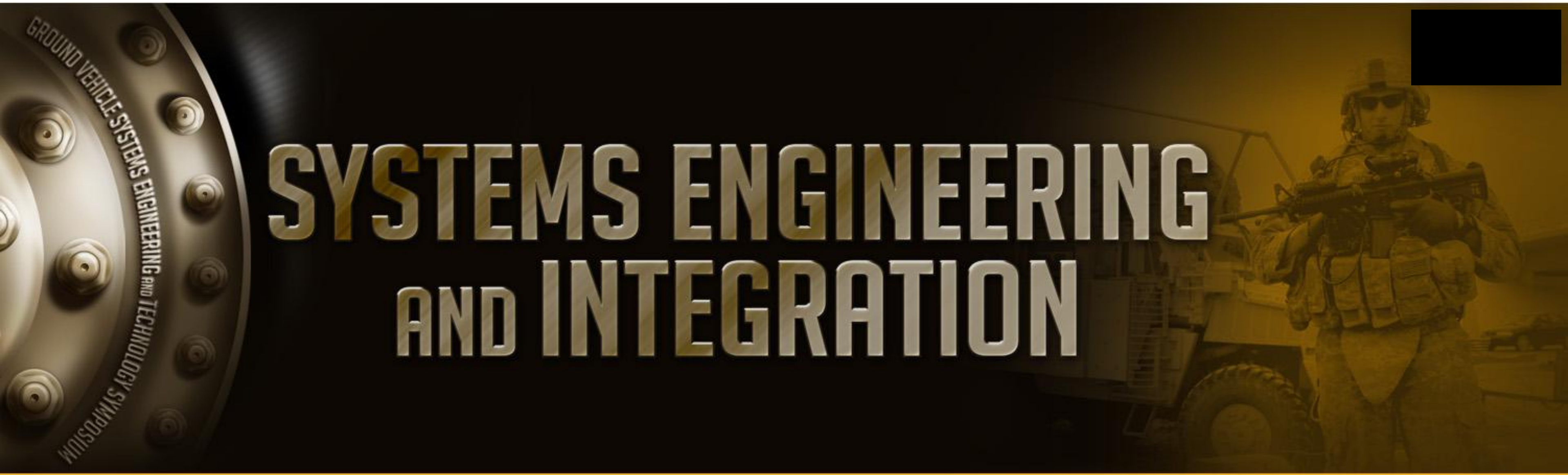

GROUND VEHICLE SAFETY OPTIMIZATION CONSIDERING BLASTWORTHINESS AND THE RISKS OF HIGH WEIGHT AND FUEL CONSUMPTION

Modeling and Optimization Results

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GVSETS

21 July 2011

Report Documentation Page

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Standard Form 298 (Rev. 8-98)
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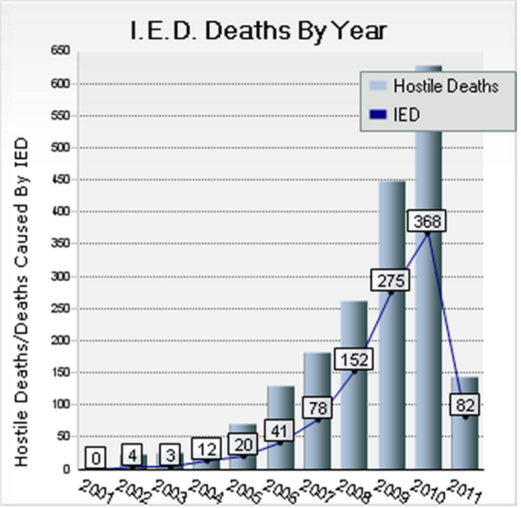
Presentation Outline

- Motivation
- Research Objective
- Modeling Approach
  - Blast event simulation
  - Fuel consumption data
- Optimization Results
- Discussion
- Conclusions
- Ongoing Work

http://www.armscontrolcenter.org/policy/securityspending/articles/mrap_cougar.jpg

Motivation

- Blast-induced casualties and fatalities have increased at an alarming rate in recent years
- Fuel convoys have become a major target for insurgency efforts
  - Approximately 1,000 Americans have been killed in on fuel-related missions in Iraq and Afghanistan in the last ten years.
  - An average of one casualty occurs for every twenty-four fuel convoys in Afghanistan



Anderson (2011). "Save Energy, Save Our Troops," The New York Times, January 12.
http://www.consumerenergyreport.com/2010/10/30/the-u-s-navy-and-biofuels-%E2%80%93-part-iii/, accessed January 24, 2011.
iCasualties (2011). "IED Fatalities." http://icasualties.org/oef, accessed May 16, 2011.

