Multilevel Vehicle Design: Fuel Economy, Mobility and Safety Considerations, Part B

Ground Vehicle Weight and Occupant Safety Under Blast Loading

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http://editoriale.files.wordpress.com/2008/03/mrap.jpg, accessed on April 22, 2010.

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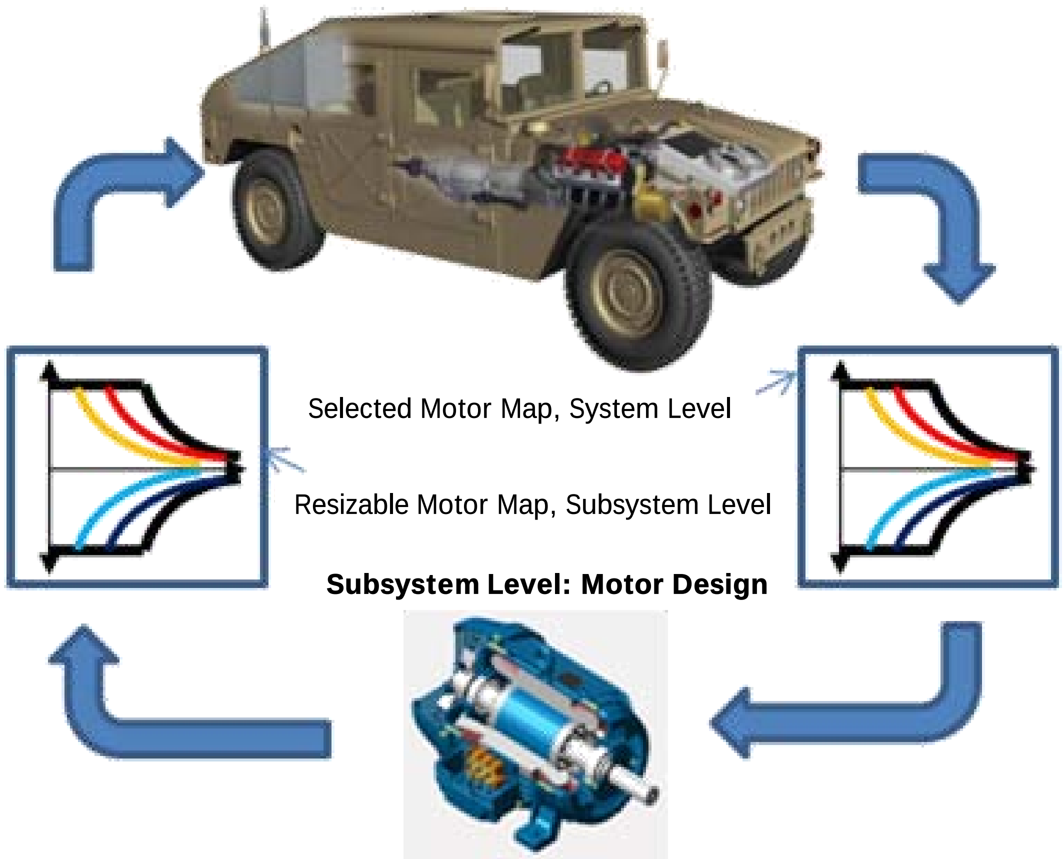
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Fuel Economy, Mobility and Safety

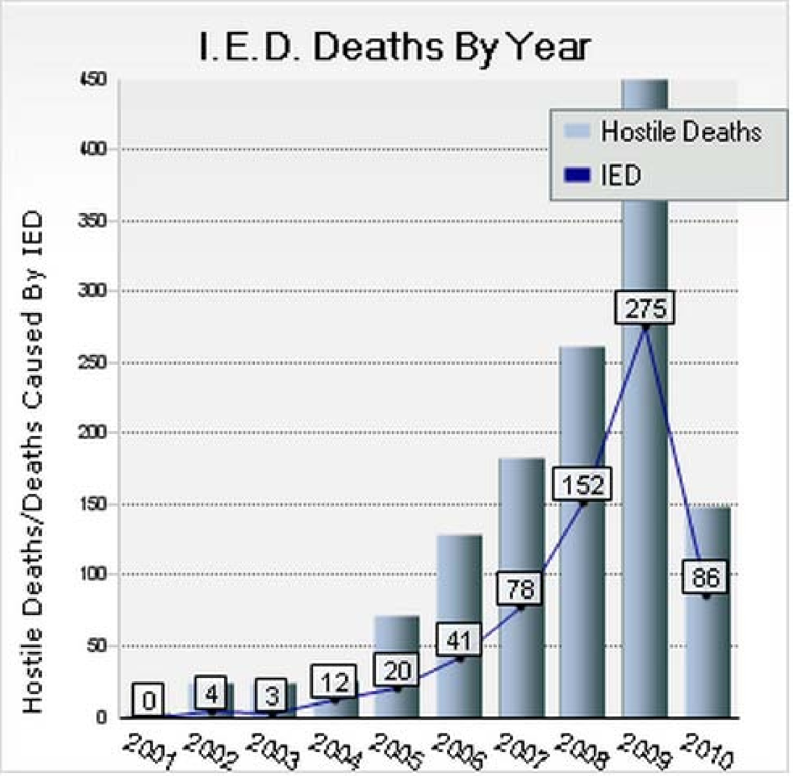
System Level: Battery, Gearbox, Occupant Compartment Design; Motor Map Selection



http://c0378172.cdn.cloudfiles.rackspacecloud.com/7770_9080764544.jpg, accessed on April 29, 2010.
http://www.motor-design.com, accessed on January 10, 2010.

Motivation

Underbody blast events are a top threat facing U.S. Army ground personnel



http://www.focusblog.ro/wp-content/uploads/2010/03/LAND_M1114_HMMWV_IEDed_lg.jpg, accessed April 29, 2010
iCasualties (2010). "IED Fatalities." http://icasualties.org/oef, accessed April 6, 2010.

