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Airbag-Based Crew Impact Attenuation Systems for the Orion CEV

Anonymous MIT Students

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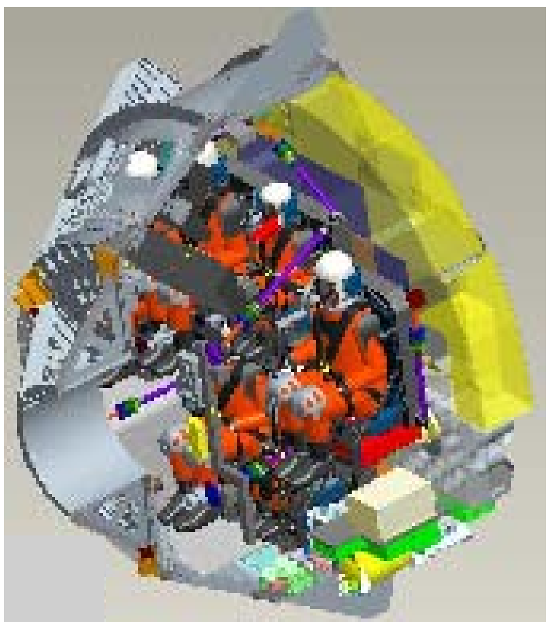
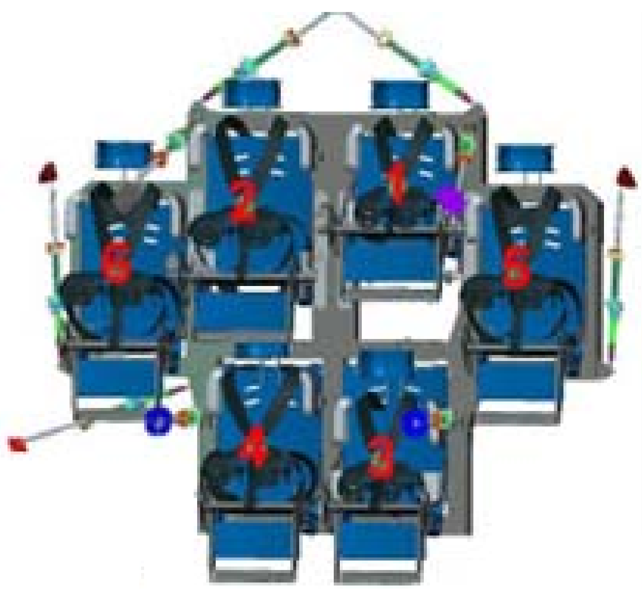
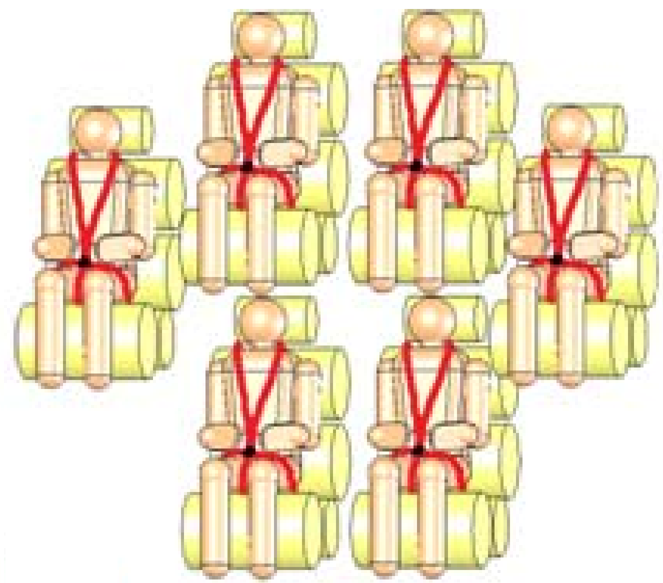
Background and Motivation

- **Orion CEV performance has been continually downgraded over the past two years due to continuing mass constraints**
- **Exploring an alternative airbag-based landing attenuation system concept**

