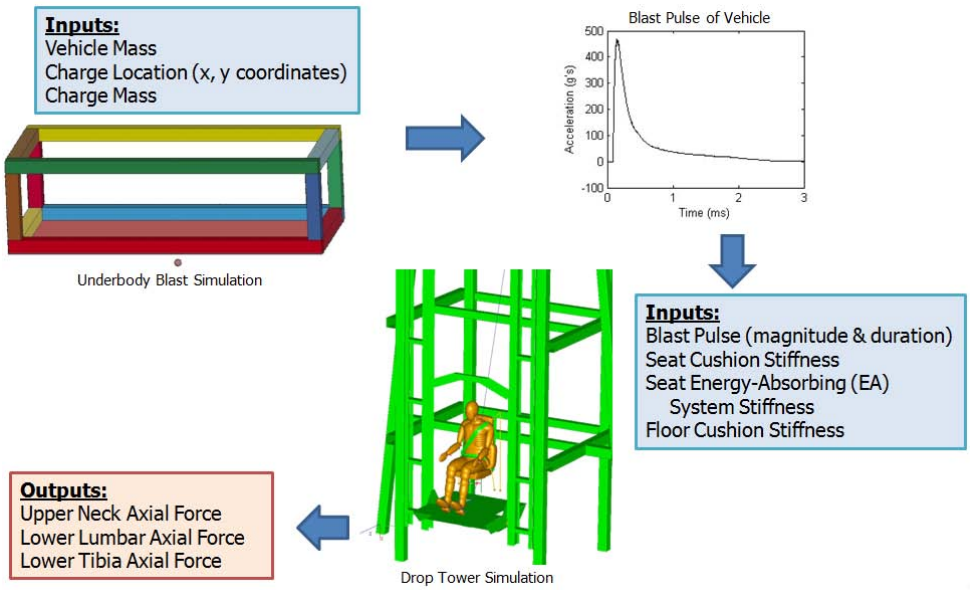

Figure 1 Models and approach

direction) are varied. Thus, we can obtain a general prediction of the impact that vehicle mass, charge intensity, and charge location have on the acceleration pulse experienced by the occupant. It should be noted that this study only examines the response at the position of the driver's seat, though it is expected that passengers should experience a comparable range of acceleration pulses given that the blast positioning is uniform and random.

Linking these simulations, we simulate the vehicle acceleration response for different vehicle masses and charge parameters, and then input that response to the occupant model to optimize the seating system design for occupant safety. As injuries can occur in many different locations and modes throughout the body, it is practical to simplify the analysis by choosing the particular injury types that are most likely to occur in blast scenerios and are also indicative of other injuries that are likely to occur. The North Atlantic Treaty Organization (NATO) published a report to this effect in 2007 that establishes three particular injury modes to be monitored in blast events: upper neck compressive injury, vertical loading of the lower lumber spine, and lower tibia fracture. The upper neck injury criterion was developed by Mertz et al. (1978) and is used as the indicator for all neck and head injury modes that may occur in a blast scenario; the limit for axial compression in the upper neck is at 4 kN for an instantaneous event and 1.1 kN for a 30-millisecond pulse, representing a 10-percent probability of a moderate injury on the Abbreviated Injury Scale (AIS) (AAAM, 1990). The lower lumbar injury criterion that represents the probability of injuries in the occupant torso is specified by NATO as the Dynamic Response Index (DRI); however, this metric was found by Chandler (1985) to correlate strongly with axial compression of the lower lumbar spine, and for simplicity and consistency this study considers the compression

measure. The threshold for a 10-percent probability of moderate lumbar spine injury is set at 6.7 kN, regardless of duration. Lastly, lower extremity injuries are characterized by a fracture injury in the lower tibia, following a report by Yoganandan et al. (1996) on the compressive force associated with such fracture; this sets the 10-percent threshold for lower tibia compression at 5.4 kN, also independent of event duration.