Motivation

Vehicle weight has mixed effects on different design objectives

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

Multi-objective optimization of ground vehicles for reduced weight and occupant injury

Determine occupant injury as a response to structural and occupant compartment design parameters

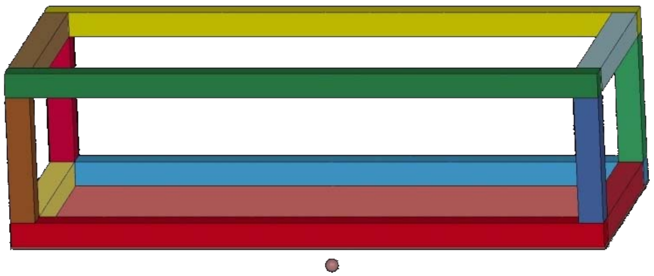
Develop surrogate models for vehicle and occupant responses to a blast event

Account for uncertainty in blast location and size

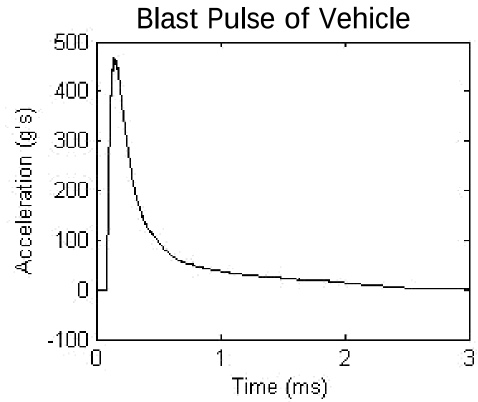
http://c0378172.cdn.cloudfiles.rackspacecloud.com/7770_9080764544.jpg, accessed on April 29, 2010.
http://mocoloco.com/art/archives/pickering_land_mine_mar_06.jpg, accessed on April 14, 2010.

Modeling Approach

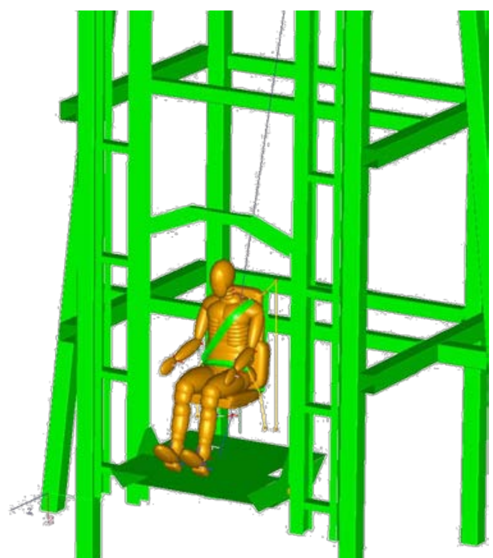
Inputs:
Vehicle Mass
Charge Location (x, y coordinates)
Charge Mass



Underbody Blast Simulation



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

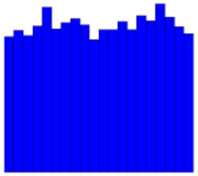


Drop Tower Simulation

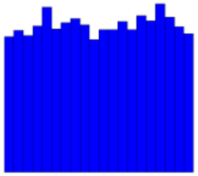
Outputs:
Upper Neck Axial Force
Lower Lumbar Axial Force
Lower Tibia Axial Force

Charge Uncertainty

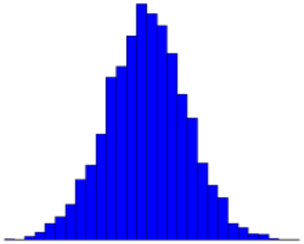
Field data about charge distribution is sensitive, so I postulate distributions:



Charge longitudinal/ x-location ~ *U(a,b)* (m)



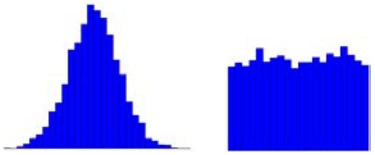
Charge lateral/ y-location ~ *U(a,b)* (m)

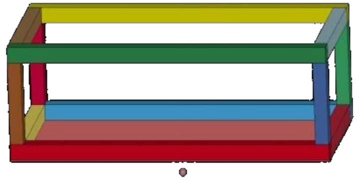


Charge mass ~ $N(\mu,\sigma)$ (TNT-equivalent)

Charge Uncertainty Propagation

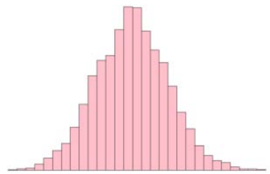
Uncertainty in Charge Size & Location

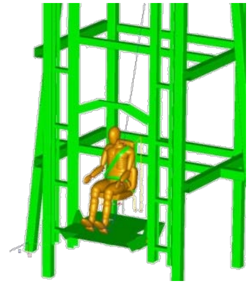




Underbody Blast Simulation

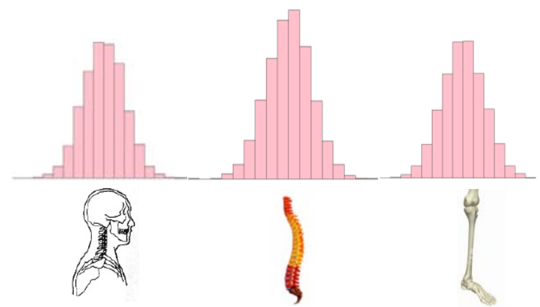
Uncertainty in Vehicle Peak Acceleration





Drop Tower Simulation

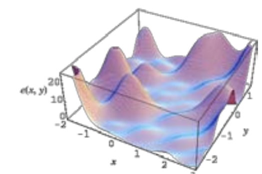
Uncertainty in Occupant Body Forces



Upper Neck Compression

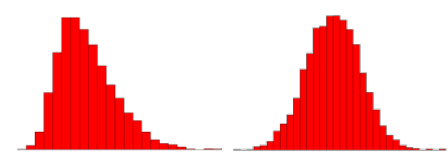
Lumbar Spine Compression

Lower Leg Compression



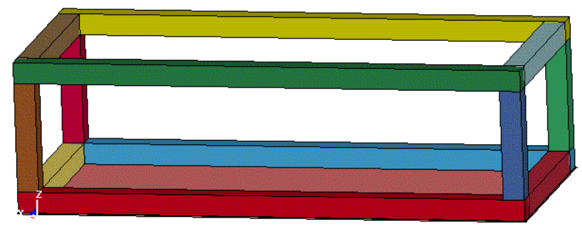
Optimization to Minimize Injury Probability

Uncertainty in Optimal Seat System Design Variables

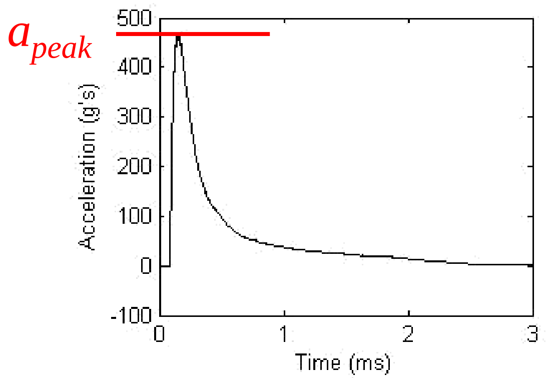


Structural Model

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



Output:
Blast pulse (a_{peak})