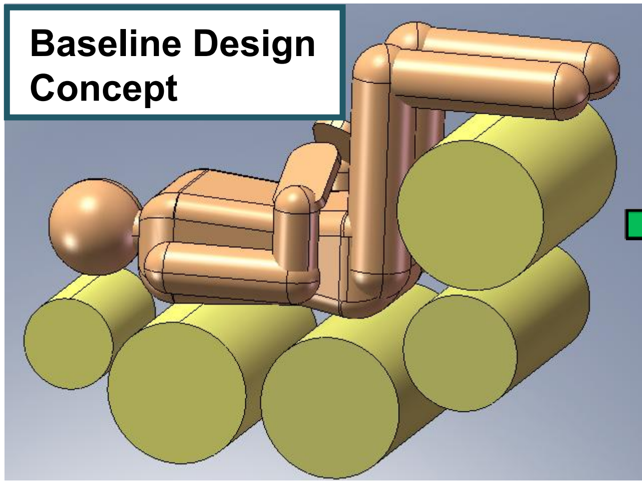


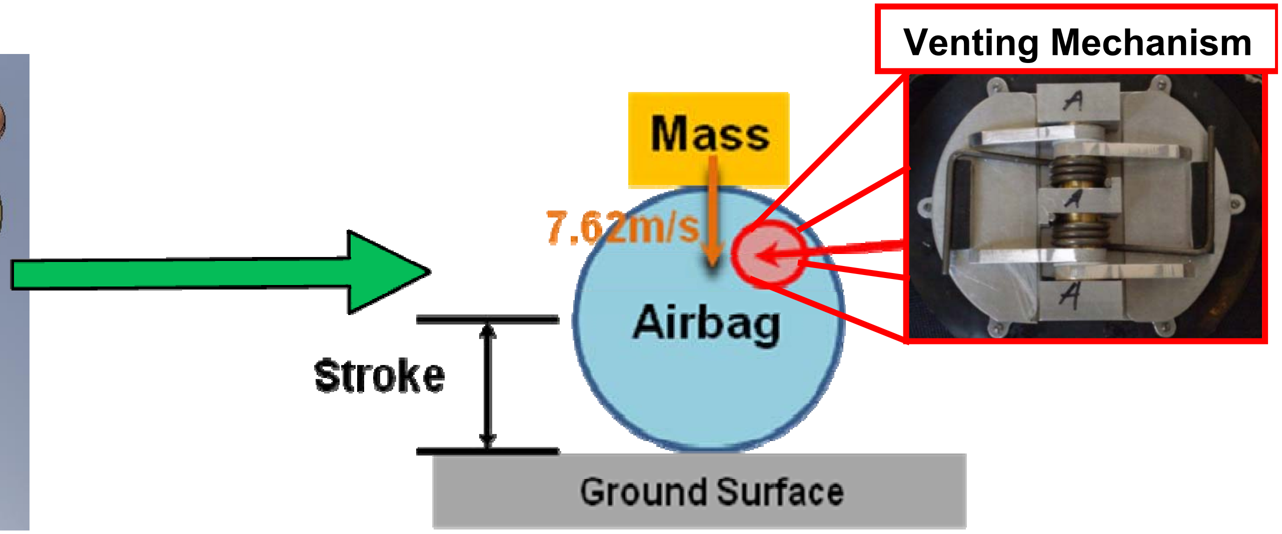




Problem Formulation

Problem Definition:





Project Goals:

Optimize over a single airbag system to:

-Gain insight into the influence of the design variables on overall impact attenuation performance

-Develop a framework for future use with a multi-airbag model

Fixed Parameter	Value
Venting Area	Equiv. 2xØ2" area
Operating Medium (γ)	Air (1.4)
Impact Velocity	7.62m/s
Gravitational Acceleration	9.81m/s²
Atmospheric Pressure	101.325kPa
Loaded Mass	2.5kg

Design Parameters

-Radius [R]

-Length [L]

-Inflation Pressure [P_{bagI}]

-Valve Burst Pressure (measured as pressure in addition to inflation pressure) [ΔP_{burst}]

Formulation

min. β = Injury risk

s.t.

$0.1 \le R \le 0.5$ [m]

$0.3 \le L \le 0.85$ [m]

$P_{bagI} \ge 101325$ [Pa]

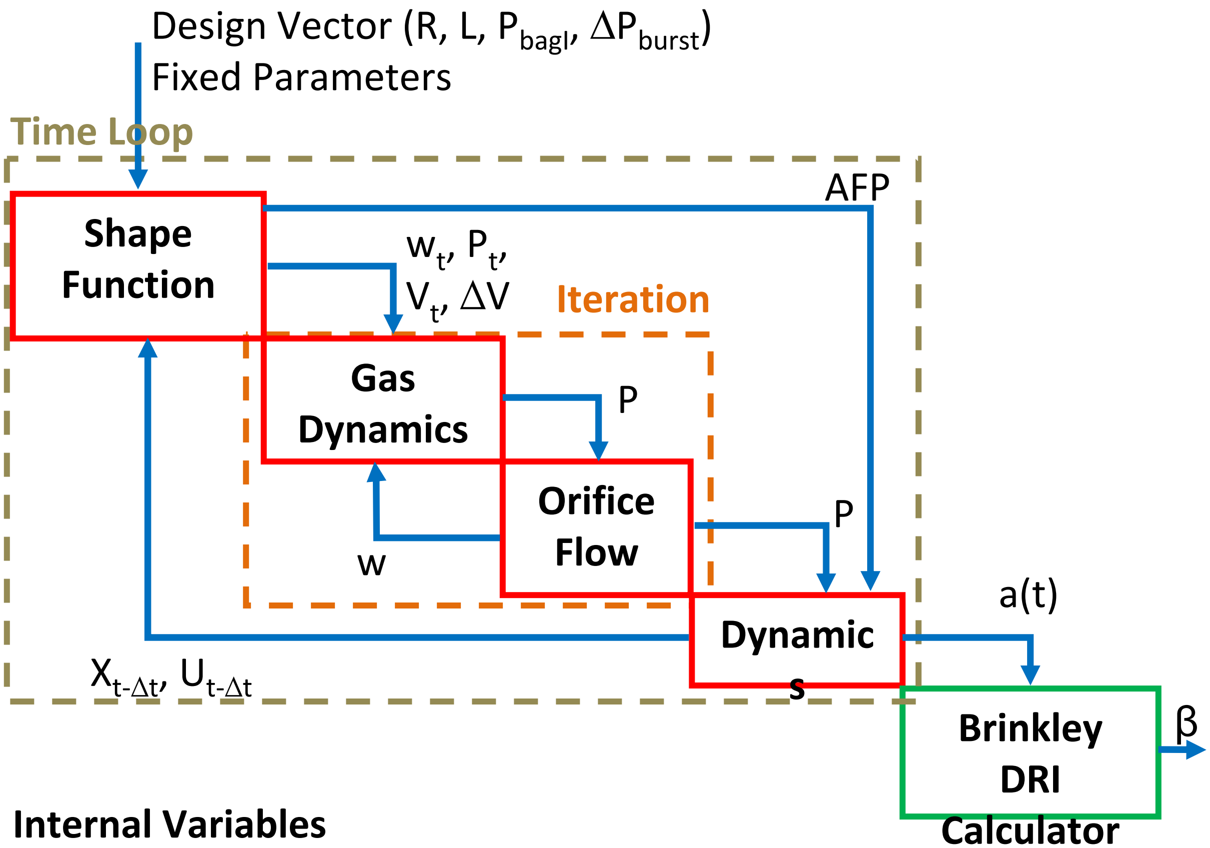
$\Delta P_{burst} \ge 0$ [Pa]

System Modeling

Low fidelity model used

-Based on preliminary design code for Mars Pathfinder airbag system (BAG)