The present study uses this linked-model approach to optimize a vehicle's seating system at particular mass values. As IEDs are by nature crude and unpredictable, the explosive charge parameters are prescribed as postulated distributions. These distributions are based on estimates that are entirely independent of any blast data, which is unavailable to the authors and for publication. Therefore, the optimization must account for this uncertainty in the formulation, and three separate formulations are presented for comparison.

Initially, the vehicle blast response model required approximately 3 hours for evaluation; this model was simplified by removing the surfaces unaffected by the blast and increasing the time step so that the final model required only 20 minutes of computation without any significant loss in fidelity. The occupant response model is evaluated in approximately 8 minutes. Since most optimization schemes require a large number of function evaluations for convergence, it is impractical to embed the models in an optimization formulation. A common method for optimizing under such circumstances, and the method employed in this study, is to conduct a Design of Experiments (DOE) to sample the design space, and then to use the resulting data to create mathematical surrogate models whose computational time is relatively small.

2.1 Vehicle Structure Surrogate Modeling

The vehicle blast model was simulated 100 times with a Latin-hypercube sampling strategy (McKay et al., 1979) over the four input parameters: vehicle mass (m_v) in kilograms, charge longitudinal x-position (x_c) in meters, charge lateral y-position (y_c) in meters, and charge mass (m_c) in kilograms TNT-equivalent. As vehicle mass is an input that can be designed for, the sample for m_v is taken uniformly with a lower bound a 2,000 kg and an upper bound of 12,000 kg. As mentioned previously, empirical information on IEDs is sensitive, and the distributions used in this work are entirely independent of such data and based on unsubstantiated estimates. Since many IEDs are remotely detonated and not necessarily triggered by pressures on the ground, an assumed uniform distribution of the charge position in x- and y- directions spans the entire footprint of the vehicle with equal probability. Since other studies often use a standard 5-kilogram or 10-pound (4.5-kilogram) charge, the charge size in this study is assumed to be distributed normally with a mean of 5 kilograms and a standard deviation of 2 kilograms, not allowing for negative values (which mathematically would occur but are physically impossible). While these distributions are more important for the optimization than for the surrogate modeling, they are used in the Latin-hypercube to assure that the metamodel fidelity is highest where it will be evaluated most often.

The results of this DOE were examined to determine the most appropriate way to parameterize the output of interest, which is the blast pulse. The pulses had a common shape and duration similar to that shown in Figure 1, with the

only significant difference among simulations being the magnitude, or intensity, of the pulse. Thus, the entire blast pulse was parameterized by this single value of peak acceleration magnitude (a_{peak}), measured in g's. The data were then fit with a linear regression model using the R software package (Venables et al., 2010) to approximate a_{peak} as a function of the four inputs, m_v, x_c, y_c and m_c. Prior knowledge that the mass of the vehicle impacts peak velocity with an inverse relationship was used, and a model was then fit using all second-order and interaction terms. The insignificant terms were pruned, resulting in a linear model of the below form with an R-squared value of 0.96.

$$\begin{aligned} a_{peak} = \quad & 52.1 + 575,000\frac{1}{m_v} - 30.9x_c - 220y_c - 2.53m_c + 373,000\frac{x_c}{m_v} \\ & + 1,630,000\frac{y_c}{m_v} + 518,000\frac{m_c}{m_v} + 34.9y_cm_c - 129{y_c}^2 \end{aligned}$$

As the goal with this first simulation is to understand how vehicle mass impacts the distribution of a_{peak}, the above polynomial model is evaluated at different vehicle masses with the distributed charge inputs. For each m_v between 2,000 and 12,000 at intervals of 500 kg, a 3,000-point Latin hypercube was evaluated to observe the output distributions. These distributions were all very well approximated as normal, and the means and standard deviations were plotted as a function of vehicle mass. They were fit with power function regressions (Microsoft, 2006), and the resulting equations are given below, both with R-squared values above 0.999. These allow us to interpolate the distribution of peak accelerations experienced by any vehicle mass within the simulated range.

$$\begin{aligned} \mu_{a_{peak}} &= 4 \times 10^6 m_v^{-1.023} \\ \sigma_{a_{peak}} &= 2 \times 10^6 m_v^{-1.035} \end{aligned}$$

