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DOI: 10.1177/1548512912459596

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What is This?
A multi-objective optimization framework for assessing military ground vehicle design for safety

Steven Hoffenson¹, Sudhakar Arepally² and Panos Y Papalambros¹

Abstract
In recent years, the greatest safety threat to military personnel has been from underbody vehicle blast events, but other major threats exist against fuel convoys and due to rollover events. Ground vehicle designers make choices that affect one or more of these risk areas, including the weight and structural design of the vehicle underbody, as well as the design of seating systems that cushion the occupants from the rapid accelerations caused by blast loading. This study uses mathematical and computational tools to evaluate underbody blast, fuel convoy, and rollover safety criteria, and the models are combined into a multi-objective design optimization formulation that minimizes personnel casualties. The models and framework are highlighted and described in detail, and preliminary optimization results are presented under various conditions. The multi-objective behavior of the design problem is explored through weighted-objective Pareto frontiers, and the utility of the model in real-world situations is discussed.

Keywords
multi-objective design optimization, military ground vehicle design, occupant blast safety, fuel convoy safety, rollover safety

Submitted 25 April 2012, Revised 18 July 2012, Accepted 5 August 2012

1. Introduction
Occupant safety is a top priority of military vehicle designers, and in recent years this focus has shifted heavily toward protecting against the threat of underbody explosives. Improvised explosive devices (IEDs), sometimes referred to as “roadside bombs,” have been used with increasing frequency over the past decade, and in recent years they have accounted for more than half of hostile US personnel fatalities in Iraq and Afghanistan.¹ This has led military strategists to replace relatively compact multipurpose vehicles, such as the High Mobility Multipurpose Wheeled Vehicle (HMMWV), with larger, more blast-protective ones, such as the Mine Resistant Ambush Protected Vehicle (MRAP).² Much of the MRAP’s safety advantage is tied to its v-shaped underbody, which deflects a portion of the blast energy away from the vehicle,³ and its higher mass, which is approximately four times that of its predecessor.⁴ Unfortunately, these improvements have consequences on other safety objectives: the v-shaped hull raises the vehicle’s center of gravity, making it more susceptible to rollovers, and its higher mass decreases fuel economy and mobility. In fact, many of the MRAPs that were initially deployed to Afghanistan have been reported as inactive due to limitations caused by their size and weight.⁵ Because of the link with vehicle mass, fuel economy improvements in military vehicles have been considered a tradeoff with safety. Recent reports, however, indicate that convoys transporting fuel to military operations have become a major target of adversaries.⁶ Thus, using vehicles that consume more fuel might be

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disadvantageous to broader safety objectives. This paper presents three distinct safety concerns—underbody blasts, fuel convoy exposure, and rollover events—within a multi-objective design optimization framework to demonstrate the tradeoffs associated with designing a multipurpose military ground vehicle for safety.

Vehicle blast protection is a subject of increasing interest, and many studies have been done by academic and government institutions with aims to improve occupant survivability under explosive threats. Due to the high costs of physically testing the responses of vehicles and occupants to underbody explosions, computational models have been developed to measure such outcomes, which are typically validated using physical experimentation. Central to the validity of physical and computational tests is the biodidelity of the human dummy models, known in the testing community as anthropomorphic test devices (ATDs), and much research has gone into understanding how injuries occur in the human body due to blast events. The North Atlantic Treaty Organization (NATO) published a report compiling the results of several studies on how forces and accelerations in different areas of the body correspond with likelihood of injury. More recently, researchers such as Gondusky and Reiter and Champion et al. have used empirical data to better understand the frequencies of different injury types, but new public standards have not yet been established. Most experimental studies, as well as the standards prescribed by NATO, employ the Hybrid III ATD, which was developed for civilian vehicle frontal crash loading and has not been successfully validated for use in vertical loading scenarios; this practice is likely to continue until an acceptable alternative is available, such as the Warrior Injury Assessment Manikin (WIAMan) currently under development by Army researchers.

Emphasis on blast protection has spurred several innovations. For example, the Self-Protection Adaptive Roller Kit (SPARK) has been deployed as an attachment to the front end of HMMWVs and other vehicles. This device detonates pressure-sensitive IEDs before the vehicle is positioned above the explosive, thereby reducing the probability that the vehicle or occupants will be harmed in a blast event. This apparatus, however, only addresses explosive threats that are triggered by pressure and does not address remote detonation. Other innovations include the development of materials that are better suited to protect against blast threats. Ma et al. developed a nanocomposite material that was shown to be effective against ballistic and blast threats. Lockheed Martin has developed a macrocomposite protection system that claims better protection and lighter weight. Such materials can be implemented in new vehicles to improve safety, but adding mass will continue to enhance blastworthiness regardless of the material.

Military vehicle designers focus on two general areas of occupant safety: the vehicle structure itself, and the occupant compartment and seating system. Structural design has seen improvement with v-shaped hulls to deflect blast energy and stronger materials to prevent cabin intrusions. Occupant compartment design has made similar progress with energy-absorbing seat systems and impact-absorbing floor pads, such as Skydex. Kargus et al. developed a test methodology and conducted physical experiments with vertical and horizontal shock machines to evaluate the impact of three different seating systems on ATD loading. Arepally et al. used data from vertical drop tower experimentation to develop and validate a mathematical model for occupant response to blast loading, and a parametric study was conducted over a range of blast pulses and seating design configurations.