-Approx. 3sec function evaluation time



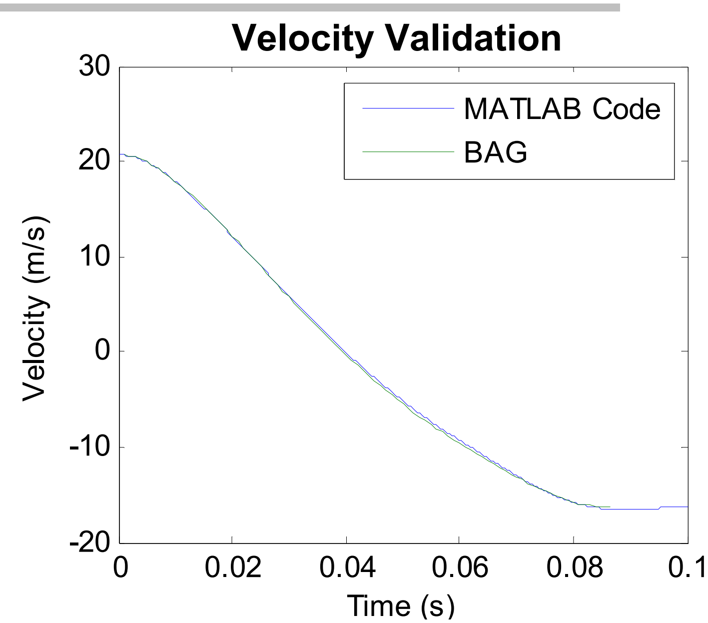
Internal Variables

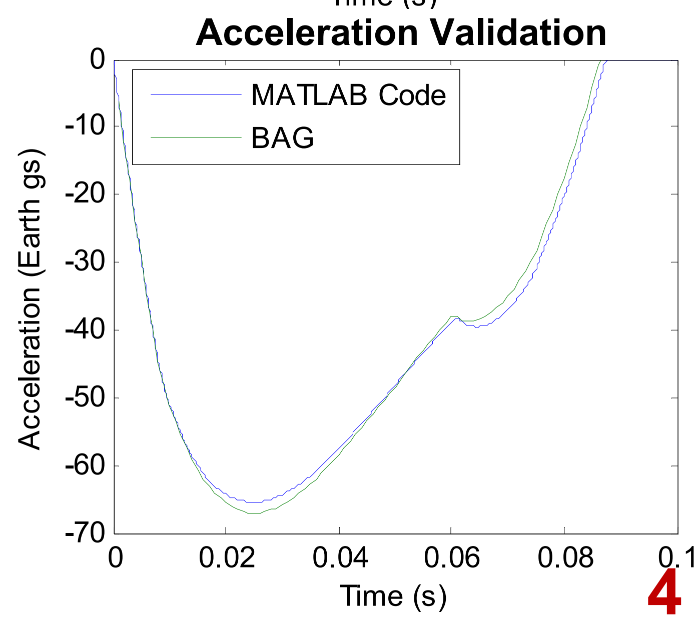
w – mass of gas within airbag

ΔV – change in airbag volume

V – airbag volume

AFP – airbag footprint area





Single Objective Optimization

Design of Experiments: <u>Orthogonal Array</u>
- Efficient and balanced
- Reduced number of experiments required

Factor	Level 1	Level 2	Level 3
Radius (m)	0.2	0.3	0.4
Length (m)	0.3	0.5	0.7
P_{bagI} (atm)	1.0	1.1	1.2
ΔP_{burst} (kPa)	8	12	16

Starting Point

R=0.2m, L=0.3m, P_{bagI}=1.1atm, ΔP_{burst}=8kPa

Sequential Quadratic Programming
- Gradient based method
- No analytical expression for gradient
- Availability of the program 'fmincon.m'

DRI	R	L	Pbag	Pburst
3.220 ↓	0.100 ↓	0.300 ↓	101325 ↓	8000 •

Simulated Annealing
- Heuristic method
- Noisy design space
- Reasonable number of function evaluations

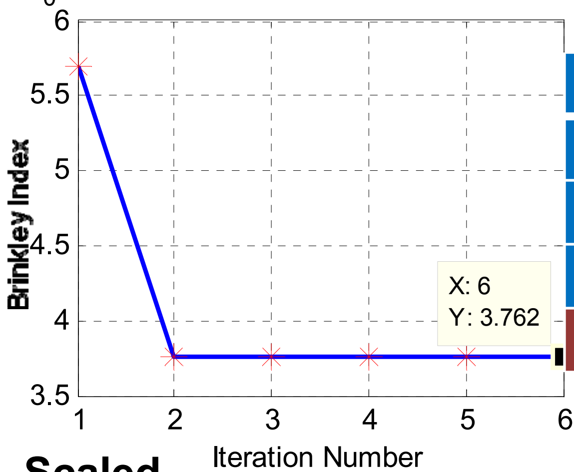
DRI	R	L	Pbag	Pburst
2.890 ↓	0.122	0.311	101820	4088