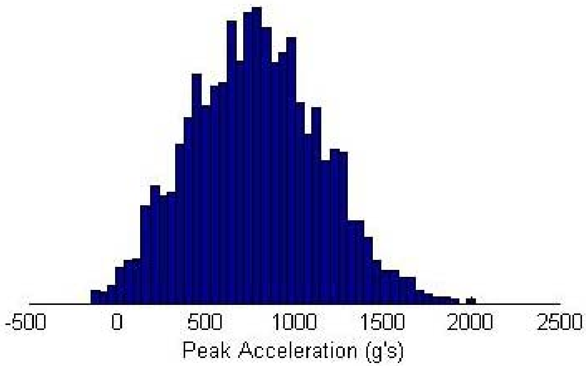


Surrogate model from linear regression on 100 data points:

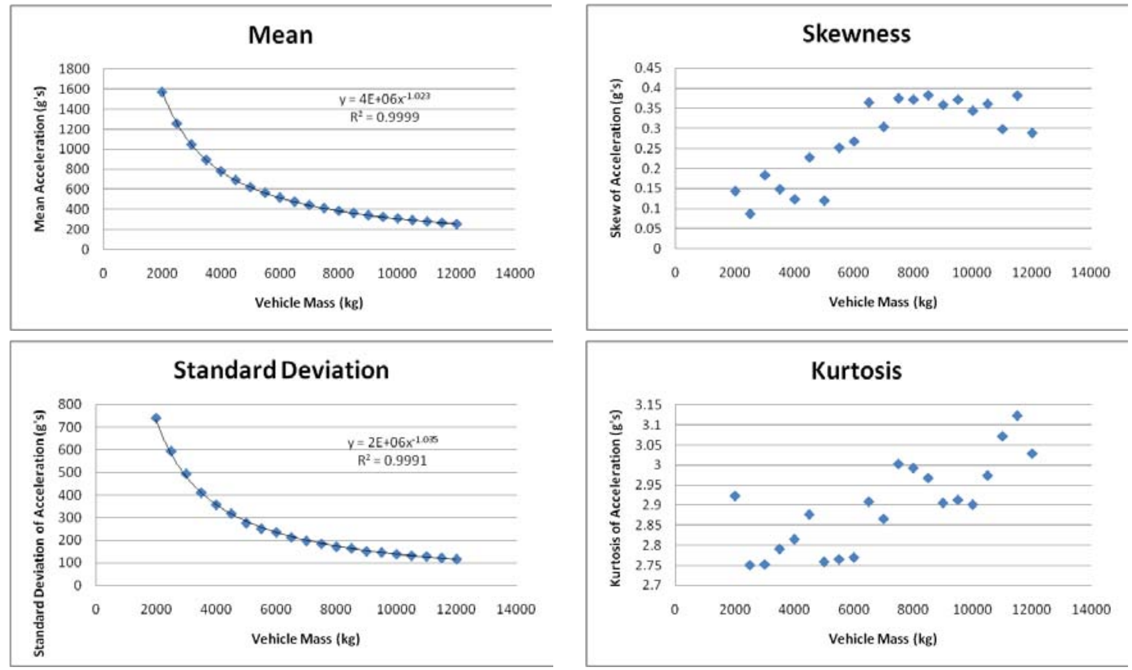
$$a_{peak} = \beta_0 + \beta_1 \frac{1}{m_v} + \beta_2 x_c + \beta_3 y_c + \beta_4 m_c + \beta_5 \frac{x_c}{m_v} + \beta_6 \frac{y_c}{m_v} + \beta_7 \frac{m_c}{m_v} + \beta_8 y_c m_c + \beta_9 y_c^2$$

Livermore Software Technology Corporation (2007). LS-DYNA Keyword User's Manual. http://lstc.com/pdf/ls-dyna_971_manual_k.pdf, accessed April 29, 2010.

Blast Pulse Uncertainty



Peak accelerations for 4,000 kg vehicle



Distribution moments plotted versus vehicle mass

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

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

Occupant Model

Inputs:

Blast Pulse (a_{peak})

Seat Cushion Foam Stiffness (s_c)

Seat EA System Stiffness (s_{EA})

Outputs:

Upper Neck Axial Force (F_{neck})

Lower Lumbar Axial Force (F_{lumbar})

Lower Tibia Axial Force (F_{tibia})

Arepally, S. et. al. (2008). Application of Mathematical Modeling in Potentially Survivable Blast Threats in Military Vehicles. http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA496843&Location=U2&doc=GetTRDoc.pdf, accessed on April 29, 2010.

Occupant Model

Surrogate model from linear regression on 500 data points:

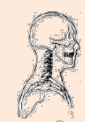
$$F_{neck} = e^{\left(3.809 - 0.03954 s_{EA} + 0.4289 s_c + 0.003446 a_{peak} + 0.0002161 s_{EA} a_{peak} - 0.000001781 a_{peak}^2\right)}$$

$$F_{spine} = 383 - 462 s_{EA} + 416 s_c + 1.4 a_{peak} + 262 s_{EA} s_c + 0.7 s_{EA} a_{peak} + s_c a_{peak} - 232 s_c^2 - 0.0006 a_{peak}^2$$

$$F_{combined\ tibia} = 97 + 63 s_{EA} - 495 s_c + 3.7 a_{peak} - 0.16 s_{EA} a_{peak} - 0.38 s_c a_{peak} + 99 s_c^2 + 0.0003 a_{peak}^2$$

U.S. Army aims for no more than 10% probability of moderate injury (AIS2+)

Thresholds:



F_{neck} = 4 kN

F_{lumbar} = 6.7 kN

F_{tibia} = 5.4 kN

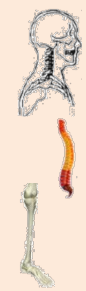
Research and Technology Organisation (2007). "Test Methodology for Protection of Vehicle Occupants against Anti-Vehicular Landmine Effects." North Atlantic Treaty Organisation, Neuilly-sur-Seine Cedex, France. Accession number RTO-TR-HFM-090.

Optimization Formulation

General Safety Objective: minimize occupant injury

What is the explicit objective function?