Motivation (2)

- Increasing vehicle weight has mixed effects on different design objectives
  - Underbody blast protection ↑
  - Fuel efficiency ↓
  - Mobility ↓
  - Acceleration performance ↓
- MRAP is 4-6 times the weight of the HMMWV
  - MRAP consumes twice as much fuel as HMMWV
  - MRAP's fuel tank is three times the size of the HMMWV

High Mobility Multipurpose Wheeled Vehicle (HMMWV)

2,700 kg

Mine Resistant Ambush Protected Vehicle (MRAP)
14,000 kg

http://www.amgeneral.com/vehicles/hmmwv/a2-series/details/m1097a2-base
http://www.globalsecurity.org/military/systems/ground/caiman-specs.htm

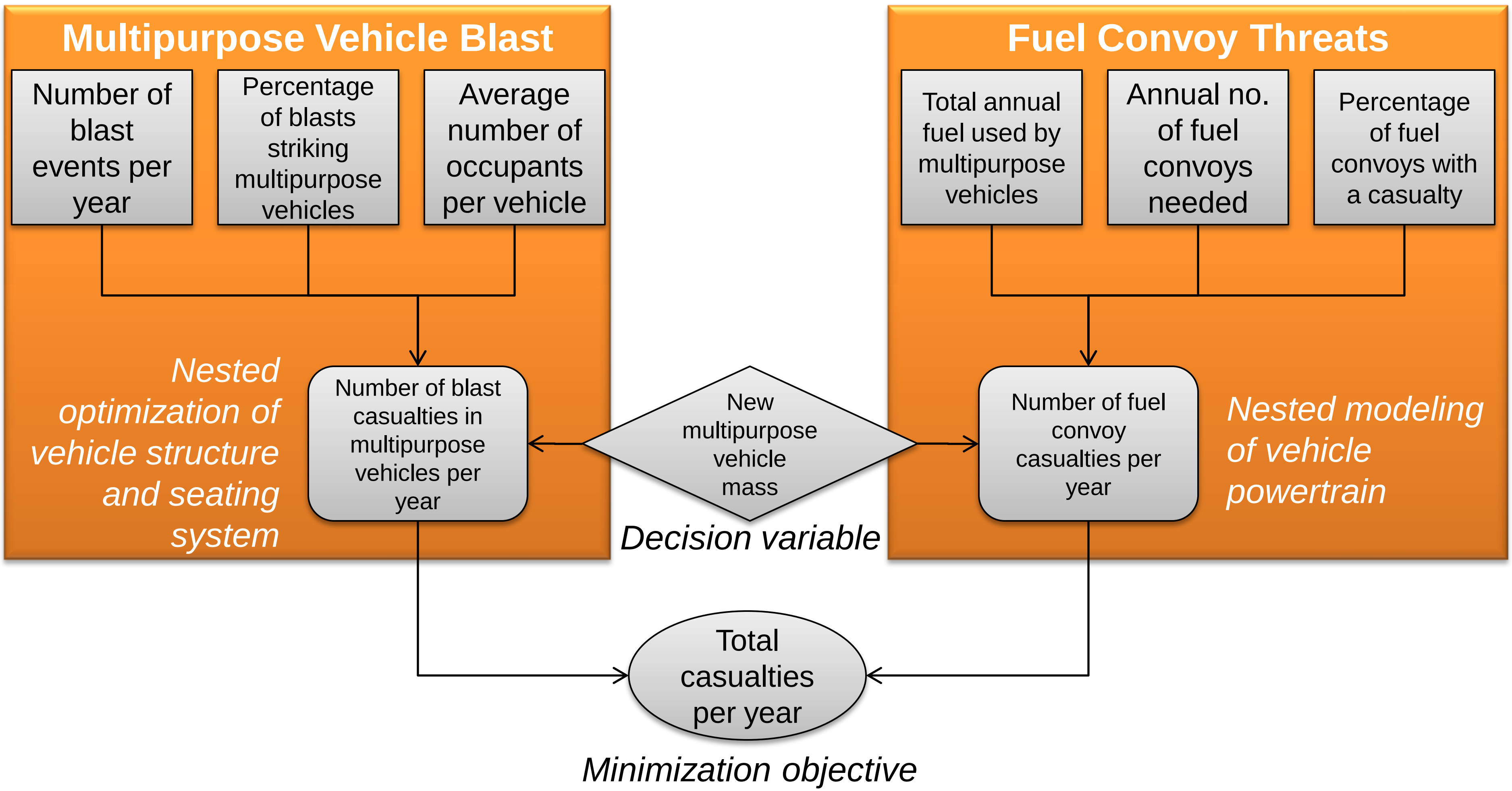
Research Objective

Optimization of ground vehicle design to minimize casualties from blast events and from fuel convoy exposure

Nested seating system design for blastworthiness modeling and optimization

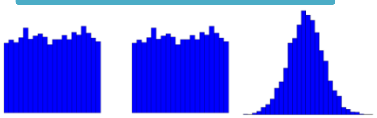
Nested fuel consumption modeling (with implicit powertrain optimization)