Single Objective Optimization

Sequential Quadratic Programming

Unscaled

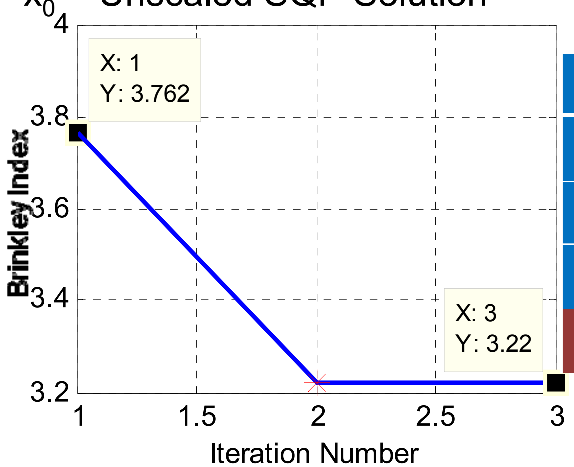
x_0 = DOE Solution



R	0.100 ↓
L	0.300 ↓
P_{bagl}	107000
ΔP_{burst}	8000 ●
DRI	3.762 ↓

Scaled

x_0 = Unscaled SQP Solution

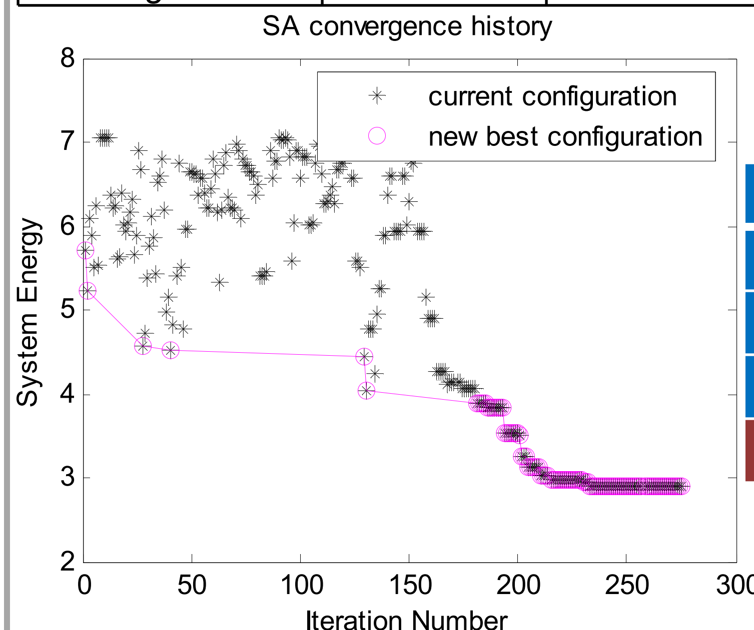


R	0.100 ↓
L	0.300 ↓
P_{bagl}	101325 ↓
ΔP_{burst}	8000 ●
DRI	3.220 ↓

Termination: Change in function value < 10^{-6}

Simulated Annealing

SA Parameters	Values	Rationale
To - Initial system temperature	500	Initial melted state
Cooling Schedule	Exponential	Outperforms linear schedule
Cooling Schedule Factor	0.1	Produced best result when compared to other factors
Number of rearrangements	20	Good sample of design space at each temperature state

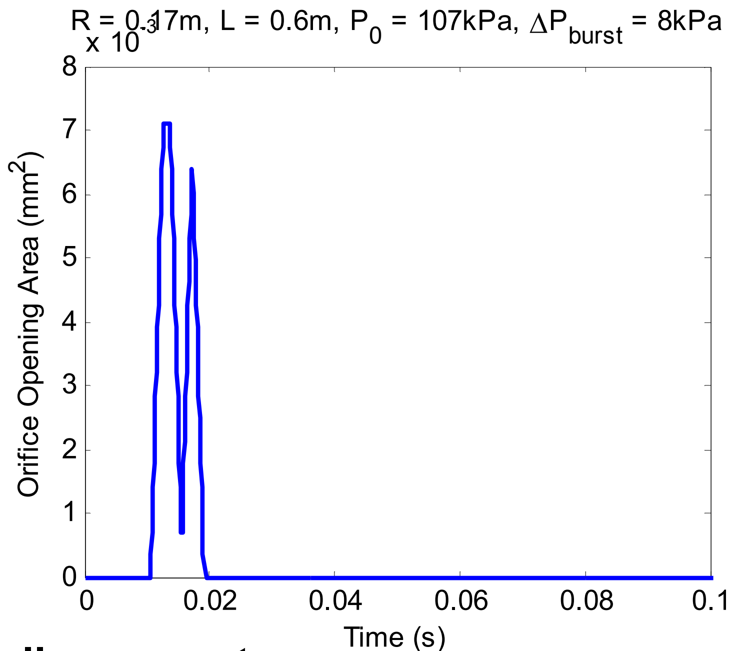


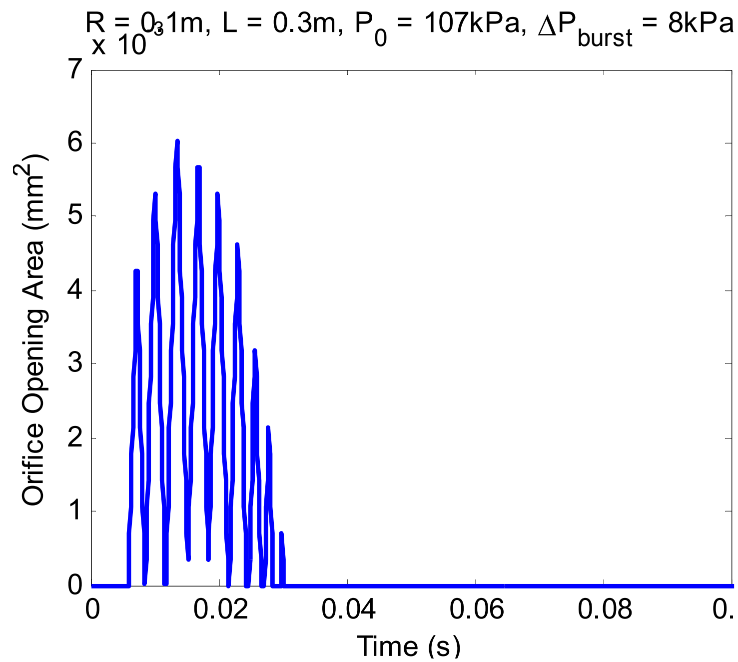
R	0.122
L	0.311
P_{bagl}	101820
ΔP_{burst}	4088
DRI	2.890 ↓

Termination:
Number of consecutive temperatures at which the new configuration is not accepted ≥ 5

Solution Interrogation

– **Why does the optimizer prefer smaller geometries?**





– **Smaller geometry**

→ **Higher pressure maintained over a longer period of time**

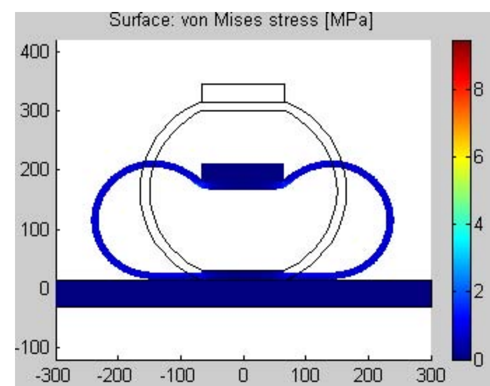
→ **Pressure relief valve open for a longer period of time**