Thresholds:



F_{neck} = 4 kN

F_{lumbar} = 6.7 kN

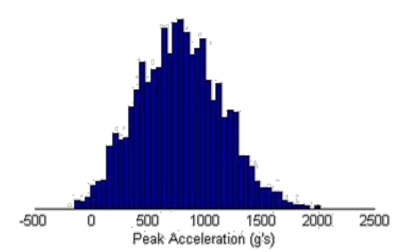
F_{tibia} = 5.4 kN

min f(x) = probability of AIS2 Injury

Complication: unknown injury probability distributions

min f(x) = body forces experienced when vehicle is attacked

Complications: uncertainty in charge parameters, multiple body forces of interest



Formulation 1: Model

Objective: minimize the maximum of the body forces (percentage of threshold)

$$\min_{s_{EA},s_c} \max\left(\frac{F_{neck}}{4kN}, \frac{F_{lumbar}}{6.7kN}, \frac{F_{tibia(combined)}}{5.4kN}\right)$$

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

$$F_{neck} = F_{neck}\left(s_{EA}, s_c, a_{peak}\right)$$

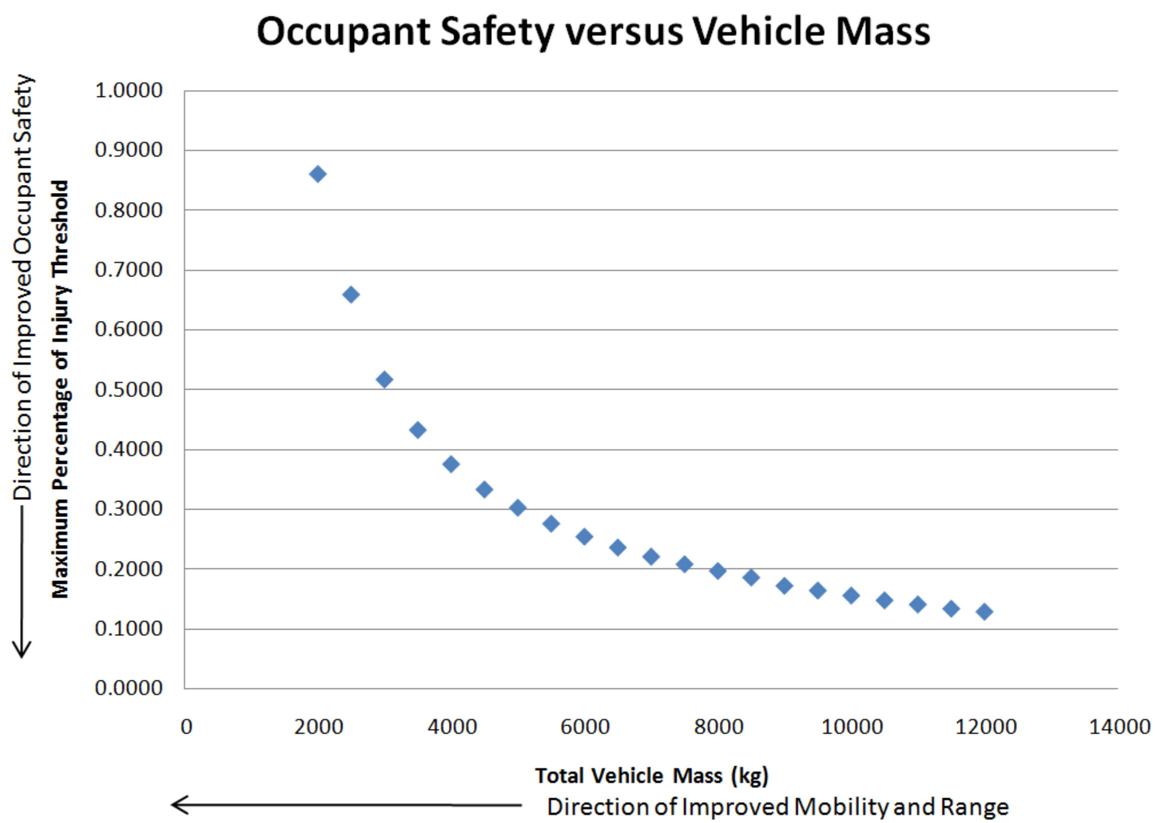
$$F_{lumbar} = F_{lumbar}\left(s_{EA}, s_c, a_{peak}\right)$$

$$F_{combined\ tibia} = F_{combined\ tibia}\left(s_{EA}, s_c, a_{peak}\right)$$

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

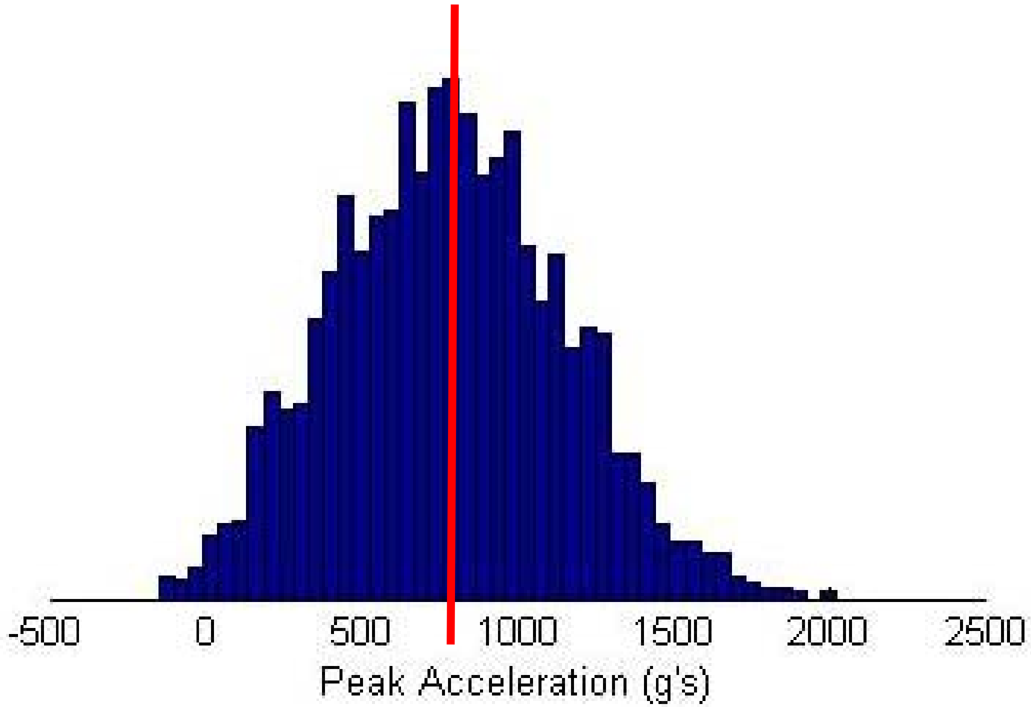
Formulation 1: Results

<u>Objective</u>: minimize the maximum of the body forces (percentage of threshold)