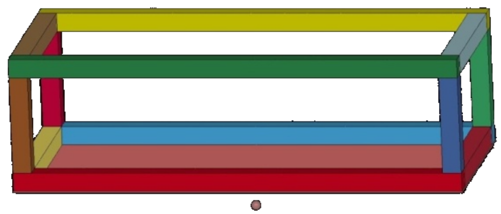
Modeling Approach



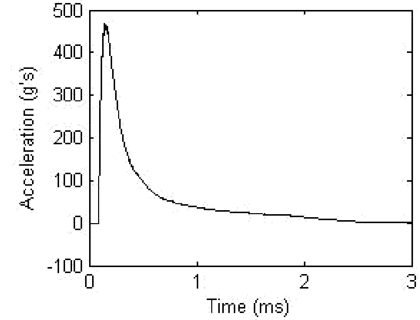
Blast Modeling

Inputs:
Vehicle Mass
Charge Location
Charge Mass

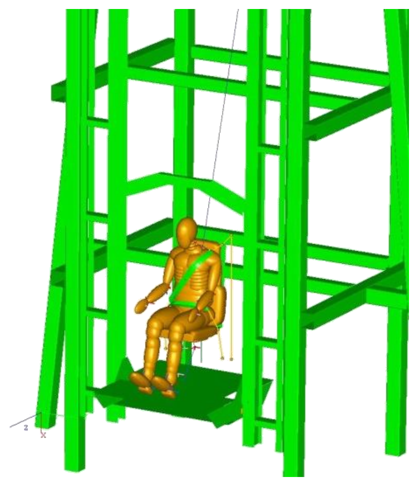

Uncertainty in charge parameters


Underbody Blast Simulation

Blast Pulse of Vehicle



Inputs:
Blast Pulse (magnitude & duration)
Seat Cushion Stiffness
Seat Energy-Absorbing (EA)
System Stiffness
Floor Cushion Stiffness

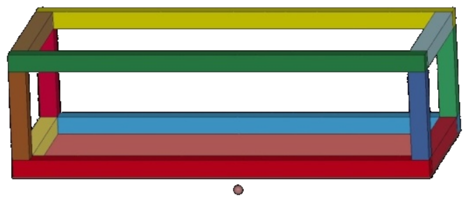

Drop Tower Simulation

Outputs:
Upper Neck Axial Force
Lower Lumbar Axial Force
Lower Tibia Axial Force

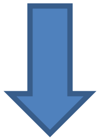
Vehicle Blast Model

SYSTEMS ENGINEERING AND INTEGRATION

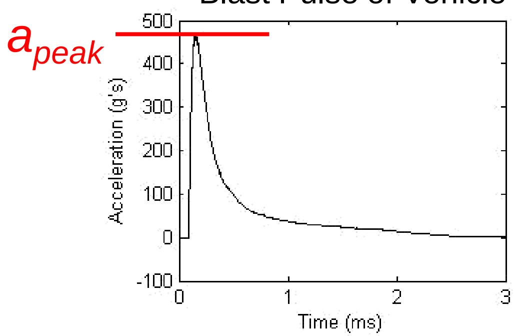
Inputs:
Vehicle Mass (m_v)
Charge Location (x_c, y_c)
Charge Mass (m_c)



Underbody Blast Simulation



Blast Pulse of Vehicle

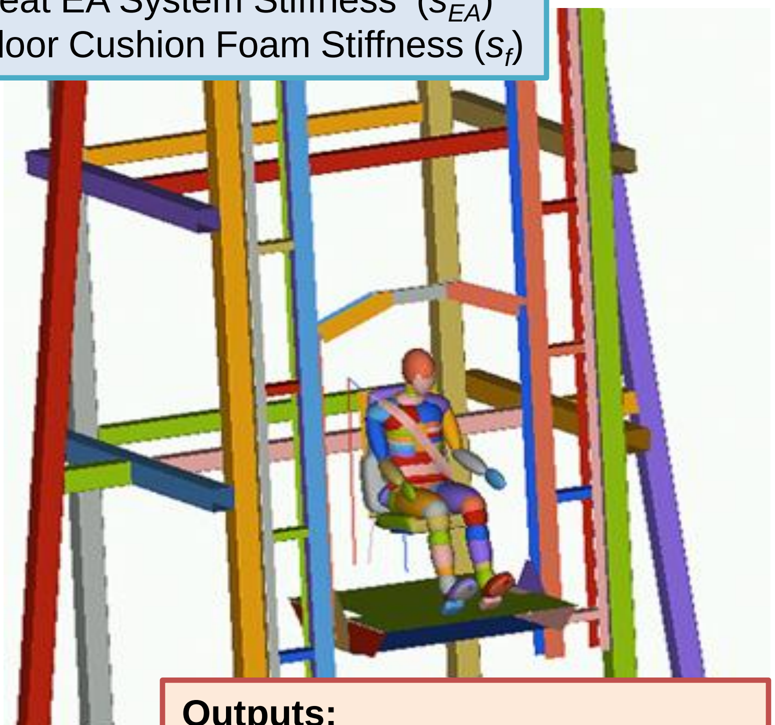


Output:
Blast pulse (a_{peak})

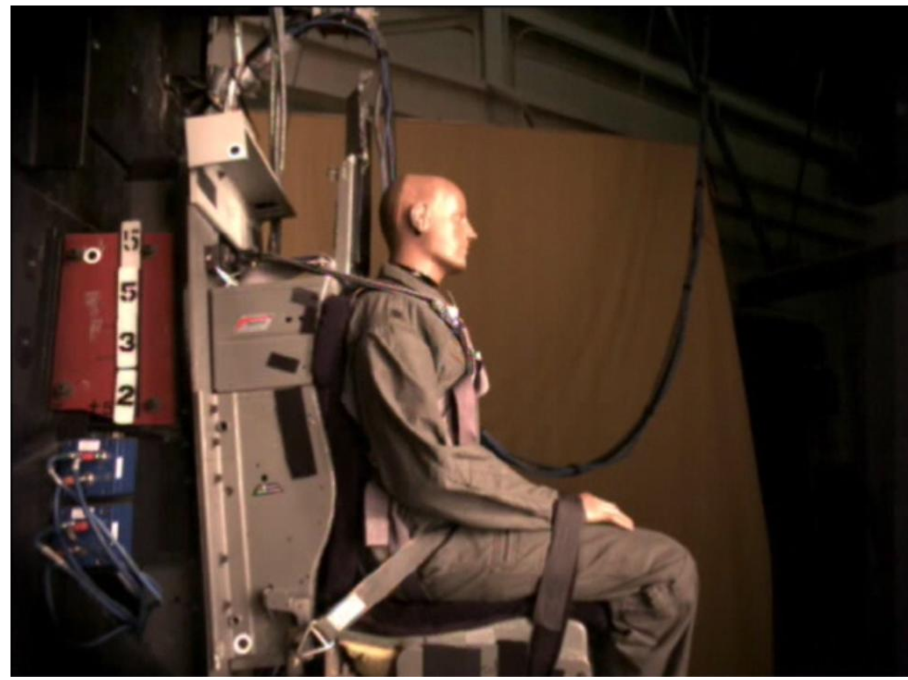
Scherer, R. (2010) "Vehicle and Crash Dummy Response to an Underbelly Blast Event"