→ **More gas (energy) vented from the system**

→ **Better impact attenuation**

– **Lower limit of geometry occurs just before bottoming-out occurs**

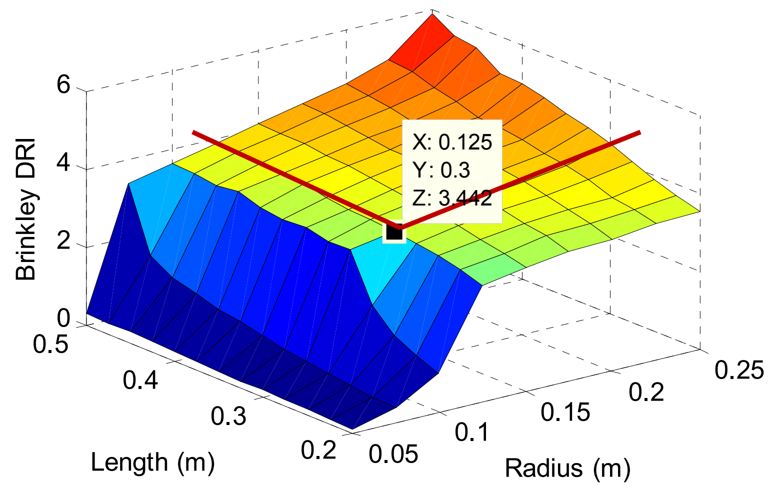
– **Accuracy of the prediction of this point is directly influenced by the airbag shape function**



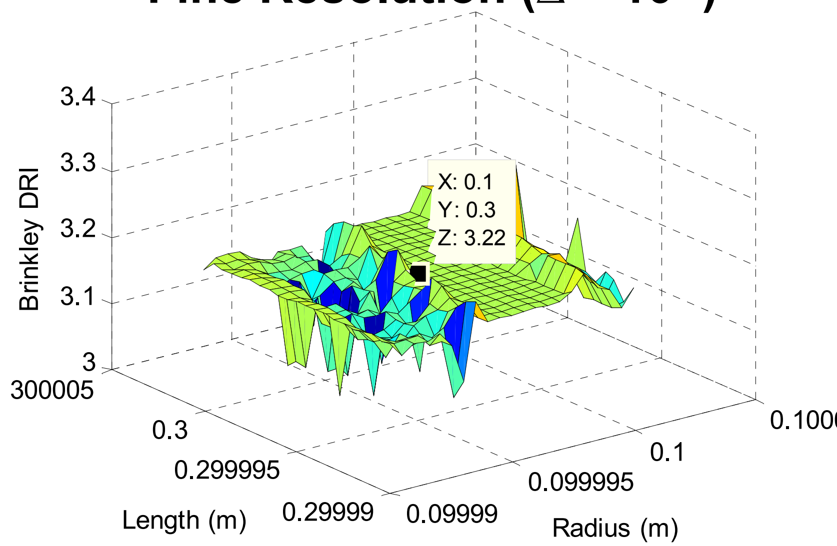
Solution Interrogation

– **Why does the improved SA solution not hit the geometric lower bounds?**

Coarse Resolution (Δ = 0.025)



Fine Resolution (Δ = 10^{-6})



– **SQP stepped over the low amplitude high frequency noise**

– **The stochastic nature of SA allowed it to find better solutions "amongst the noise"**

– **Noise is an artifact of the calculation of the Brinkley Index**

  – **Looping through time to obtain a Brinkley DRI time history and obtaining the maximum value from this**

– **Noise affects how the sensitivity analysis is performed**

  – **Results are dependent on how much noise is captured by choice of step size**

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Sensitivity Analysis

- Performed on the solution obtained from SQP
  - Explored only dJ/dx
  - Did not explore dx/dp or dJ/dp
    - Lower bounds are active
    - Currently not confident in the physical correctness of these lower bound values

- Nondimensionalized sensitivities in objective with respect to design variables:

Sensitivity	Step Size	Value
dJ/dR	10^{-3}	0.9863
dJ/dL	10^{-3}	1.7877
dJ/dP_{bagl}	10^{-3}	1.2892
dJ/dP_{burst}	10^{-3}	0

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Multi-Objective Optimization

Objectives:

– Minimize Brinkley Index

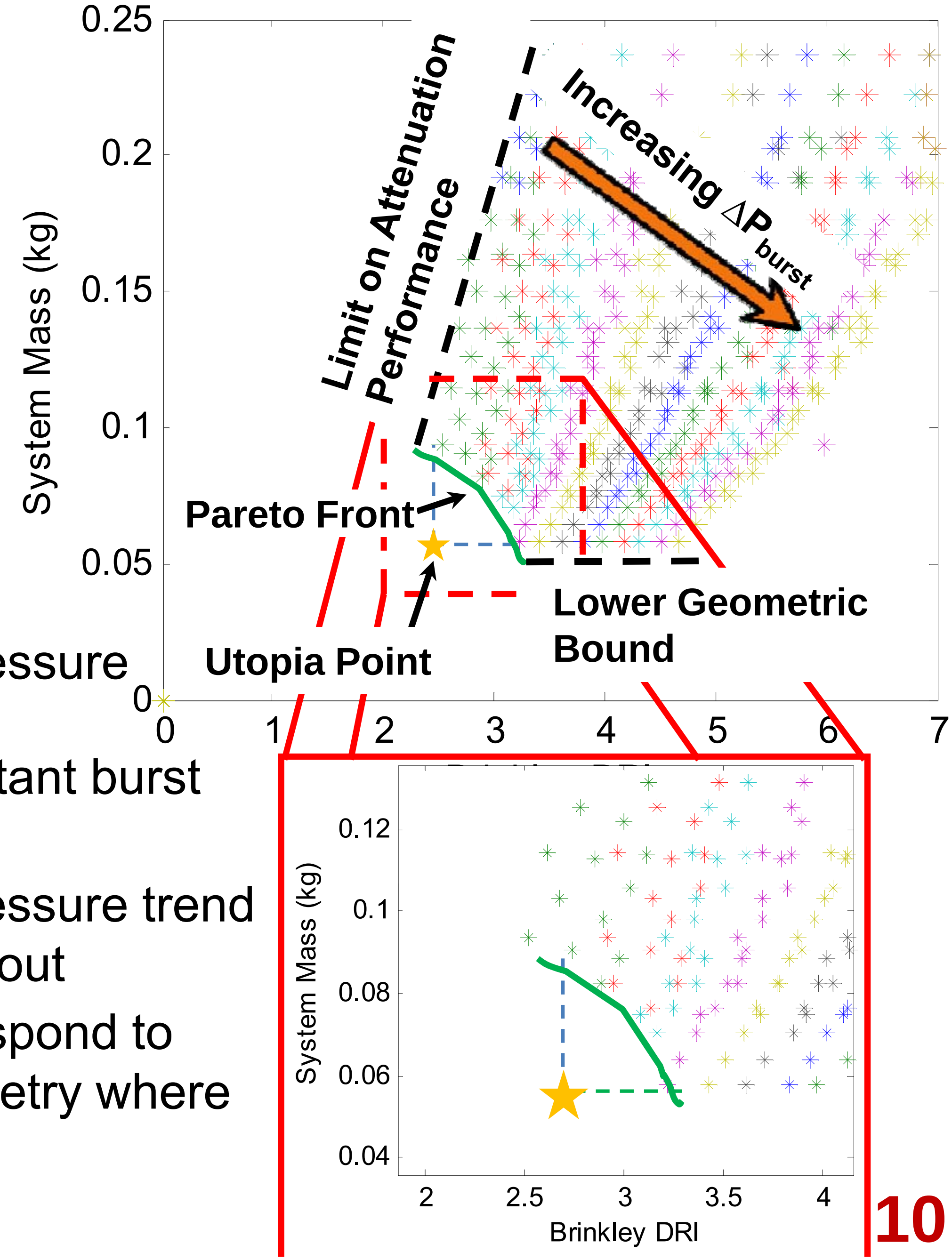
– Minimize system mass (Airbag + Gas)