2.2 Occupant Compartment Surrogate Modeling

A DOE was also conducted to develop appropriate surrogate models for the occupant compartment model. Here, the inputs to be varied included the peak acceleration as well as the three seating design parameters: seat energy-absorbing (EA) system stiffness (s_{EA}), seat cushion stiffness (s_c), and floor pad stiffness (s_f), all of which are scaling factors of the original material force-deflection curves. A 300-point Latin hypercube was constructed varying each input uniformly across its practical range, and polynomial surrogates using second-order and interaction terms were fit for the occupant neck, lumbar spine, and tibia responses. Preliminary tests revealed a strong correlation between the left and right tibias, and as a result the two tibia responses were averaged and combined into one model. Each surrogate was pruned using backward elimination until all higher-order terms had p-values below 0.001 significance, and the Box-Cox method was employed when applicable for response transformation, resulting in exponential terms (Box & Cox, 1964). The resulting models had R-squared values of 0.95, 0.95 and 0.98, respectively, and they are presented below.

$$
\begin{aligned}
F_{neck} &= e^{(3.84+0.12s_{EA}+0.88s_c+0.002a_{peak}+0.058s_{EA}s_c+0.000084s_{EA}a_{peak} \\
&\quad -0.000063s_ca_{peak}-0.058s_{EA}^2-0.14s_c^2-0.00000054a_{peak}^2)} \\
F_{lumbar} &= e^{(5.66+0.12s_{EA}+0.81s_c+0.002a_{peak}+0.062s_{EA}s_c+0.000087s_{EA}a_{peak} \\
&\quad -0.000068s_ca_{peak}-0.059s_{EA}^2-0.13s_c^2-0.00000056a_{peak}^2)} \\
F_{tibia} &= 332 - 245s_c - 80.2s_f + 1.30a_{peak} + 35.8s_cs_f \\
&\quad + 14.0s_f^2 + 0.0012a_{peak}^2
\end{aligned}
$$

From these equations, a strong correlation is evident between the neck and the lumbar responses, which is expected given that both are positioned along the spinal column; however, given the differences in the injury force thresholds, these remained separate for optimization. It is also interesting to note that the floor pad is not a significant variable in the neck and lumbar responses, nor is the EA system significant for the tibia response. The seat cushion, which is significant to all three forces, has opposite effects on lower extremities versus the upper body; increasing the cushion stiffness tends to increase the forces felt in the neck and spine while decreasing the forces felt in the tibias. In other words, the seat cushion stiffness can be tuned to shift the load between the spine and the lower legs, and seat cushion designers must seek a balance when choosing an appropriate seat cushion stiffness. Peak acceleration, as expected, has a strong positive correlation with all occupant force responses.

3 Optimization

Given that the overwhelming majority of military vehicle-related casualties involve underbody blast events, the primary objective of seating system design is to protect occupants against these threats. More specifically, the goal is to minimize the occupants' probability of being injured; however, this is complicated by a number of factors, three of which are presented here. The first is that this approach considers three separate injury modes, and minimizing one injury criterion does not necessarily correspond with reducing the other two criteria; in fact, minimizing one injury criterion often competes with the minimization of other criteria. The second factor is that the knowledge that connects the model outputs, which are force quantities, to the objectives, which are injury probabilities, is incomplete. The Yoganandan literature on lower tibia injury does present complete functions for moderate injury probablity curves as a function of axial force; however, the other two injury modes in the neck and spine simply present the 10-percent threshold values. Because of this, we cannot confidently minimize injury probability, as we don't know how forces outside of the threshold values translate to probabilities. The final factor is the uncertainty introduced in the blast parameters, which is input as a range rather than a single set of values. Since these factors complicate the formulation of a straightforward objective, we present three different optimization formulations and specify their strengths and limitations.