Occupant Drop Tower Model

Inputs:
Blast Pulse (a_{peak})
Seat Cushion Foam Stiffness (s_c)
Seat EA System Stiffness (s_{EA})
Floor Cushion Foam Stiffness (s_f)



Outputs:
Upper Neck Axial Force (F_{neck})
Lower Lumbar Axial Force (F_{lumbar})
Lower Tibia Axial Force (F_{tibia})



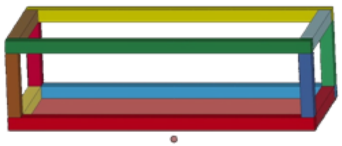
Air Force Research Lab (AFRL) Vertical Drop Tower Test

Surrogate Modeling

- Simulations are too time-consuming to directly optimize
- Surrogate models constructed
  - Design of Experiments conducted using Latin-Hypercube sampling
    - 100 design points for vehicle blast response model (~ 20 minutes/simulation)
    - 300 design points for drop tower model (~ 8 minutes/simulation)
  - Polynomial response surfaces fit using regression
  - Function evaluations reduced from > 20 minutes to fractions of a second!
- Uncertainty in charge parameters applied to surrogate
  - Monte Carlo simulation of blast surrogate with assumed input distributions gives distribution of peak acceleration outputs
  - 10,000 design points fit with power regression

Surrogate Models

100-point Latin hypercube vehicle simulations



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

Accounting for distributed charge random variables with 10,000-point Monte Carlo:

$$\mu_{a_{peak}} = 4 \times 10^6 m_v^{-1.023}$$

$$\sigma_{a_{peak}} = 2 \times 10^6 m_v^{-1.035}$$

300-point Latin hypercube drop tower simulations

$$F_{neck} = e^{(3.84+0.12s_{EA}+0.88s_c+0.002a_{peak}+0.058s_{EA}s_c+0.000084s_{EA}a_{peak} -0.000063s_c a_{peak}-0.058s_{EA}^2-0.14s_c^2-0.00000054a_{peak}^2)}$$

$$F_{lumbar} = e^{(5.66+0.12s_{EA}+0.81s_c+0.002a_{peak}+0.062s_{EA}s_c+0.000087s_{EA}a_{peak} -0.000068s_c a_{peak}-0.059s_{EA}^2-0.13s_c^2-0.00000056a_{peak}^2)}$$

$$F_{tibia} = 332 - 245s_c - 80.2s_f + 1.30a_{peak} + 35.8s_c s_f + 14.0s_f^2 + 0.0012a_{peak}^2$$

<u>Objective</u>: Minimize the probability of an AIS2+ injury, using postulated injury probability curves

$$\underset{s_{EA},s_c,s_f}{\text{minimize}} \quad \int_0^{\infty} P_{injury} \cdot \phi(a_{peak}) \cdot da_{peak}$$

where

$$P_{injury} = 1 - (1 - P_{neck})(1 - P_{lumbar})(1 - P_{tibia})$$

$$P_{neck} = 1 - e^{-(F_{neck}/5.82)^6}$$

$$P_{lumbar} = 1 - e^{-(F_{lumbar}/7.57)^{18.5}}$$

$$P_{tibia} = 1 - e^{-((1.57+0.42F_{tibia})/5.13)^{7.43}}$$

$$\phi(a_{peak}) = \frac{1}{\sqrt{2\pi\sigma^2_{a_{peak}}}} \cdot e^{\frac{-(a_{peak}-\mu_{a_{peak}})^2}{2\sigma^2_{a_{peak}}}}$$