Method:

- Full factorial expansion over design space
- Originally tried MOGA
    - Took 5.5hrs compared to 30min
    - Clustering of Pareto front experienced

Observations:

- All Pareto points have an initial inflation pressure of 101325Pa
- Objectives are mutually supporting at constant burst pressures
    - Lower bound to each constant burst pressure trend is caused occurs just before bottoming-out
- Change along points on Pareto front correspond to changing burst pressure at minimum geometry where bottoming out does not occur
- Concave Pareto Front



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Summary and Conclusions

Single Objective Optimization

- The choice of valve concept drives the sensitivities observed in the system
  - Drive towards lower geometries originally unexpected for pressure relief valve type venting mechanisms
  - For PRV's, there are two opposing influences on the airbag geometry
    - Smaller geometry → More gas vented
    - Larger geometry → More stroke for impact attenuation
  - The accuracy of this point is driven by the accuracy of the airbag shape function (change in geometry of the airbag as it strokes)
- The choice of step size drives the interpretation of the observed sensitivity when working with a noisy design space

Multi Objective Optimization

- Valve burst pressure drives location of designs along the Pareto front (at atmospheric inflation pressure and minimum geometry such that bottoming-out does not occur)
- Mutually supporting objectives at constant burst pressures drive a concave Pareto front

Thank You

End of Presentation

Backup slides

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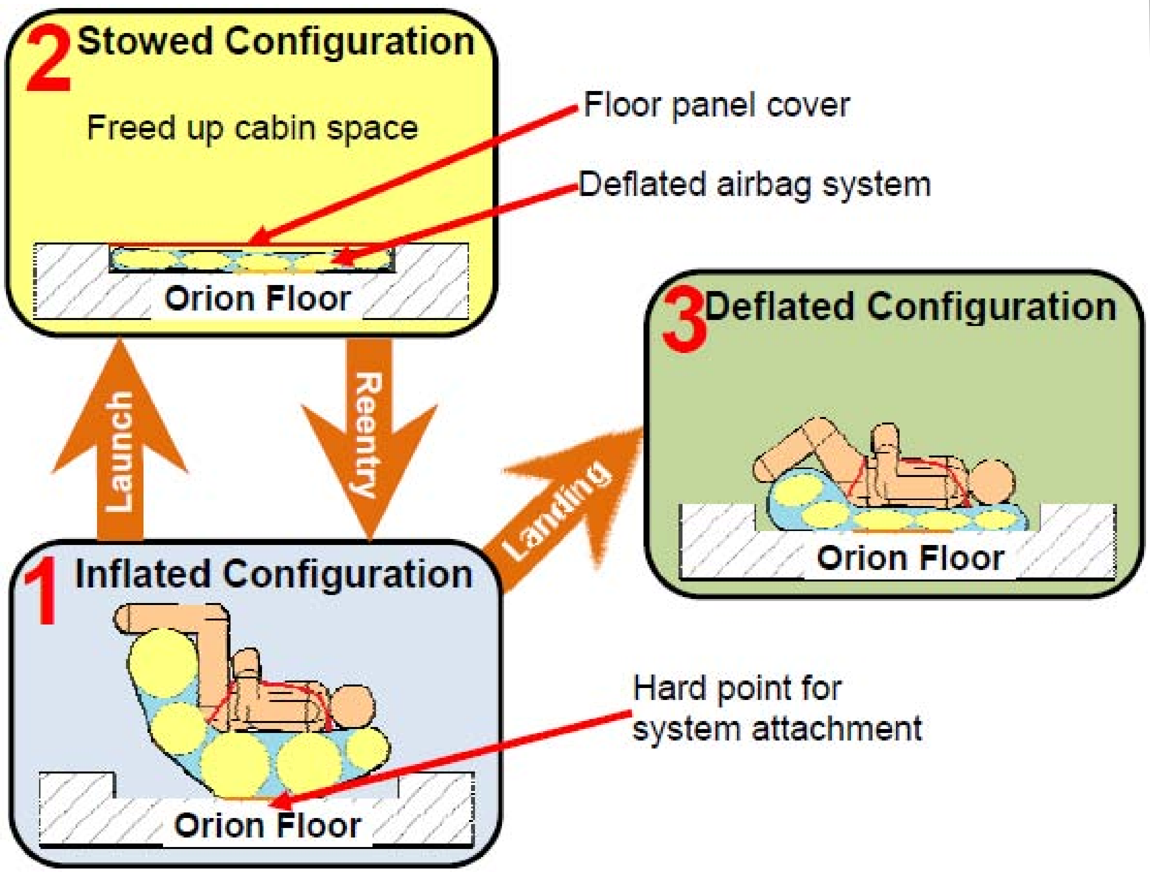
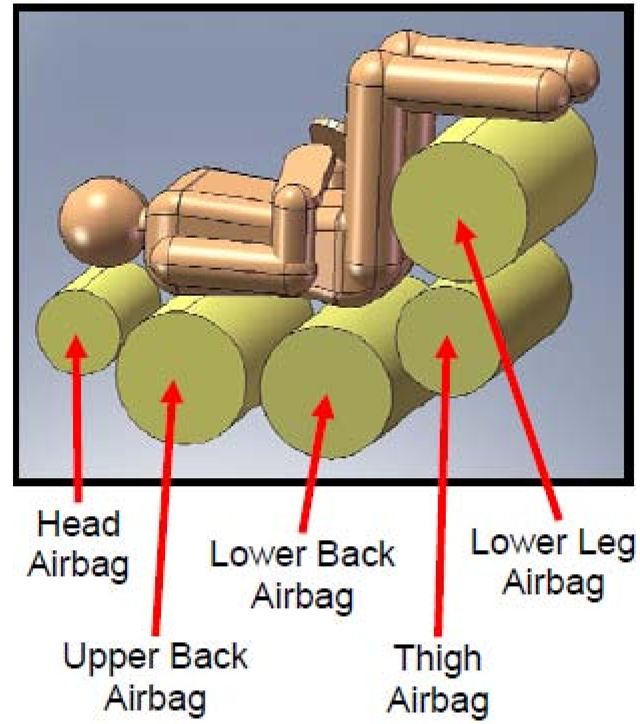
System Concept