Several arguments have been made over the years for improved fuel economy in US military vehicles: the environmental impact of carbon emissions, national security concerns regarding dependence on supplies from geopolitically unstable regions, and costs. Safety advocates tend to claim that occupant safety is more important than fuel-related concerns, but with the increasing prevalence of hostile attacks on fuel convoys, fuel consumption itself has become a safety and security concern. This article shows the complex relationship between fuel consumption and overall personnel safety due to the tradeoff in choosing a vehicle mass. While the authors recognize that mass is frequently chosen for other design objectives, such as armoring and mobility, arguments for using advanced and lightweight technologies to reduce vehicle mass are often met with criticism from the blast safety perspective.

The final component of the present multi-objective design framework is a model of rollover incidents as they relate to a vehicle’s designed center of mass. From November 2007 to January 2010, over 230 rollovers occurred in MRAPS alone, resulting in 13 documented fatalities and additional injuries. This has prompted initiatives to provide better training for military personnel traveling in rollover-prone vehicles or terrains, including the development of the HMVV Egress Awareness Trainer (HEAT) and the MRAP Egress Trainer (MET) for soldiers to practice rollover scenarios in a simulated environment. Advanced modeling and simulation of rollover events have also been used to recommend designs and procedures for minimizing rollover events, although rollover safety is not the highest priority, since IEDs account for the large majority of casualties. Design decisions, such as ground clearance and hull shape, have impacts on both of these safety outcomes, and therefore designers must consider these threats together in their decision making.

This study reveals a framework that simultaneously accounts for underbody blast, fuel convoy, and rollover threats related to multipurpose ground vehicle design. Efficient models are developed for each safety objective,
and they are combined and optimized under various scenarios to minimize overall personnel safety. Results demonstrate how safety objectives alone might suggest lighter, lower vehicle designs, contrary to the optimal design with maximized mass when only blast threats are considered.

2. Model development

A mathematical modeling framework was developed to quantify the impact of vehicle and seating system design variables on blast protection, fuel consumption and its relation to fuel convoy threats, and rollover safety. Here, a casualty refers to any personnel injury of at least moderate severity as defined on the Abbreviated Injury Scale (AIS), including more severe injuries and fatalities. The ensuing sections present the blast protection modeling technique, which takes advantage of physics-based computational models of a vehicle and a separate vertical drop tower system; the fuel consumption model, which uses regression on empirical data of military vehicles; and the rollover model, making use of the static stability factor (SSF) to calculate the propensity of a vehicle to roll over based on the track width and height of the center of gravity. Finally, the combined system optimization formulation is presented for combining these tools to minimize total casualties through optimal vehicle design.

2.1. Blast protection modeling

A simplified, rigid finite-element model of a vehicle structure (Figure 1(a)) was developed in the LS-DYNA software program using the CONWEP blast function to understand the impact of structural design on blast-induced vehicle accelerations, known as the blast pulse when plotted over time (Figure 1(b)). This was then coupled with the multi-body dynamics model of a vertical drop tower (Figure 1(c)) developed and validated by Arepally et al., which estimates the impact of rapid vehicle accelerations on a seated occupant. Computational designs of experiments combined with response surface methodology were used to determine the impact of structural variables and seating system parameters on the predicted probability of occupant injury. Observing that the blast pulse shape and duration is not significantly affected by vehicle design and blast intensity, the blast pulse curve is parameterized by the highest, or peak, acceleration value \(a_{\text{peak}}\), measured with respect to gravitational force \(g\).

A computational design of experiments model for the structure in Figure 1(a) was conducted with a 200-point optimal Latin hypercube sampling over a range of values for vehicle mass \(m_v\), v-hull angle \(\theta\), ground clearance \(h\), and mass of the explosive charge \(m_c\). The last variable is modeled as a random one due to the unpredictable nature of IEDs, and the lack of sensitive information about charge masses as they have been observed in the field. A log-normal distribution is postulated with mean 5 kilograms (kg) of TNT-equivalent explosive and variance 5 kg. A quadratic surrogate model of the outcome, \(a_{\text{peak}}\), as a function of these four quantities, was fit to the results using linear regression, pruned using backward elimination according to the Akaike Information Criterion, and transformed using the Box–Cox method, resulting in a surrogate model that fit the 200 points with a coefficient of determination \(R^2\) of 0.99. Although this model has quadratic terms, the function behaves monotonically over the appropriate ranges of each variable: \(a_{\text{peak}}\) decreases as \(m_v\) and \(h\) increase, and \(a_{\text{peak}}\) increases as \(\theta\) and \(m_c\) increase. Furthermore, for a given vehicle design, peak acceleration can be denoted as a distributed random quantity \(f(a_{\text{peak}})\).

Figure 1. Modeling tools used for simulating the effects of underbody explosives on ground vehicle occupants.
since the random distribution of the variable \( m_c \) passes through the regression function.