subject to $lb \leq s_{EA}, s_c, s_f \leq ub$

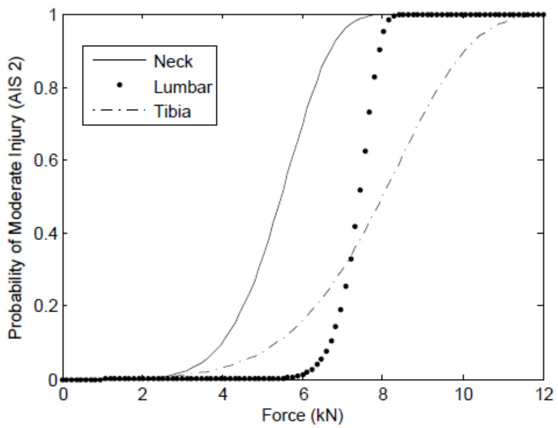
<u>10% AIS2+ Thresholds:</u>

F_{neck} = 4 kN

F_{lumbar} = 6.7 kN

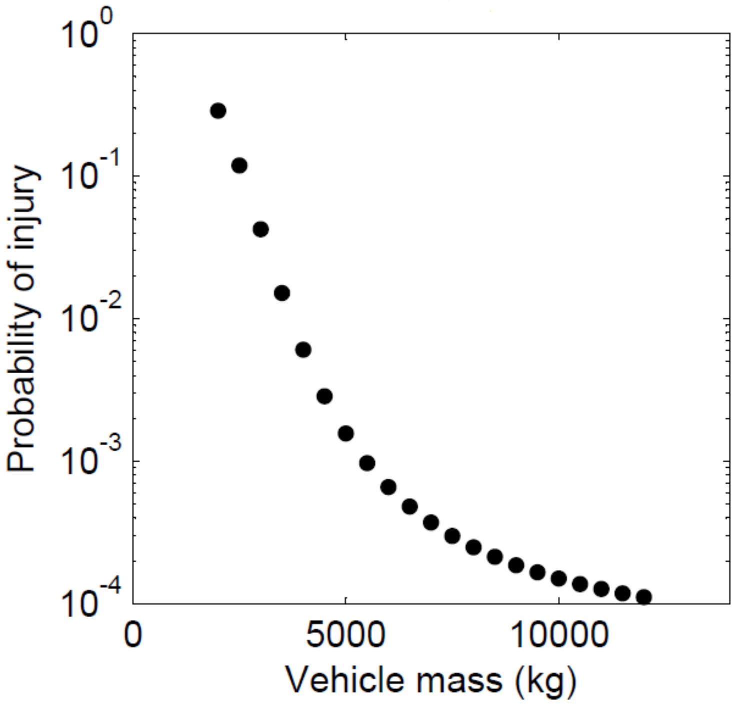
F_{tibia} = 5.4 kN

Source: NATO RTO Technical Report HFM-090



Resulting Optima

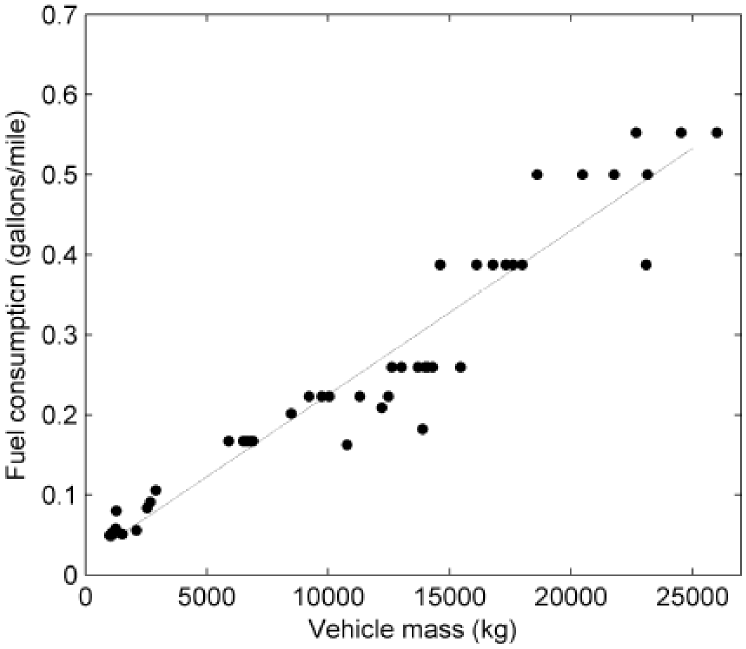
- Optimization results for a range of vehicle mass values
- Blastworthiness and mass are inversely related
- Increasing vehicle mass has diminishing returns on increased blast protection
  - Increase from 2,500 kg to 3,500 kg reduces injury probability by 87%
  - Increase from 10,000 kg to 11,000 kg only reduces injury probability by 15%



$$P_{injury} = 2.178 \times 10^{14} m_v^{-4.506}$$

Fuel Consumption Model

From empirical data on U.S. Army ground vehicles, fuel consumption as a function of mass is estimated