Concept of Operations



Baseline Configuration



- **Configuration chosen to attenuate impact loads at key regions within the body**
- **Cylindrical bags chosen for manufacturability**
- **Each bag to consist of venting mechanisms for gas expulsion**

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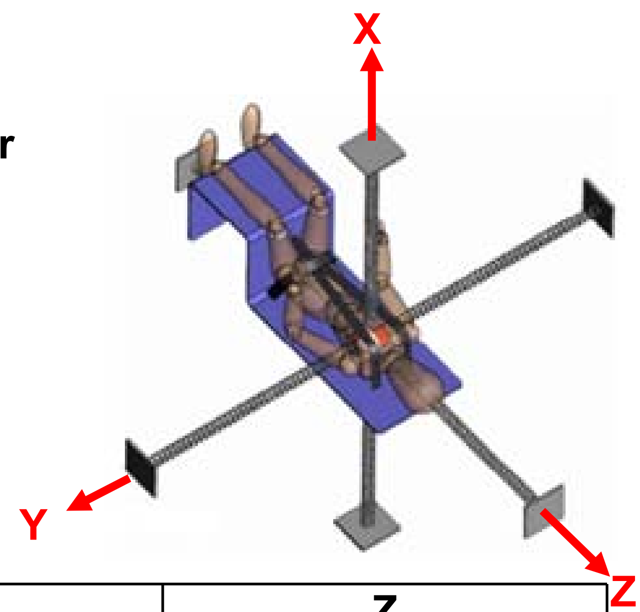
Brinkley Model

- **Metric used to gauge the risk of injury to an occupant in an accelerating frame of reference**
- **Based on approximating the human as a spring-mass-damper system:**

$$\ddot{x}(t) + 2\xi\omega_n \dot{x}(t) + \omega_n^2 x(t) = A(t)$$

  - **Brinkley Direct Response Index is obtained from:**

$$DR = \omega_n^2 x(t) / g$$



- **Risk of injury is measured by comparison with predefined Brinkley Limits, with a lower Brinkley Number corresponding to a lower risk of injury:**

	X		Y		Z	
Direct Response Level	**$DR_X < 0$**	**$DR_X > 0$**	**$DR_Y < 0$**	**$DR_Y > 0$**	**$DR_Z < 0$**	**$DR_Z > 0$**
Very Low (Nominal)	-22.4	31	-11.8	11.8	-11	13.1
Low (Off-Nominal)	-28	35	-14	14	-13.4	15.2
Moderate	-35	40	-17	17	-16.5	18
High Risk	-46	46	-22	22	-20.4	22.4

These values are used to calculate the β-Number, which gives an overall indication of the risk to injury during a drop.
β < 1 indicates that the Brinkley criteria for the inputted level of injury risk has been satisfied

$$\beta = \sqrt{\left(\frac{DR_x(t)}{DR_x^{\lim}}\right)^2 + \left(\frac{DR_x(t)}{DR_x^{\lim}}\right)^2 + \left(\frac{DR_x(t)}{DR_x^{\lim}}\right)^2}$$