The next step is to input the blast pulse as a prescribed motion to the occupant drop tower model of Figure 1(c), using a 300-point optimal Latin hypercube varying \( a_{\text{peak}} \) and three seating system variables: the seat energy-absorbing system stiffness \( (s_{\text{EA}}) \), the seat cushion foam stiffness \( (s_c) \), and the floor pad stiffness \( (s_f) \). The output of interest is the probability of injury to the occupant, calculated using the NATO criteria for axial force in the upper neck \( (F_{\text{neck}}) \), lower lumbar spine \( (F_{\text{lumbar}}) \), and lower tibia \( (F_{\text{tibia}}) \).\(^7\) Each of the three force responses was fitted with a quadratic surrogate model using similar regression techniques as in the vehicle model, creating closed-form equations for body forces as functions of the four inputs \( R^2\)-values of 0.95, 0.95, and 0.98, respectively. Monotonicity analysis of these regression functions shows that increasing \( s_{\text{EA}} \) increases the forces in the neck and spine, increasing \( s_c \) increases forces in the neck and spine while decreasing forces in the tibia, and increasing \( s_f \) increases forces in the tibia only; as expected, increasing \( a_{\text{peak}} \) increases all three of the axial forces. Thus, optimizing the seating system for minimizing these forces is trivial with respect to \( s_{\text{EA}} \) and \( s_f \), both of which reach their lower bound, while the solution for \( s_c \) is more complicated, as adjusting it shifts the loads between the upper and lower body. To solve for \( s_c \), more information is needed about the loads themselves and how they relate to overall injury probability, which is the objective of the blastworthiness optimization problem.

The injury criteria themselves are specified by NATO with threshold levels that represent a 10% probability of sustaining a moderate injury, where the threshold for \( F_{\text{neck}} \) is 4 kilonewtons (kN), the threshold for \( F_{\text{lumbar}} \) is 6.7 kN, and the threshold for \( F_{\text{tibia}} \) is 5.4 kN. However, only the tibia criterion has an associated curve in the literature to prescribe probability of lower extremity injury \( (P_{\text{tibia}}) \) as a function of \( F_{\text{tibia}} \).\(^{27}\) For the neck and lumbar force criteria \( F_{\text{neck}} \) and \( F_{\text{lumbar}} \), similar probability curves \( P_{\text{neck}} \) and \( P_{\text{lumbar}} \) were postulated as Weibull functions to be used for predicting the probability of overall injury as a function of axial body forces, as shown in Figure 2. These injury probability curves are combined to calculate an overall probability that an occupant sustains at least one injury, assuming that the injury modes are independent of one another. This probability, \( P \), is the complement of the product of probabilities of not being injured in each body region, specified by Equation (1).

\[
P = 1 - (1 - P_{\text{neck}})(1 - P_{\text{lumbar}})(1 - P_{\text{tibia}}) \quad (1)
\]

Since each of the three \( P \) quantities on the right-hand side of the equation are functions of their corresponding axial forces \( F_i \), which are in turn functions of the seating system model input quantities \( a_{\text{peak}}, s_{\text{EA}}, s_c, \) and \( s_f \), \( P \) is a function of these four seating system model inputs.

To account for the variability in charge size, this probability of overall injury is multiplied by the distribution \( f(a_{\text{peak}}) \), and this product is integrated across the full range of \( a_{\text{peak}} \) values. For a given set of vehicle design parameters \( m_v, \theta, \) and \( h \), the expected probability of injury given a blast event is calculated by Equation (2), where \( a_{\text{peak}} \) and its distribution \( f(a_{\text{peak}}) \) are functions of vehicle design:

\[
E[P] = \int P(a_{\text{peak}}, s_c, s_{\text{EA}}, s_f)f(a_{\text{peak}})da_{\text{peak}} \quad (2)
\]

From minimizing this function over the full range of vehicle designs, it becomes clear that \( P_{\text{tibia}} \) contributes the most to \( P \), and so the optimal seating system design seeks to minimize \( F_{\text{tibia}} \) and therefore maximize \( s_c \). Upper and lower bounds on \( s_{\text{EA}}, s_c, \) and \( s_f \) were passed on from the ranges that the design of experiments was conducted across, which were originally chosen because they span the capability of the simulation model. With \( s_{\text{EA}} \) and \( s_f \) fixed at their lower bounds and \( s_c \) at its upper bound, the previous formulation for \( E[P] \) is simplified as Equation (3):

\[
E[P] = \int P(a_{\text{peak}})f(a_{\text{peak}})da_{\text{peak}} \quad (3)
\]

Using this estimation of injury probability, a formula is developed to calculate the number of total injuries per year attributed to blast events in the multipurpose vehicle being designed, \( N_{\text{blast}} \). This relies on information about the total number of blast events that occur each year in the military(first sentence of the image)
where a blast event is an explosive detonating beneath a vehicle, the average number of occupants per vehicle \( n_{\text{avg}} \), and the percentage of the total blasts that occur against the multipurpose vehicles \( \phi_{\text{bmv}} \). For security reasons, precise information on these parameters is unavailable for this study, but baseline values were estimated based on press releases and author intuition, given in Table 1. Recent press releases report the total number of blast events per year at or around 16,500,\(^2\)\(^8\) and assumptions are made that an average of four occupants are in each vehicle and about 50% of vehicles attacked by underbody blasts are multipurpose vehicles.