$$FC = 2.0528 \times 10^{-5} m_v + 1.9705 \times 10^{-2}$$

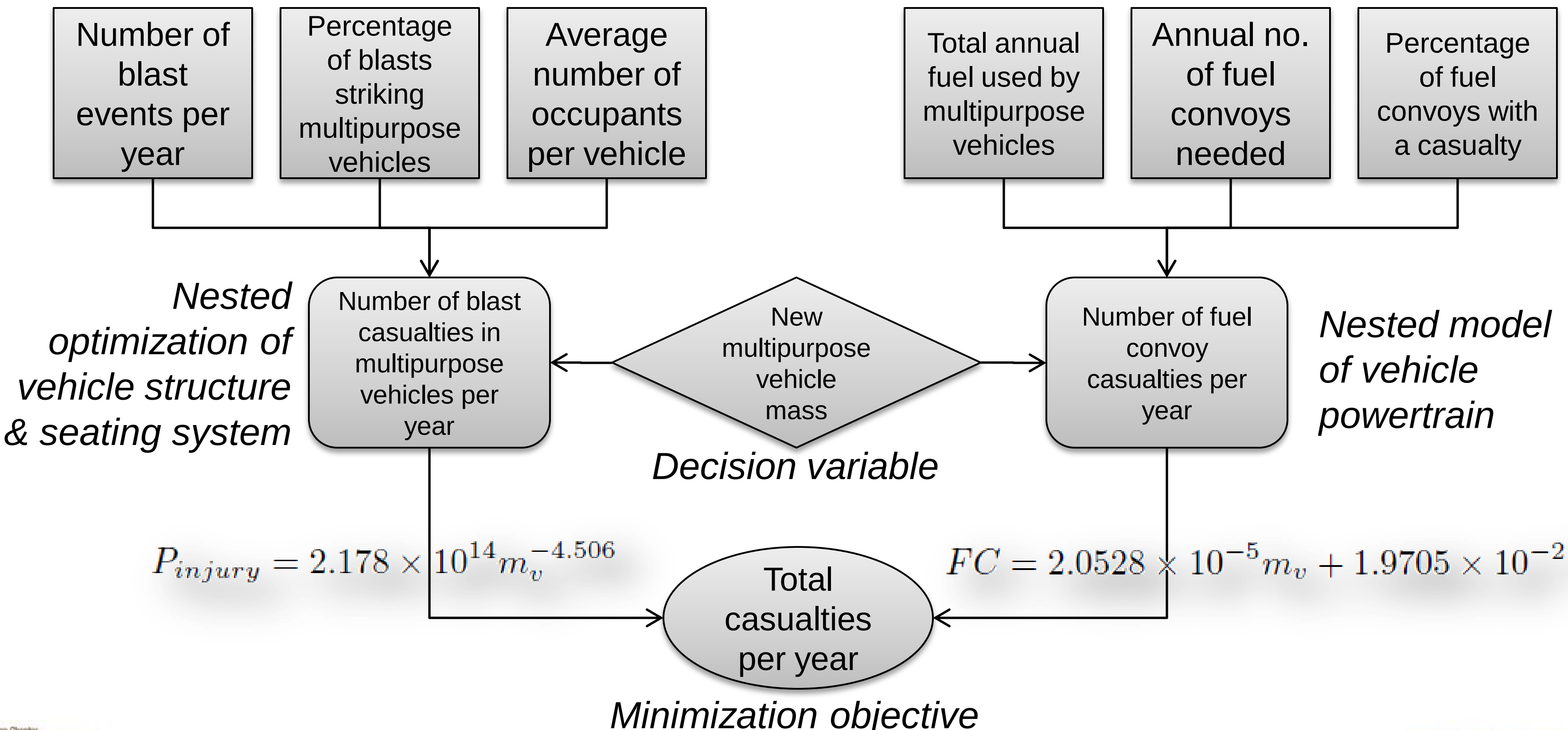
S.C. Connors and C.F. Foss, Jane's Military Vehicles and Logistics 2009-2010, Jane's Information Group Limited, Surrey, 2009.

Combined Optimization Formulation

$$\underset{m_v}{\text{minimize}} \quad E[casualties] = E[blast\ casualties] + E[fuel\ convoy\ casualties]$$

$$\text{where} \quad E[blast\ casualties] = P_{injury}(m_v) \cdot N_{blasts} \cdot N_{personnel\ per\ vehicle}$$

$$E[fuel\ convoy\ casualties] = R_{fuel\ convoy\ casualty} \cdot N_{fuel\ convoys}(m_v)$$



$$P_{injury} = 2.178 \times 10^{14} m_v^{-4.506}$$

$$FC = 2.0528 \times 10^{-5} m_v + 1.9705 \times 10^{-2}$$

Baseline Scenario

Parameters*:

Number of blast events per year	%age of blasts against multipurpose vehicle	Average number of occupants per vehicle	Baseline multipurpose vehicle mass (kg)	Baseline total fuel consumption (gallons)	%age of fuel consumed by multipurpose vehicle	Baseline number of fuel convoys per year	%age of fuel convoys with a casualty
16,800	0.50	4	5,000	620,000,000	0.20	6,000	0.042