3.1 Minimizing Probability of Failure

Based on the NATO report on protecting vehicle occupants from landmine effects, the ground vehicle safety benchmark is for occupants to have no greater than a 10 percent probability of moderate injury (AIS2). Unfortunately, it is impractical (if not impossible) to guarantee that this benchmark will be met in all possible blast scenarios given that there is no upper limit to the size of a threat. We can, however, use the distribution of blast scenarios to minimize the percentage of such events that exceed the 10-percent threshold. In this formulation, the cumulative distribution function of the normally-distributed peak acceleration is in the objective in attempt to minimize the probability of failure (P_f) to meet the injury threshold. Here, the seating system variables s_{EA}, s_c and s_f are allowed to vary along with the peak acceleration itself, a_{peak}, and the surrogate models for occupant forces are constrained at the threshold values.

$$
\begin{aligned}
\underset{s_{EA},s_c,s_f,a_{peak}}{\text{minimize}} \quad & P_f = 1 - \Phi(a_{peak}) \\
\text{where} \quad & \Phi\left(a_{peak}\right) = \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{a_{peak} - \mu_{a_{peak}}}{\sqrt{2\sigma^2_{a_{peak}}}}\right)\right] \\
& \mu_{a_{peak}}\left(m_v\right) = 4 \times 10^6 m_v^{-1.023} \\
& \sigma_{a_{peak}}\left(m_v\right) = 2 \times 10^6 m_v^{-1.035} \\
\text{subject to} \quad & F_{neck}\left(s_{EA}, s_c, a_{peak}\right) \leq 4000 \\
& F_{lumbar}\left(s_{EA}, s_c, a_{peak}\right) \leq 6700 \\
& F_{tibia}\left(s_c, s_f, a_{peak}\right) \leq 5400 \\
& lb \leq s_{EA}, s_c, s_f \leq ub
\end{aligned}
$$

By accounting for function monotonicity, constants, and scaling factors, we can deduce that this formulation yields equivalent resulting designs as maximizing a_{peak} under the same constraints. Following this logic, the formulation essentially optimizes the seating system design for the most extreme scenario that meets the threshold, regardless of vehicle mass. The resulting seating system designs will thus produce acceptable, but not necessarily optimal, results in the more frequently-occurring blast scenarios, and could consequently produce a greater absolute number of injuries.

An additional limitation of this formulation is in the presentation and interpretation of the results; if the evaluation of vehicle X converges to a 1 percent probability of failure, then an occupant of vehicle X has a 1 percent probability of sustaining body forces that correspond to a 10 percent probability of moderate injury. However, that same occupant may have a 50 percent probability of sustaining body forces corresponding to a 9 percent probability of moderate injury, but such information will not be captured by this formulation. Most stakeholders in the military vehicle design process would have difficulty interpreting and analyzing results in the form of a percentage of a percentage.

3.2 Minimizing Normalized Forces

In an attempt to account for the most common blast scenarios rather than the most extreme cases, the second optimization approach seeks to minimize the actual body force values in the mode, or most frequent case, using the knowledge that lower forces in the body correspond with lower probabilities of injury. To account for all three criteria we use a minimax approach where the highest, or maximum, of the three forces is minimized, recognizing that the force which is initially the highest may shift during the course of the optimization. We also consider the known differences in the associated 10-percent probability forces, and so these force values are normalized according to their threshold values, essentially minimizing them as a percentage of their respective thresholds. Since the distribution is modeled as normal, the mode peak acceleration is equal to the median and mean.

$$\begin{aligned} \underset{s_{EA},s_c,s_f}{\text{minimize}} \quad & \text{maximum}\left(\frac{F_{neck}}{4}, \frac{F_{lumbar}}{6.7}, \frac{F_{tibia}}{5.4}\right) \\ \text{where} \quad & a_{peak} = \mu_{a_{peak}}\left(m_v\right) \\ \text{subject to} \quad & lb \leq s_{EA}, s_c, s_f \leq ub \end{aligned}$$

Here, the optimization scheme finds the best combination of values for the seating system parameters, s_{EA}, s_c and s_f, while the peak acceleration is fixed based on the vehicle mass. The forces represented in the objective function, F_{neck}, F_{lumbar} and F_{tibia}, are obtained from the surrogate models presented in Section 2.2. Since the peak acceleration is dependent on vehicle mass, this formulation, in contrast to the probability of failure approach, may yield different results for different vehicle weights. This provides opportunities to understand the effect of seat design parameter tuning on the safety of different vehicles and different vehicle configurations. However, the major limitation here is that this optimization approach only considers one scenario of a continuous set of possible blast inputs, and choosing that scenario as the mode is an arbitrary choice that affects the results.