Multiplying these quantities together as shown in Equation (4) yields a value for \( N_{\text{blast}} \), and with baseline parameters this arrives at 319 blast-induced casualties per year, which is in a range consistent with public data:\(^1\)

\[
N_{\text{blast}} = n_{\text{be}} \times n_{\text{avg}} \times \phi_{\text{bmv}} \times E[P]
\]  

From the previously discussed monotonicity of the blast function, it is evident that vehicle design optimization to minimize \( N_{\text{blast}} \) would result in a vehicle of maximum mass \( m_v \) and stand-off height \( h \) and minimum \( v \)-hull angle \( \theta \). However, objectives for minimizing casualties exhibit opposing monotonicity on each of the three vehicle design variables, resulting in a well-bounded optimization problem.

### 2.2. Fuel consumption modeling

To model fuel consumption and its effect on personnel safety, empirical data were used from publicly available US Army ground vehicle specifications. The database includes 48 vehicles with specifications including vehicle curb weight, driving range, and fuel tank capacity,\(^4\) from which estimates of fuel consumption (in gallons per mile) were calculated for each vehicle. As expected, fuel consumption tends to increase as curb weight increases. A linear fit with an \( R^2 \)-value of 0.92 is presented in Equation (5) and shown, along with the original data points, in Figure 3. Here, \( FC \) is fuel consumption in gallons per mile and \( m_v \) is again vehicle mass in kilograms:

\[
FC = 2.053 \times 10^{-5} m_v + 1.971 \times 10^{-2} \tag{5}
\]

This model intentionally disregards vehicle powertrain design parameters, and in doing so operates under the assumption that these data represent vehicles with powertrains optimally designed for their respective vehicle sizes and masses. If the model were enhanced to include such powertrain factors, constraints would be needed to ensure that the vehicles meet the specification requirements of the military, such as minimum acceleration and top speed. The authors postulate that these performance attributes have their own contributions to the safety of ground personnel (e.g., the ability to move more quickly in and out of hostile situations would improve safety), and this is left as an opportunity for future research.

Using the model for fuel consumption as a function of vehicle design, a formula was developed to estimate the number of annual casualties resulting from fuel convoy attacks, \( N_{\text{convoy}} \). Similar to the annual blast casualty estimation in the previous section, the formula relies on information that is mostly unpublished for security reasons, and so preliminary results are based on parameters whose values are again derived from press release data and author intuition, shown in Table 2. Estimates from recent reports are that approximately 6000 fuel convoys are deployed each year with an average of one casualty in every 24 convoys (4.2%).\(^5\) The authors postulate that approximately 20% of the total Army fuel consumption is accounted for by multipurpose vehicle use, and a baseline average vehicle mass is approximated as 5000 kilograms,
which is slightly higher than the mass of a loaded and up-armored HMMWV to account for the smaller proportion of the heavier MRAPs that are currently in use.

The first step in the calculation is to estimate the percentage change to total Army fuel requirements ($\Delta_{fr}$); this is found by multiplying the ratio of fuel consumption for the designed scenario ($FC(mv)$) versus the baseline scenario ($FC(mb)$) with the percentage of total Army fuel used specifically by the multipurpose vehicles being designed ($\phi_{fmv}$), and this quantity is summed with the percentage of fuel not being used by the multipurpose vehicles ($1 - \phi_{fmv}$), as shown in Equation (6):

$$\Delta_{fr} = \frac{FC(mb)}{FC(mv)} \phi_{fmv} + (1 - \phi_{fmv})$$

This value is then multiplied by the current (baseline) number of fuel convoys per year ($n_{fc}$) and the average percentage of fuel convoys that experience a casualty ($\phi_{fcc}$), as shown in Equation (7):

$$N_{convoy} = n_{fc} \times \phi_{fcc} \times \Delta_{fr}$$

The above equation is clearly monotonic with the only design variable present in the formulation, where increases to vehicle mass increase $N_{convoy}$. This bounds $m_v$ from above in the multiobjective optimization problem.

### 2.3. Rollover modeling

The SSF is a common tool for measuring the likelihood of vehicle rollover based purely on the geometry of the vehicle, and it is used by the US National Highway Traffic Safety Administration (NHTSA) to develop rollover star ratings for civilian vehicles. The formula is one-half the track width ($T$):

$$SSF = \frac{T}{2H}$$

This is used in the present formulation to estimate the number of rollover casualties to be expected from a particular vehicle design, depending on the geometric variables $\theta$ and $h$ and assuming a constant track width consistent with that of the HMMWV. For simplification, this is calculated as if the vehicle has uniformly distributed mass, even though the mass is likely to be concentrated in the lower half of the vehicle.

From the simple geometric vehicle model in Figure 4, the height of the center of mass above the vertex of the v-hull ($h_{com}$) can be calculated using Equation (9):

$$h_{com} = \frac{h_1}{2} + \frac{3h_2}{4}$$

Using trigonometry, $h_2$ can be calculated from $\theta$ using the tangent function, where the full width of the vehicle is 2.2 meters:

$$h_2 = \frac{1.1}{\tan\frac{\theta}{2}}$$

With $h_1$ fixed at 1.4 meters, inserting Equation (10) into Equation (9) and summing $h_{com}$ with $h$ gives the height above the ground of the center of mass, $H$, used in the calculation of the SSF:

$$H = h + h_{com}$$

The NHTSA calculates the probability of rollover based on data from six states regarding single-vehicle crashes between 1994 and 1998. A regression function was fit to the dataset, which represents approximately 226,117 crashes in those states, to predict the likelihood of rollover.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Baseline value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{fc}$</td>
<td>No. of fuel convoys per year</td>
<td>6000</td>
</tr>
<tr>
<td>$\phi_{fc}$</td>
<td>Percentage convoys w/ casualty</td>
<td>0.042</td>
</tr>
<tr>
<td>$\phi_{fmv}$</td>
<td>Percentage fuel used by mpv</td>
<td>0.20</td>
</tr>
<tr>
<td>$m_b$</td>
<td>Baseline mpv mass (kg)</td>
<td>5000</td>
</tr>
<tr>
<td>$FC$</td>
<td>Fuel cons. of mpv (gal/mi)</td>
<td>0.122</td>
</tr>
<tr>
<td>$N_{convoy}$</td>
<td>No. of fuel casualties per year</td>
<td>252</td>
</tr>
</tbody>
</table>

mpv: multipurpose (designed) vehicle

![Figure 4. Vehicle geometry model for rollover calculation.](image)
Table 3. Parameters and baseline values used in rollover casualty calculation.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Baseline value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n_{ro})</td>
<td>No. baseline rollovers per year</td>
<td>100</td>
</tr>
<tr>
<td>(\phi_{roc})</td>
<td>Percent rollovers with casualty</td>
<td>0.5</td>
</tr>
<tr>
<td>(\phi_{ro})</td>
<td>Probability of rollover</td>
<td>0.49</td>
</tr>
<tr>
<td>(T)</td>
<td>Track width of mpv</td>
<td>2.2</td>
</tr>
<tr>
<td>(H)</td>
<td>Height of vehicle center of mass</td>
<td>1.15</td>
</tr>
<tr>
<td>(SSF)</td>
<td>Static stability factor of vehicle</td>
<td>0.96</td>
</tr>
<tr>
<td>(N_{rollover})</td>
<td>No. rollover casualties per year</td>
<td>50</td>
</tr>
</tbody>
</table>

mpv: multipurpose (designed) vehicle

in a single-vehicle crash as a function of the SSF.\(^{20}\) This function, shown in Equation (12), is used in the present study to indicate a vehicle’s likelihood to roll over:

\[
\phi_{ro} = 10.99 \times e^{-3.2356 \times SSF} \quad (12)
\]

Computing the impact of this value on annual military vehicle rollover casualties is based on prior knowledge of existing military vehicles and rollover incidents, and so \(\phi_{ro}\) is first divided by the rollover probability of the baseline vehicle \(\phi_{ro, base}\) to determine the percent change in rollover likelihood of the multipurpose vehicle. To obtain a total number of rollover injuries per year \(N_{rollover}\), this ratio is multiplied by the number of rollover incidents per year \(n_{ro}\), estimated as 100 based on press releases,\(^{20}\) as well as the percentage of rollover incidents that result in a casualty \(\phi_{roc}\), postulated to be around 50%. These parameters and their baseline values are provided in Table 3, and the formula is given as Equation (13):

\[
N_{rollover} = n_{ro} \times \phi_{roc} \times \frac{\phi_{ro}}{\phi_{ro, base}} \quad (13)
\]

In this formula, decreasing \(\theta\) and increasing \(h\) monotonically increase \(N_{rollover}\), bounding the variables in the multi-objective optimization formulation from above \((h)\) and below \((\theta)\). With the addition of this third component in the objective, each of the three structural design variables is bounded both above and below, and therefore unconstrained optimization will yield non-trivial solutions whenever the three objectives have non-zero weighting.

3. Combined casualties framework

Adding together the three quantities \(N_{blast}\), \(N_{convoy}\), and \(N_{rollover}\) produces the total number of annual personnel casualties from the threats discussed in the previous sections. Assuming that these are the only major sources of casualties in the military and that the calculations are independent of one another, this sum should be the single objective when designing for vehicle occupant safety. However, these assumptions may not hold, and therefore this is explored as a multi-objective optimization formulation with upper and lower bounds \((ub\) and \(lb\)) on the variables, given as Equation (14):

\[
\text{minimize } \quad w_1 N_{blast} + w_2 N_{convoy} + w_3 N_{rollover}
\]

where
\[
\begin{align*}
N_{blast} &= f_1(P(m_c^-, \theta^+, h^-)) \\
N_{convoy} &= f_2(FC(m_c^+)) \\
N_{rollover} &= f_3(SSF(\theta^-, h^+))
\end{align*}
\]

subject to \(lb \leq m_c, \theta, h \leq ub\)

Recall that \(N_{blast}\) is a function of probability of occupant injury in a blast and increases with \(m_c\) while decreasing with \(\theta\) and \(h\); \(N_{convoy}\) is a function of vehicle fuel consumption and increases with \(m_c\); \(N_{rollover}\) is a function of the SSF and increases with \(h\) while decreasing with \(\theta\).

The results are dependent on the parameters chosen. A flow chart of the input parameters and decision variables contributing to the objectives is provided in Figure 5. Solutions will be explored parametrically to demonstrate how changing a parameter influences the resulting optimal design and number of casualties. No single set of results presented in this article is suitable for detailed decision making; rather, the modeling and optimization process provides insights into the tradeoffs when designing new military ground vehicles and making strategic contracting and deployment decisions.