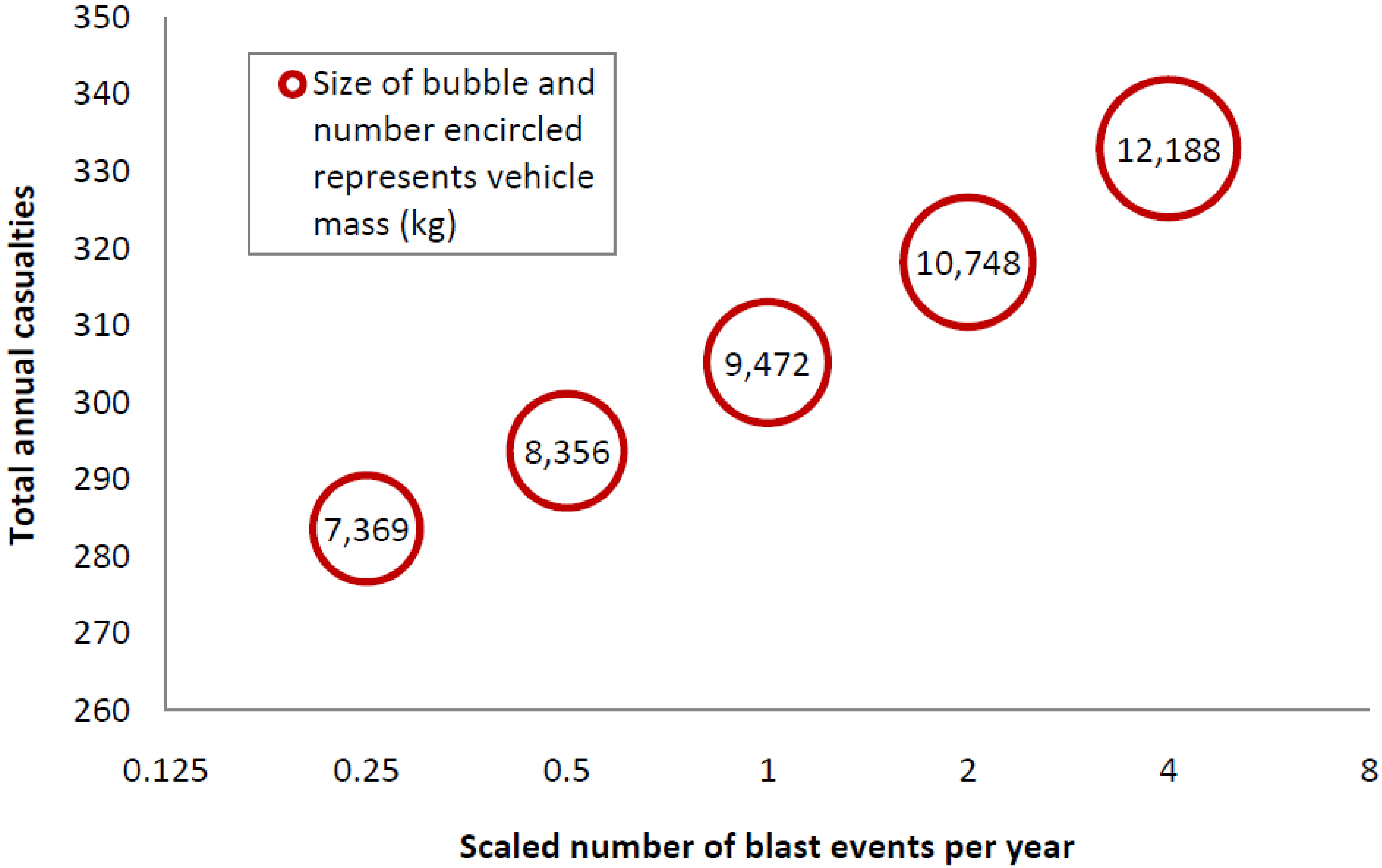
Results:

	Multipurpose vehicle mass (kg)	Total number of annual casualties	Multipurpose vehicle blast casualties	Total fuel convoy-related casualties
Pre-optimization	5,000	565	315	250
Post-optimization	9,472	305	18	288

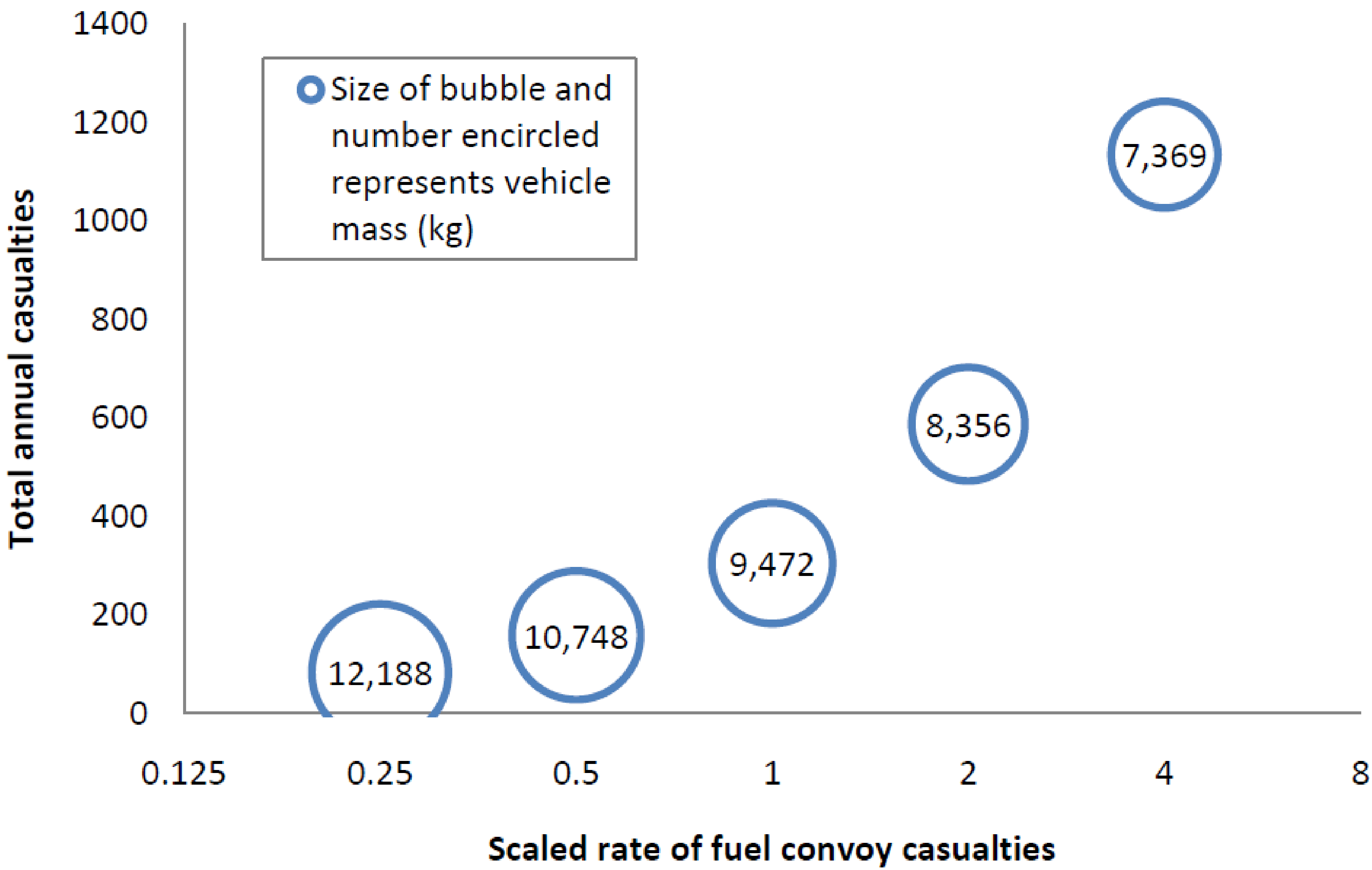
Optimization increases vehicle mass by 89% and decreases expected casualties by 46%