3.3 Minimizing Postulated Injury Probabilities

The final optimization approach examined in this study is to minimize the overall probability of injury, as postulated by some force-injury probability curves. As a tibia force-probability curve has already been published (Yoganandan et al., 1996), only the lumbar and neck curves must be approximated. As most injury curves tend to be approximated by Weibull functions of the form $P = 1 - e^{-(F/\alpha)^{\beta}}$, where P is probability of injury on a scale of 0 to 1 and F is the axial force in kN, and the force associated with a 10-percent probability is already known, only one further point must be approximated for each injury mode to fit the two parameters (Weibull, 1951). Chandler (1985), who studied lumbar spine injuries, approximated some values of how the dynamic response index (DRI) relates to the probability of injury, and converting these values to an approximation of how compressive force relates to DRI, an approximation was made for a lumbar injury curve as below. Known data for approximating the neck force-probability curve was not available, and so a curve was postulated to have a similar shape as the lumbar and tibia curves and pass through the 10-percent threshold at 4 kN.

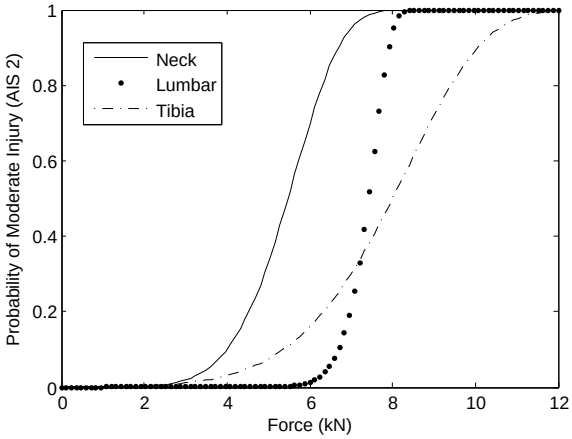

Figure 2 Postulated injury probability curves

$$
\begin{aligned}
P_{neck} &= 1 - e^{-(F_{neck}/5.82)^6} \\
P_{lumbar} &= 1 - e^{-(F_{lumbar}/7.57)^{18.5}} \\
P_{tibia} &= 1 - e^{-((1.57+0.42F_{tibia})/5.13)^{7.43}}
\end{aligned}
$$

Using these curves as if they represent the relationship between body forces and injury probabilities, the following optimization problem was formulated. Here, the distribution of a_{peak} values was integrated across to account for the variance in blast scenarios; the integral is evaluated from zero through a maximum set at five standard deviations above the mean, which accounts for 99.9999 percent of the distribution. Also, a combined probability of injury is used, P_{injury}, representing the probability of sustaining at least one moderate injury and accounting for the potential for multiple injuries in the same occupant, which should only be counted once.

$$
\begin{aligned}
\underset{s_{EA},s_c,s_f}{\text{minimize}} \quad & \int_0^{\mu_{a_{peak}}+5\sigma_{a_{peak}}} P_{injury} \cdot \phi(a_{peak}) \cdot da_{peak} \\
\text{where} \quad & P_{injury} = 1 - (1 - P_{neck})(1 - P_{lumbar})(1 - P_{tibia}) \\
& \phi(a_{peak}) = \frac{1}{\sqrt{2\pi\sigma^2_{a_{peak}}}} \cdot e^{\frac{-(x-\mu_{a_{peak}})^2}{2\sigma^2_{a_{peak}}}} \\
\text{subject to} \quad & lb \leq s_{EA}, s_c, s_f \leq ub
\end{aligned}
$$

The main limitation of this formulation is that two of the injury curves have been postulated without adequate validation based on available data. The integral adds complexity to the model, but reduces the need to select a scenario for optimization, such as the extreme case or the frequent case as in the first two approaches. It is recognized that the normalized force minimization formulation could have used a similar integral to account for the range of inputs, but the

authors chose not to in order to show a wider range of approaches and result sets. It should also be noted that the three formulations presented in this section are not an exhaustive list of safety optimization approaches, and countless more could be constructed if further analyses were warranted.