The results presented in the following section were produced using sequential quadratic programming under various conditions of objective function weighting and input parameter values.

4. Results

Optimization of the baseline scenario, using the parameter values prescribed in Tables 1–3 and with equal weighting \(w_1 = w_2 = w_3\), produces the results given in Table 4. Here, \(N_{total}\) represents the unweighted sum of \(N_{blast}\), \(N_{convoy}\), and \(N_{rollover}\), and it is shown that, given the assumptions of the baseline scenario, optimization can reduce personnel casualties by approximately 45%. This is a result of nearly doubling the mass, which reduces blast casualties, and reducing the ground clearance of the designed multipurpose vehicle, which reduces rollover casualties. While these reductions result in an increase in fuel convoy casualties, this is justified by benefits in the other safety criteria. Interestingly, the hull of the vehicle remains flat, as a v-shaped hull in this 10,000-kg vehicle would be more damaging to the vehicle’s rollover probability than it would be beneficial for blast safety.
The results of Table 4 rely on the input parameter values, which were in some cases chosen without access to empirical data, and on the models, which are simplified to enable quick function evaluation. The following section assesses the sensitivity of the results to parameters from each of the three models. In addition, the objectives are explored as a multi-objective problem in Section 4.2.

4.1. Parametric studies

Parametric studies examine how the results in Table 4 would change if the parameter values are off by a factor of 2 or 4 in either direction. The first parametric study varies the number of blast events per year, $n_{be}$. It is evident from Equation (4) that modifying this value is equivalent to corresponding changes to $n_{opp}$ and $\phi_{bmv}$, as well as scaling the calculation of expected probability of injury ($E|P|$). Figure 6 plots the results of modifying $n_{be}$ on the total number of annual casualties ($N_{total}$), where the optimal design is represented by the image plotted. The results show that as blasts become more frequent, optimal vehicle designs first increase slightly in $m_v$ and in $h$, and they subsequently decrease in $\theta$ (i.e., the hull angles become non-flat and sharper). This reduces the blast casualties per blast event with a consequent increase in rollover casualties and slight increase in fuel convoy casualties.

In the fuel convoy safety model, $\phi_{fcc}$ is modified. This is equivalent to modifying $n_{fc}$ in Equation (7), and similar to modifying $\phi_{mv}$ or $m_v$ in Equation (6). The results are illustrated in Figure 7. If an increasing percentage of fuel convoys is attacked, optimal $m_v$ should decrease, while $h$ increases initially and later decreases when $\theta$ begins to decrease. The resulting optimal design changes suppress the increases to fuel convoy casualties while balancing

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Pre-optimization</th>
<th>Post-optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_v$ (kg)</td>
<td>5000</td>
<td>9982</td>
</tr>
<tr>
<td>$\theta$ ($^\circ$)</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>$h$ (m)</td>
<td>0.430</td>
<td>0.204</td>
</tr>
<tr>
<td>$N_{blast}$</td>
<td>319</td>
<td>24</td>
</tr>
<tr>
<td>$N_{convey}$</td>
<td>252</td>
<td>294</td>
</tr>
<tr>
<td>$N_{rollover}$</td>
<td>50</td>
<td>23</td>
</tr>
<tr>
<td>$N_{total}$</td>
<td>621</td>
<td>341</td>
</tr>
</tbody>
</table>
less increases to rollover and blast casualties. Note also that the scale of changes to $N_{\text{total}}$ is much higher here than in Figure 6, indicating that fuel convoy casualties are the most difficult objective to overcome with this formulation and these design variables, as changes to the input parameters have nearly proportional effects on the number of casualties expected post-optimization.

In the rollover model, $\phi_{\text{roc}}$ is investigated parametrically, which is identical in Equation (13) to modifying $n_{\text{ro}}$, and the results are shown in Figure 8. As expected, increasing the rollover threat causes a flatter hull (higher $\theta$) and a lower ground clearance (lower $h$), both of which serve to lower the center of mass and, consequently, raise the SSF. Since these changes are detrimental to $N_{\text{blast}}$, increases to $m_v$ are observed to suppress the impact on blast casualties. Once a certain level of $\phi_{\text{roc}}$ is reached, somewhere between 0.5 and 1.0, no further design changes can be made to improve the rollover risk, and thus the design variables, $N_{\text{blast}}$, and $N_{\text{convoy}}$, become fixed, while $N_{\text{rollover}}$ increases linearly with $\phi_{\text{roc}}$. While a $\phi_{\text{roc}}$ value above 1.0 may initially seem infeasible, consider that a single vehicle rolling over might often result in injuries to more than one occupant, and so $\phi_{\text{roc}} = 2$ would imply that two casualties occur on average per vehicle rollover.

### 4.2. Multi-objective optimization

This section examines the multi-objective optimization framework where the weights $w_1$, $w_2$, and $w_3$ from Equation (14) are not necessarily equal. Although the fuel convoy and rollover models have no shared variables and do not directly trade off with one another, each shares its variables with the blast model, and tradeoffs between $N_{\text{convoy}}$ and $N_{\text{rollover}}$ will be evident when $w_1 \neq 0$.