Formulation 1 Limitation

Minimizes body forces for a given vehicle mass for 50th percentile of charges



Formulation 2: Model

<u>Objective</u>: minimize the probability of "failure" to meet injury threshold

$$\min_{s_{EA},s_c} \quad P_f = 1 - \Phi(a_{peak})$$

where

$$\Phi(a_{peak}) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{a_{peak} - \mu_{a_{peak}}}{\sqrt{2\sigma^2_{a_{peak}}}}\right)\right]$$

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

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

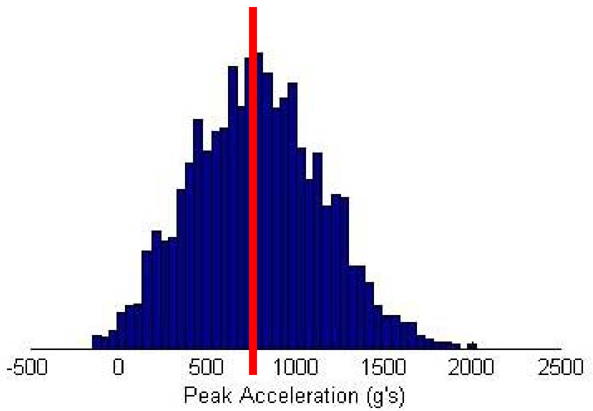
subject to

$$F_{neck} = g_1(s_{EA}, s_c, a_{peak}) \leq 4000$$

$$F_{lumbar} = g_2(s_{EA}, s_c, a_{peak}) \leq 6700$$

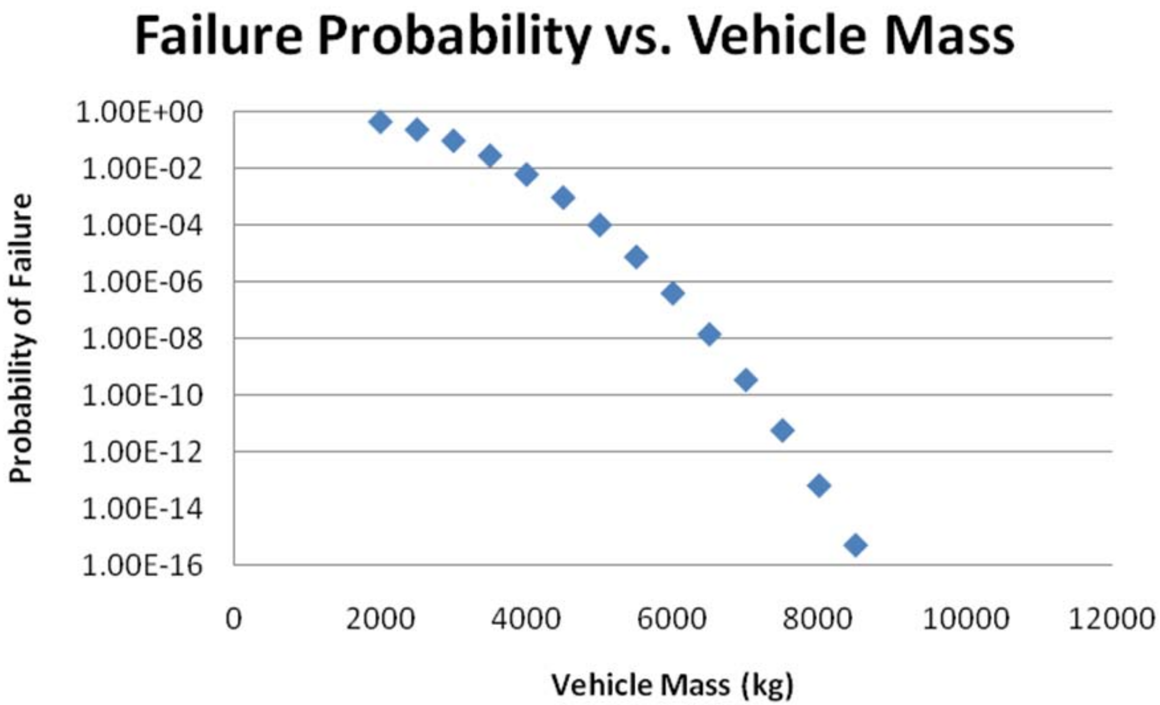
$$F_{combined\ tibia} = g_3(s_{EA}, s_c, a_{peak}) \leq 5400$$

$$lb \leq s_{EA}, s_c \leq ub$$



Formulation 2: Results

<u>Objective</u>: minimize the probability of "failure" to meet injury threshold



Vehicle Mass (kg)	Probability of Failure
2000	4.60E-01
2500	2.45E-01
3000	9.93E-02
3500	2.97E-02
4000	6.43E-03
4500	9.90E-04
5000	1.07E-04
5500	8.06E-06
6000	4.20E-07
6500	1.51E-08
7000	3.69E-10
7500	6.16E-12
8000	6.99E-14
8500	5.55E-16
9000	0.00E+00

$$s_{EA} = 1.5, s_c = 2.0$$

Occupant Model with Floor Pad

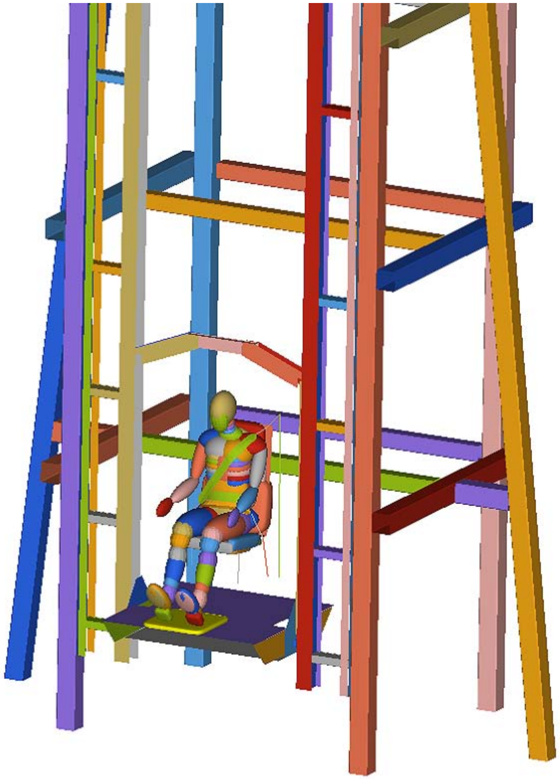
Inputs:

Blast Pulse (a_{peak})

Seat Cushion Foam Stiffness (s_c)

Seat EA System Stiffness (s_{EA})

Floor Pad Foam Stiffness (s_f)



Surrogate model from linear regression on 300 data points:

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

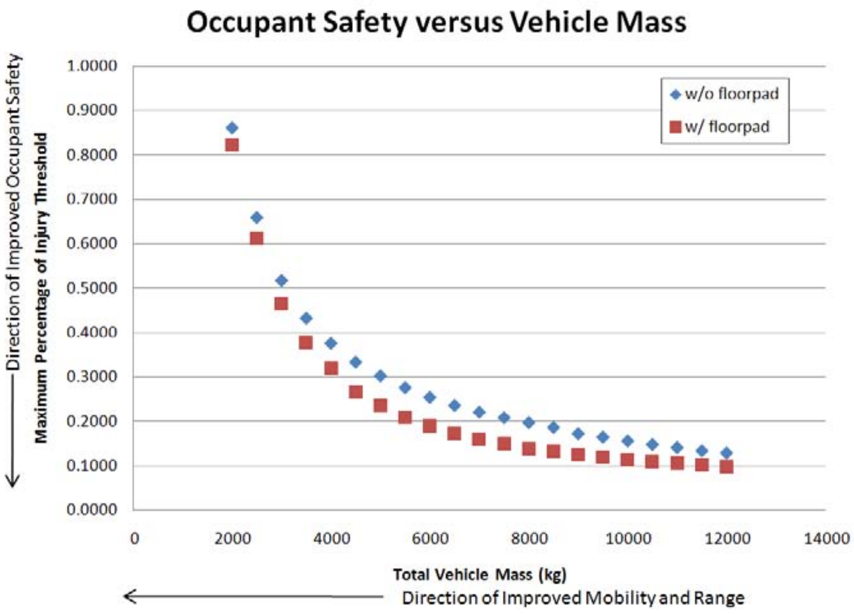
$$F_{spine} = e^{\left(5.664+0.12s_{EA}+0.81s_c+0.002a_{peak}+0.062s_{EA}s_c+0.000087s_{EA}a_{peak}-0.000068s_c a_{peak}-0.059s_{EA}^2-0.13s_c^2-0.00000056a_{peak}^2\right)}$$

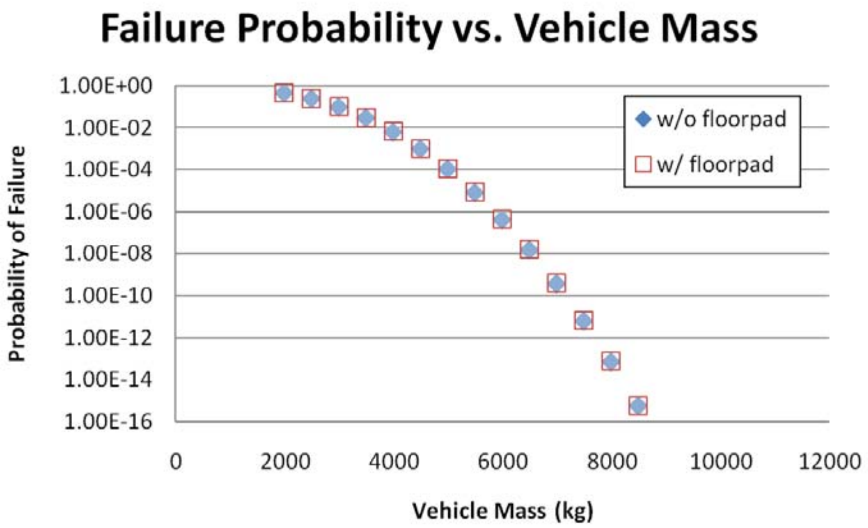
$$F_{combined\,tibia} = 332 - 245s_c - 80.23s_f + 1.3a_{peak} + 35.84s_c s_f + 14.0s_f^2 + 0.0012a_{peak}^2$$

Results with Floor Pad

Objective 1: minimize the maximum of the body force percentages

Objective 2: minimize the probability of "failure" to meet injury threshold



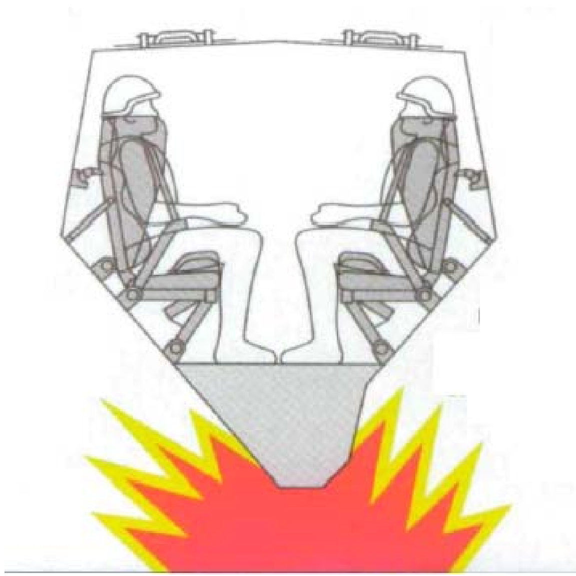


Summary

- Developed a modeling approach to evaluate structural and occupant responses to ground vehicle underbody blasts
- Fit surrogate models to reduce computational expense
- Demonstrated two optimization formulations and their results
  - Accounted for uncertainty in charge parameters
  - Quantified negative correlation between vehicle mass and occupant injury probability
- Added floor padding to reduce tibia impact

Ongoing Work

Structural energy absorption



Effects of v-shaped hull

Rollover safety modeling

http://www.defense-update.com/products/t/tarps_291009.html, accessed April 27, 2010.
tank-net.org, accessed Apri 27, 2010.
http://www.usaasc.info/alt_online/images/080901_Photo2.jpg, accessed April 29, 2010.

Q & A

?