4 Results and Discussion

The three optimization problems presented in the previous section were solved using a sequential quadratic programming algorithm (Mathworks, 2010), and the results are presented in Table 1. A range of vehicle mass inputs was assessed parametrically in each formulation to demonstrate the relationship between vehicle mass and optimal seating system design. Since different vehicle masses respond to the same blast inputs with different acceleration pulses, one might expect that the seating system parameters could be tuned to optimize for the appropriate range of blast pulses.

Table 1 Optimized Designs for Varying Vehicle Masses

	Minimizing Probability of Failure				*Minimizing Normalized Forces*				*Minimizing Postulated Injury Probability*		
m_v *(kg)*	a_{peak} *(g)*	s_{EA}	s_c	s_f	a_{peak} *(g)*	s_{EA}	s_c	s_f	s_{EA}	s_c	s_f
2000	1755	0.25	4.00	0.10	1679	0.25	4.00	0.10	0.25	4.00	0.10
3000	1755	0.25	4.00	0.10	1109	0.25	1.65	0.75	0.25	4.00	0.10
4000	1755	0.25	4.00	0.10	826	0.25	1.25	1.25	0.25	4.00	0.10
5000	1755	0.25	4.00	0.10	658	0.25	1.02	1.43	0.25	4.00	0.10
6000	1755	0.25	4.00	0.10	546	0.25	0.87	1.57	0.25	4.00	0.10
7000	1755	0.25	4.00	0.10	466	0.25	0.76	1.89	0.25	4.00	0.10
8000	1755	0.25	4.00	0.10	407	0.25	0.67	2.00	0.25	4.00	0.10
9000	1755	0.25	4.00	0.10	361	0.25	0.60	2.09	0.25	4.00	0.10
10000	1755	0.25	4.00	0.10	324	0.25	0.54	2.16	0.25	4.00	0.10
11000	1755	0.25	4.00	0.10	294	0.25	0.50	2.21	0.25	4.00	0.10
12000	1755	0.25	4.00	0.10	269	0.25	0.46	2.27	0.25	4.00	0.10

As described in Section 3.1, the first formulation is independent of vehicle mass, and the results expectedly have the same optimizers for every vehicle mass. The optima, or failure probabilities themselves, are very different for each vehicle mass, beginnning at almost 50 percent for the 2,000 kg vehicle and quickly declining to less than 1 percent around 4,000 kg. Under this optimization scheme, the seating system design would be optimized for a 1750-G blast pulse, regardless of whether that falls in the 55th quantile of the blast pulse distribution as in the 2,000 kg vehicle or in the 99.9999th quantile as in the 6,000 kg vehicle. Due to the rarity of a 1750-G pulse in the higher-mass vehicles, this formulation may not produce the actual best designs for minimizing injuries.

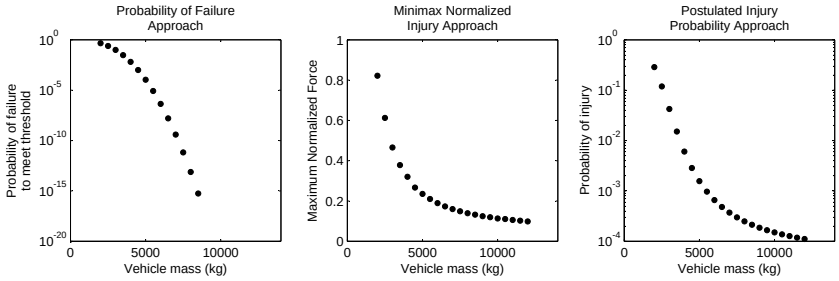

Figure 3 Pareto sets of the response versus vehicle mass for three formulations
Note: Scale is logarithmic for first and third approaches