Firstly, a three-dimensional Pareto frontier among the objectives was generated by plotting 10,000 points distributed throughout the feasible space of weighting values, shown in Figure 9. Apart from the flattened bottom edge, which is an artifact of zero weighting on $N_{\text{blast}}$ and $N_{\text{convoy}}$, this shows a strictly convex Pareto frontier, which is

![Figure 7. Effect of $\phi_{\text{fcc}}$ on optimal solution; here, the drawings represent a cross-sectional view of a vehicle along the lateral/vertical plane: $m_v$ is represented by the volume shaded, $\theta$ is represented by the angle at the bottom of the vehicle, and $h$ is represented by the distance between the lowest point on the vehicle and the dot underneath.](image)

![Figure 8. Effect of $\phi_{\text{roc}}$ on optimal solution; here, the drawings represent a cross-sectional view of a vehicle along the lateral/vertical plane: $m_v$ is represented by the volume shaded, $\theta$ is represented by the angle at the bottom of the vehicle, and $h$ is represented by the distance between the lowest point on the vehicle and the dot underneath.](image)

![Figure 9. Three-dimensional Pareto frontier for minimizing three safety objectives.](image)
expected in this type of problem. Each point on this plot represents a design that, if modified, could not improve in one objective without harming another objective. The ensuing paragraphs and figures present results along cross-sections of Figure 9, showing numerically how the objectives and optimal designs trade off with one another.

The tradeoff between $N_{\text{blast}}$ and $N_{\text{convoy}}$ is illustrated in Figure 10, shown for three different levels of $w_3$. Again, these three Pareto frontiers depict sets of optimal vehicles for which one objective cannot be improved through design without harming the other objective. The lighter grey figures show that when rollover is eliminated from the objective ($w_3 = 0$), $\theta$ is minimized and $h$ is maximized, and increasing $w_2$ causes $m_v$ to decrease with only slight increases in $N_{\text{blast}}$ and significant decreases to $N_{\text{convoy}}$. When rollover accounts for one-third of the objective (shown in darker grey), $\theta$ is maximized to prescribe a flat-bottomed vehicle, and as $w_1$ decreases, $m_v$ decreases and $h$ increases. For a rollover-intensive formulation where $w_3$ accounts for two-thirds of the objective (black figures), $\theta$ is always maximized and $h$ is always minimized to maintain a low center of mass, while mass decreases with increasing $w_2$.

Another interesting tradeoff is found between $N_{\text{blast}}$ and $N_{\text{rollover}}$, depicted in Figure 11. When fuel convoy safety is not considered in the objective (lighter grey), $m_v$ hits its upper bound, and increasing rollover importance results in lower, flatter optimal vehicles. It is also noted that these increases to $w_3$ result in significantly fewer rollover-related casualties with only a slight increase in blast casualties. When $w_2$ is one-third of the total sum of $w$-values, shown in darker grey, the trend is still evident that increasing $w_3$ results in decreases to $h$ and then increases to $\theta$; however, in this case the initial increases to $w_3$ are accompanied by $m_v$ increases, and then later $m_v$ begins to decrease because of the decrease in relative importance of $w_1$ compared to $w_2$. Finally, when $w_2$ accounts for two-thirds of the total objective, depicted in black, $m_v$ remains low throughout. Here, when rollover safety is minimally important, $h$ is maximized and $\theta$ minimized; as $w_3$ increases, first $h$ decreases and later $\theta$ begins to decrease.

The final tradeoff examined is between $N_{\text{convoy}}$ and $N_{\text{rollover}}$, and it is shown in Figure 12. In the absence of the blast formulation (shown in lighter grey) there is no tradeoff, and a “utopia point” exists in the bottom-left-hand corner of the plot, at which the design has reached the best possible solution for both objectives in the plot. At this point, the vehicle has minimum $m_v$ for reducing fuel convoy casualties, and it has maximum $\theta$ and minimum $h$ for reducing rollover probability. However, a vehicle with this design is predicted to result in over 20,000 blast casualties per year, and therefore $w_1$ should be non-zero in a realistic optimization scenario. When $w_1$ accounts for one-third of the total weighting (darker grey), increases to the importance of rollover safety first result in decreases to $h$, and with larger $w_3$ come flatter-bottomed, heavier vehicles. Similar effects are seen when $w_1$ accounts for two-thirds of the objective, shown in black.
Using the present framework, and new vehicles can be manufactured or existing vehicles chosen to match the optimal designs and deploy to the field. For example, researchers are developing tools to model military tactics for simulation-based training purposes, and such tools could be used to predict opposition tactics and provide information for designing safer vehicles.

When reliable prediction is not possible, this framework may be deployed in a dynamic context that accounts for fleet-mixing. For instance, a base may have at its disposal both light, flat-bottomed HMMWVs and heavy, v-hulled MRAPs, and the strategic decision-makers must make choices on the use and mix of each vehicle class. When the threats are observed to be at a particular level, the proper parameter values can be inserted in the model and used to calculate the optimal combination of multipurpose vehicle $m_\nu$.

### 5.2. Intervention approaches

Another useful application of this combined modeling framework is to study the effect of various interventions on the expected personnel casualties and the safety-optimal vehicle designs. Planners always seek new ways to improve operational safety, and they may implement interventions to reduce some of the quantities used as parameters or formulas in this study. Interventions may improve the blastworthiness of vehicles, such as using stronger materials, crushable underbody components, or more complex impact-reducing geometries, which would necessitate an update to the calculation in Equation (3). Other innovations, such as the aforementioned SPARK or programs to detect and disarm IEDs prior to detonation, would reduce the number of blast events against vehicles each year, thereby reducing $n_{be}$ in the formulation.