*All parameter values are assumptions based on publicly available data

Effect of Blast Parameter



Effect of Fuel Convoy Parameter



Using the Formulation for Strategic Decision-Making

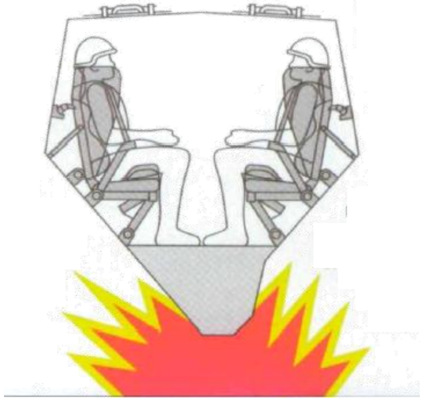
- Assessing the impact of interventions
  - Reductions to the blast threat
    - Reduce number of blast events
    - Reduce effectiveness of blasts
  - Reductions to fuel convoy threats
    - Reduce frequency of convoy attacks
    - Reduce number of convoys
- Fleet mixing
  - Enemy tactics often change quicker than vehicle design, rendering complete re-design impractical
  - Existing vehicles may be mixed strategically to meet the optimal vehicle mass target

Conclusions

- As expected, parametric increases of either threat increases predicted casualties
  - Increasing blast threat drives mass up
  - Increasing fuel convoy threat drives mass down
- Depending on parameters, optimal vehicle mass is predicted to lie between 7,000 and 12,000 kilograms
- Practical implications of framework:
  - Assessing and analyzing interventions to reduce threats to troops
  - Strategic decisions for dynamic fleet-mixing

Ongoing Work

1. Development of a more sophisticated vehicle model to account for:
   - Energy-absorbing deformation
   - V-hull/chimney architectures
   - Wheel geometry

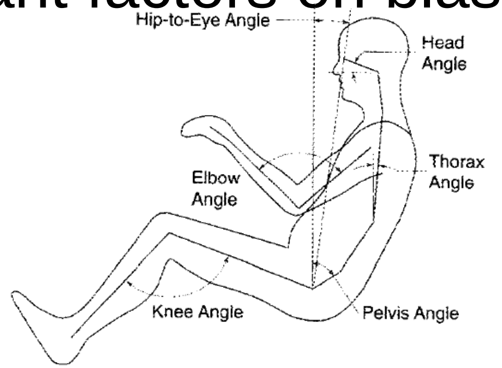


2. Incorporation of physics-based powertrain simulation
   - Design variables that impact fuel consumption using realistic drive cycles for multipurpose vehicles
   - Nested optimization in fuel convoy equation

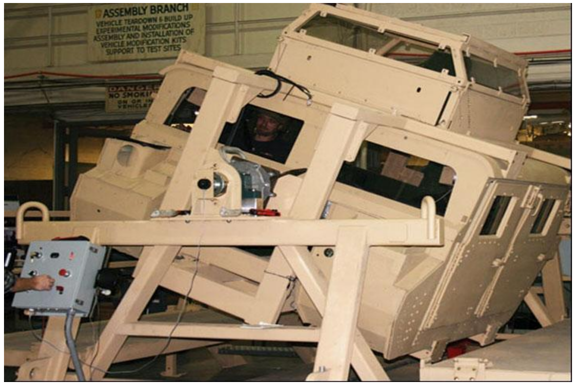
http://tank-net.org, accessed April 27, 2010.

Future Work

2. Examining the significance of occupant factors on blast safety
   - Occupant size
   - Occupant sitting position



3. Including other related design objectives
   - Ballistic & missile protection
   - Rollover resistance & protection
   - Occupant comfort



Reed, M. et al. (2000), "Effects of Vehicle Interior Geometry and Anthropometric Variables on Automobile Driving Posture," *Human Factors*, 42(4), pp.541-552.
http://www.usaasc.info/alt_online/images/080901_Photo2.jpg, accessed April 29, 2010.

Acknowledgements

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- Dr. Nickolas Vlahopoulos, University of Michigan

Q & A

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