The resulting designs of the normalized force minimization in Section 3.2 show a distinct shift as the vehicle mass increases. The first is that the seat foam stiffness tends to decrease as the vehicle mass increases. By observing the actual forces, it is evident that softening the seat foam decreases the loads in the spinal column (neck and lumbar spine) while increasing the loads in the legs. At the lowest vehicle masses, the tibia force is the active maximum that is being minimized in the minimax formulation; as the vehicle mass increases, the tibia and lumbar forces become equal and both act as the active maxima, and so the seat cushion acts as the balancing variable that can shift the loads from the spine to the legs in order to minimize both body forces. The other trend seen is that the floor pad stiffness tends to increase as the vehicle mass increases, which implies that a stiffer floor support is desired at lower blast pulses for injury prevention. These results show how seating parameter tuning plays a role in blastworthiness optimization for different vehicle weights; however, they are based on an assumption that injury probability is directly and equally related to the percentage of its 10-percent force threshold across all three injury modes.

Lastly, the results with the postulated injury curves from Section 3.3 are identical to those of the failure probability formulation, hitting the lower bounds on EA stiffness and floor pad stiffness and the upper limit on seat cushion stiffness for all vehicles. This formulation, however, is not independent of vehicle mass, and so the consistency of the results across the range of masses is less obvious. Upon further examination, it became clear that these results are the same results obtained by solely minimizing the tibia forces (and thereby disregarding the neck and spine); also, the tibia appears to be the most sensitive to forces below the 10-percent threshold based on the approximated injury probability curves, as seen in Figure 2. Because of the sensitivity of the tibia injury curve, the tibia dominates this optimization formulation, and the results simply minimize the tibia force. Since the tibia force surrogate polynomial is monotonically related to any positive peak acceleration values, the vehicle mass does not influence the design outcome. It should again be noted that the validity of these results is based entirely on the assumed probability of injury curves.

While the seating system design outcomes might not change from one vehicle to another, the actual objective function values are affected by vehicle mass. The

Pareto frontiers in Figure 3 show that, for all three objectives, increasing the vehicle mass tends to decrease an occupant's probability of blast injury, illustrating the trade-off in design between mass and blast safety. As vehicle mass has its own associated safety concerns previously mentioned, this is not as straightforward of a trade-off as it may appear, and further work would be needed to assess and quantify the safety consequences of high-mass vehicles.

5 Summary and Conclusions

This study used a two-stage simulation to examine the impact of vehicle weight and seating design variables on occupant injury. Computational expense required the use of surrogate models to conduct optimization studies, which are developed here using least-squares regression. Due to the complex nature of occupant safety optimization, three optimization problems were formulated and solved, each with its own assumptions and limitations. In two of the formulations, the optimal seating system outcome remains fixed regardless of vehicle mass, while in the other vehicle mass plays a role in determining the optimal seat cushion stiffness and floor pad stiffness. It is evident from the obtained optima that the goals to decrease vehicle weight and to increase occupant blast safety are competing objectives. However, the reduced mobility and fuel economy of high vehicle weight will at some point offset the blast safety benefits. While the absolute vehicle mass data presented may not be reliable due to the highly simplified vehicle model and the assumptions in the optimization formulations, the relative impact of vehicle mass is still apparent.

It should be noted that the first and third approaches, along with the low-mass evaluations of the second approach, all converge to the same optimal seating system design, with a minimum seat EA stiffness, maximum seat cushion stiffness, and minimum floor pad stiffness. In these cases, the tibia forces dominate the formulations, resulting in tibia-optimal seating system designs. This suggests that, provided our assumptions have not skewed the data, seating system designers should aim to minimize lower leg injuries, which would likely result in overall injury minimization.

Acknowledgements

The authors would like to thank Dr. Matthew P. Reed of the University of Michigan Transportation Research Institute for his contributions to this study.

This work has been supported partially by the Automotive Research Center (ARC), a U.S. Army Center of Excellence in Modeling and Simulation of Ground Vehicles led by the University of Michigan. Such support does not constitute an endorsement by the sponsor of the opinions expressed in this article.

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