Other strategies proposed would impact the fuel convoy part of the formulation, some of which are posed primarily for safety reasons and others for financial or environmental concerns. Reducing the energy requirements of military operations outside of the multipurpose vehicle fuel use could affect the present framework by increasing $\phi_{fmc}$ and decreasing $n_{fc}$. Other efforts could be made to directly reduce $\phi_{fmc}$ through the techniques outlined in the previous paragraph or by linking this formulation with models of military supply chain management and transportation options.

Possible rollover reduction strategies include attempts to lower $\phi_{roc}$ and $\phi_{rov}$. Egress trainers, such as the previously discussed HEAT and MET, attempt to better prepare vehicle occupants to protect themselves in a rollover event, which could effectively decrease the percentage of rollovers with a casualty ($\phi_{roc}$). Other efforts could be made to reduce $\phi_{roc}$ by training drivers to avoid rollovers altogether or even to include technologies such as...
Electronic Stability Control (ESC). ESC has been proven in civilian vehicles to reduce rollovers using intelligent braking of individual wheels, and employing this technology in military vehicles has been recommended.

Planners can use the framework proposed in this study to assess the broader impact of a proposed intervention on the expected annual casualties, objectively computing the costs and benefits of a particular approach to reducing threats to military personnel.

5.3. Opportunities for model enhancement

The model presented here is not intended to accurately represent the complex mechanisms by which multipurpose vehicle occupants and fuel convoy personnel get injured. The formulation does not presently account for ballistic or missile protection capabilities. It also does not address the overlap in the data among blast events, fuel convoy casualties, and rollovers; for instance, fuel convoy casualties might occur in blasts beneath multipurpose vehicles, and rollovers might occur as a result of underbody blasts. Since data were not available regarding the extent to which these threats might overlap, this effect was not considered in the present study, but this could be included with additional parameters. The model also does not specifically account for the fuel saved from increased convoy efficiency and effectiveness, which itself would reduce the need for fuel convoys. In addition, the model may be extended to include convoys that transport non-fuel items, which represent about half of all convoys. Approximately 40% of these convoys are for water, and therefore implementing methods for obtaining and purifying local water sources could cut down on the need for water supply trucks. Finally, considerations may be included to account for the opposition’s response to any optimization and changes, perhaps using a war game simulation tool that predicts the response of one side to the actions of another, or a simulation of insurgent behavior.

In addition, each of the three models can be improved using high-fidelity simulation tools. The blast protection model, while presently the most sophisticated of the three models, relies on a rigid-body vehicle simulation with an air-blast explosive model along with a vertical drop tower model that has limited confirmed validity. Incorporating non-rigid materials and structure-explosive interaction techniques, such as the augmented Lagrangian-Eulerian (ALE), would enhance the vehicle model, and more extensive validation of the drop tower model with a new biofidelic human surrogate model for vertical loading could provide better accuracy in occupant injury prediction. Fuel consumption modeling is possible using powertrain simulation software, which would allow for optimization of certain powertrain design variables as a nested problem within the larger combined framework. In addition, the current geometry-based rollover calculation could be replaced by a simulation tool that models occupant–vehicle interior interactions under various rollover scenarios. If each of these models were to be replaced by state-of-the-art simulations of blast events, fuel consumption, and rollover incidents, the proposed design optimization framework could be used to provide meaningful recommendations for strategic vehicle design, acquisition, and deployment.

Factors other than safety might also be considered in decision making, such as economic or environmental impacts of fuel-related decisions. Costs can be directly correlated with fuel consumption, and an additional parameter for fuel pricing would change according to market prices and forecasts. Additional costs may be considered from damage to vehicles and injuries to occupants, providing more incentive for designs that minimize both occupant injury and vehicle damage. A more complete model might deliver a quantification of the links between casualties, economic costs, and emissions, providing insights for better strategic planning.

6. Conclusions

This paper outlines and details a new modeling framework for optimizing military ground vehicle design with respect to blast protection, fuel convoy safety, and rollover safety, using a combination of physics-based modeling and empirical data. Assumptions about Army vehicle usage, blast events, fuel convoys, and rollover incidents were included based entirely on publicly available information, and parametric studies were conducted to show the influence of these assumptions. Results suggest that optimal ground vehicle mass should be somewhere between the mass of the HMMWV and that of the MRAP for all explored input conditions, exhibiting safety-driven motivation for reducing designed vehicle mass from that of the MRAP. Multi-objective weighted optimization reveals convex Pareto frontiers that, in general, exhibit anticipated behaviors with changing optimized vehicle designs and expected casualty outcomes. This type of combined modeling introduces a novel capability to assist in the strategic reduction of personnel casualties.

References


Acknowledgments
The authors would like to thank Dr Matthew P Reed of the University of Michigan Transportation Research Institute and Dr Michael Kokkolaras of the University of Michigan Department of Mechanical Engineering for their contributions to this study.

Funding
This work has been supported partially by the Automotive Research Center (ARC), a US 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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