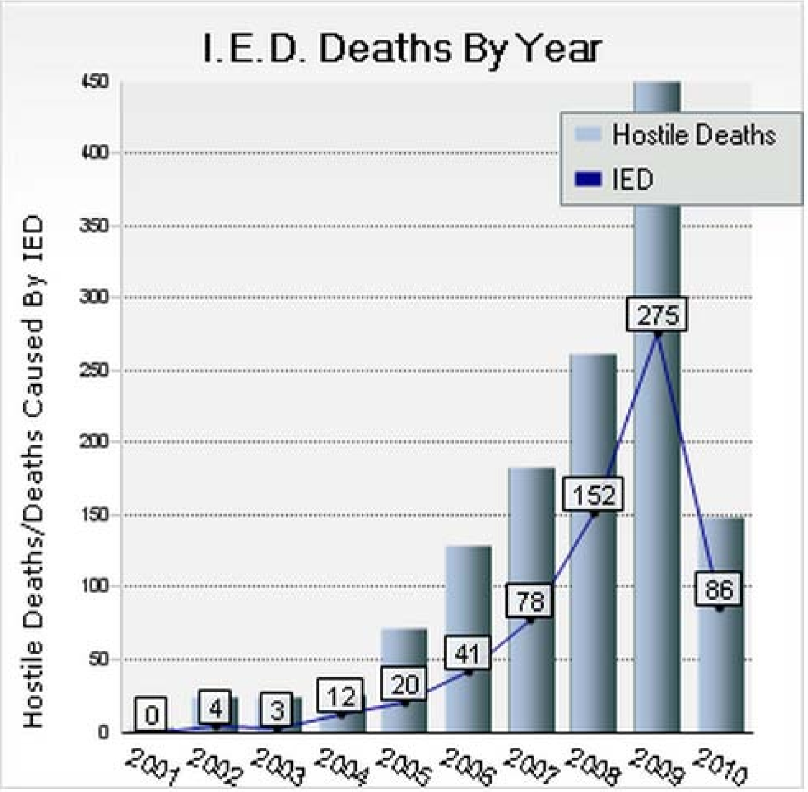
Backup Slides

Motivation

Underbody blast events are a top threat facing U.S. Army ground personnel

IED Fatalities

Period	IED	Total	Pct
2001	0	4	0.00
2002	4	25	16.00
2003	3	26	11.54
2004	12	27	44.44
2005	20	73	27.40
2006	41	130	31.54
2007	78	184	42.39
2008	152	263	57.79
2009	275	450	61.11
2010	86	150	57.33



iCasualties (2010). "IED Fatalities." http://icasualties.org/oef, accessed April 6, 2010.

Abbreviated Injury Scale

TABLE 1. Abbreviated Injury Scale (AIS)

AIS score	Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Probably lethal*

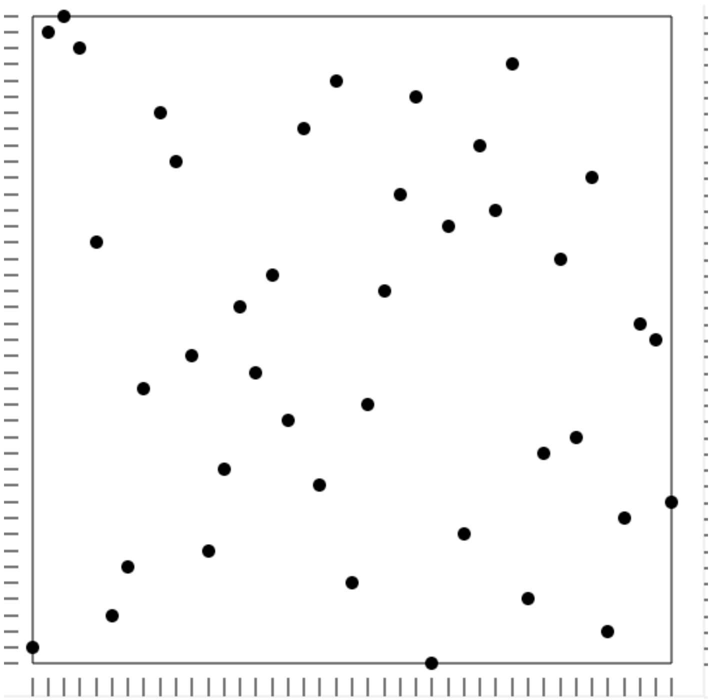
* Although a perfect linear correlation with an AIS of 6 and mortality does not exist, survivability is unlikely.

Examples of AIS 2

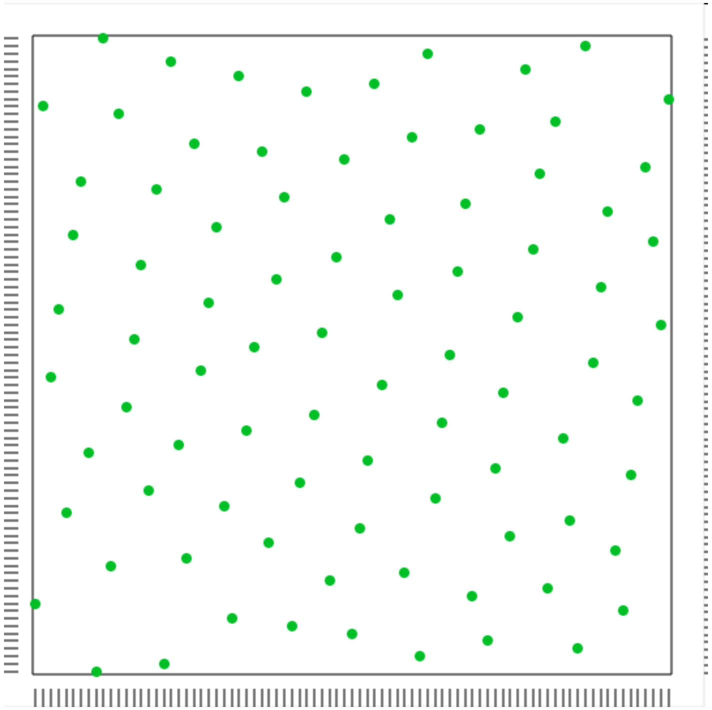
- Major skin laceration or avulsion with <20% blood loss
- Nerve contusions or lacerations
- Vertebral dislocation without fracture
- Herniated disc without nerve root damage
- Lower extremity bone fracture

Center for Disease Control and Prevention, http://www.cdc.gov/mmwr/preview/mmwrhtml/figures/r801a1t1.gif, accessed on April 30, 2010.
Association for the Advancement of Automotive Medicine (1990), The Abbreviated Injury Scale, 1990 Revision. Des Plaines, IL.

Latin Hypercube Sampling



Latin Hypercube



Optimal Latin Hypercube

http://people.sc.fsu.edu/~burkardt/m_src/lcvt_dataset/lcvt_dataset.html, accessed on December 5, 2009.

Model Comparison

Without floorpad:

500 data points

$$F_{neck} = e^{\left(3.809-0.03954 s_{EA}+0.4289 s_c+0.003446 a_{peak}+0.0002161 s_{EA} a_{peak}-0.000001781 a_{peak}^2\right)}$$

$$F_{spine} = 383 - 462 s_{EA} + 416 s_c + 1.4 a_{peak} + 262 s_{EA} s_c + 0.7 s_{EA} a_{peak} + s_c a_{peak} - 232 s_c^2 - 0.0006 a_{peak}^2$$

$$F_{combined\ tibia} = 97 + 63 s_{EA} - 495 s_c + 3.7 a_{peak} - 0.16 s_{EA} a_{peak} - 0.38 s_c a_{peak} + 99 s_c^2 + 0.0003 a_{peak}^2$$

R^2
0.985
0.979
0.994

With floorpad:

300 data points

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

$$F_{spine} = e^{\left(5.664+0.12 s_{EA}+0.81 s_c+0.002 a_{peak}+0.062 s_{EA} s_c+0.000087 s_{EA} a_{peak}-0.000068 s_c a_{peak}-0.059 s_{EA}^2-0.13 s_c^2-0.00000056 a_{peak}^2\right)}$$

$$F_{combined\ tibia} = 332 - 245 s_c - 80.23 s_f + 1.3 a_{peak} + 35.84 s_c s_f + 14.0 s_f^2 + 0.0012 a_{peak}^2$$

R^2
0.952
0.946
0.976

Formulation 1 Data

Without Floor Foam

Vehicle Mass (kg)	EA Stiffness	Cushion Stiffness	Maximum Injury Ratio
2000	1.5000	2.0000	0.8616
2500	1.1082	2.0000	0.6597
3000	0.6323	2.0000	0.5175
3500	0.2962	2.0000	0.4328
4000	0.2500	1.7909	0.3757
4500	0.2500	1.5907	0.3333
5000	0.2500	1.4406	0.3029
5500	0.2500	1.3039	0.2760
6000	0.2500	1.1905	0.2543
6500	0.2500	1.0942	0.2362
7000	0.2500	1.0110	0.2208
7500	0.2500	0.9415	0.2081
8000	0.2500	0.8789	0.1968
8500	0.2504	0.8183	0.1860
9000	1.5000	0.8094	0.1720
9500	1.5000	0.7929	0.1641
10000	1.5000	0.7754	0.1558
10500	1.5000	0.7582	0.1476
11000	1.5000	0.7437	0.1408
11500	1.5000	0.7284	0.1336
12000	1.5000	0.7178	0.1286

With Floor Foam

Vehicle Mass (kg)	EA Stiffness	Cushion Stiffness	Floorpad Stiffness	Maximum Injury Ratio
2000	0.2500	4.0000	0.1000	0.8219
2500	0.2500	2.2457	0.1000	0.6125
3000	0.2500	1.6494	0.7522	0.4655
3500	0.2500	1.4056	1.0632	0.3783
4000	0.2500	1.2530	1.2460	0.3203
4500	0.2500	1.1080	1.3507	0.2666
5000	0.2500	1.0172	1.4267	0.2351
5500	0.2500	0.9392	1.4854	0.2099
6000	0.2500	0.8702	1.5704	0.1892
6500	0.2500	0.8120	1.8208	0.1731
7000	0.2500	0.7603	1.8867	0.1598
7500	0.2500	0.7166	1.9425	0.1491
8000	0.2500	0.6736	1.9975	0.1393
8500	0.2500	0.6410	2.0391	0.1323
9000	0.2500	0.6042	2.0860	0.1247
9500	0.2500	0.5777	2.1199	0.1195
10000	0.2500	0.5449	2.1619	0.1134
10500	0.2500	0.5286	2.2053	0.1104
11000	0.2500	0.5036	2.2145	0.1060
11500	0.2500	0.4804	2.2441	0.1022
12000	0.2500	0.4588	2.2716	0.0986

Formulation 2 Data

Without Floor Foam

Vehicle Mass (kg)	EA Stiffness	Cushion Stiffness	Probability of Failure
2000	1.5	2.0	4.60E-01
2500	1.5	2.0	2.45E-01
3000	1.5	2.0	9.93E-02
3500	1.5	2.0	2.97E-02
4000	1.5	2.0	6.43E-03
4500	1.5	2.0	9.90E-04
5000	1.5	2.0	1.07E-04
5500	1.5	2.0	8.06E-06
6000	1.5	2.0	4.20E-07
6500	1.5	2.0	1.51E-08
7000	1.5	2.0	3.69E-10
7500	1.5	2.0	6.16E-12
8000	1.5	2.0	6.99E-14
8500	1.5	2.0	5.55E-16
9000	1.5	2.0	0.00E+00
9500	1.5	2.0	0.00E+00
10000	1.5	2.0	0.00E+00
10500	1.5	2.0	0.00E+00
11000	1.5	2.0	0.00E+00
11500	1.5	2.0	0.00E+00
12000	1.5	2.0	0.00E+00

a_{peak} = 1756.7 G's

With Floor Foam

Vehicle Mass (kg)	EA Stiffness	Cushion Stiffness	Floorpad Stiffness	Probability of Failure
2000	1.65	4.0	0.10	4.61E-01
2500	1.65	4.0	0.10	2.46E-01
3000	1.65	4.0	0.10	1.00E-01
3500	1.65	4.0	0.10	3.01E-02
4000	1.65	4.0	0.10	6.54E-03
4500	1.65	4.0	0.10	1.01E-03
5000	1.65	4.0	0.10	1.10E-04
5500	1.65	4.0	0.10	8.36E-06
6000	1.65	4.0	0.10	4.40E-07
6500	1.65	4.0	0.10	1.59E-08
7000	1.65	4.0	0.10	3.94E-10
7500	1.65	4.0	0.10	6.66E-12
8000	1.65	4.0	0.10	7.65E-14
8500	1.65	4.0	0.10	5.55E-16
9000	1.65	4.0	0.10	0.00E+00
9500	1.65	4.0	0.10	0.00E+00
10000	1.65	4.0	0.10	0.00E+00
10500	1.65	4.0	0.10	0.00E+00
11000	1.65	4.0	0.10	0.00E+00
11500	1.65	4.0	0.10	0.00E+00
12000	1.65	4.0	0.10	0.00E+00

a_{peak} = 1754.5 G's