Multi-Objective Optimization

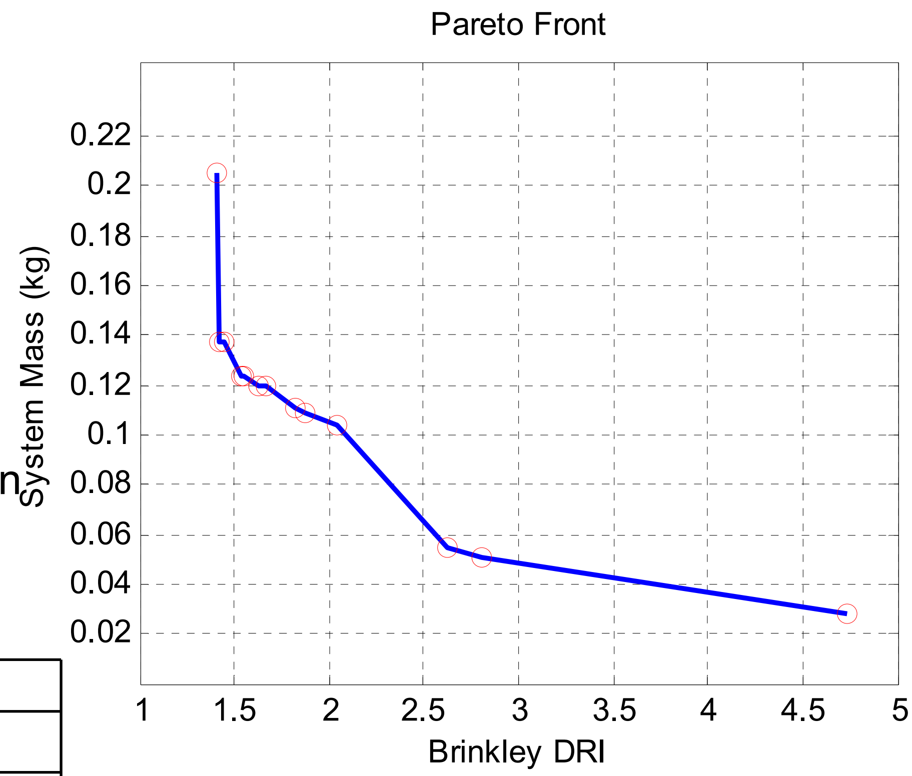
Objectives:

– Minimize Brinkley Index

– Minimize system mass (Airbag + Initial Internal Gas)

Method:

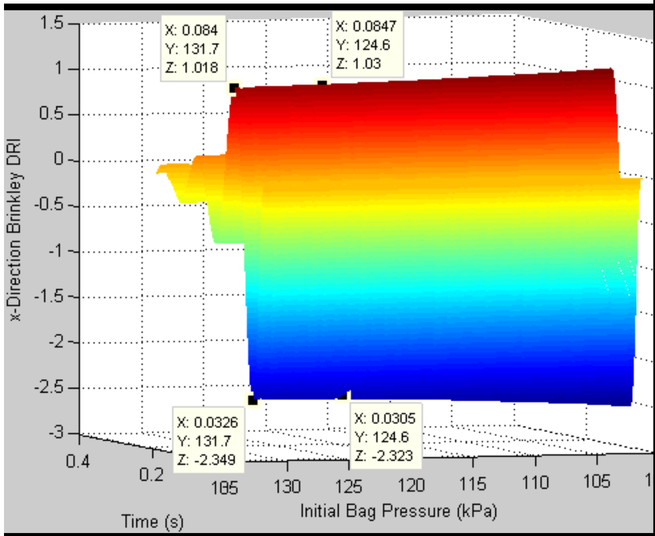
- Multi-Objective Genetic Algorithm (MATLAB gamultiobj.m)
  - Can handle non-convex regions
  - Population approach can lead to savings in computation time
  - Ease and speed of implementation



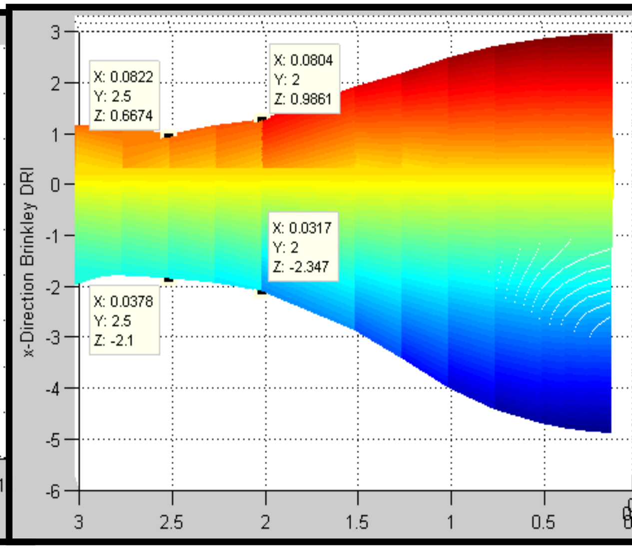
Population Size	60
Population Encoding	Real Numbered Values
Selection	Two player tournament scheme. Rankings based on fitness score.
Insertion	1 member elitist scheme
Crossover Fraction	65%
Crossover Scheme	Splices the parents into two segments and combines them to produce a child

Baseline Airbag Venting Parameter Definition - Results

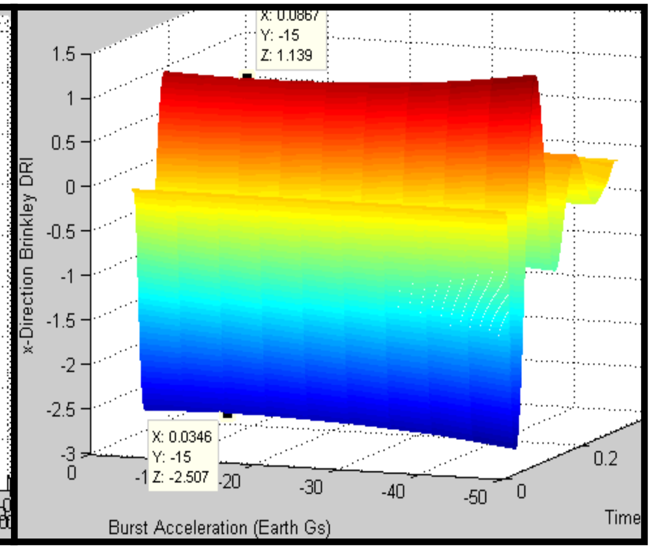
Initial Inflation Pressure



Orifice Diameter



Burst Acceleration



Summary & Conclusions:

•For a fixed geometry, external orifice area has the most influence on the overall performance of the airbag system

•Burst acceleration is the next most influential parameter, but its influence is far overshadowed by that of the external orifice area

•The system performance is essentially insensitive to the initial airbag pressure (over the low pressure range investigated)

Baseline Parameter Values

Parameter	Value
Test Mass	5 lbs (2.27kg)
Radius	110mm
Length	350mm
Total Vent Orifice Area	2 x Ø(2-2.5") holes
Initial Airbag Pressure	125kPa = 1.23atm
Burst Acceleration	-15G's
Corresponding Burst Pressure	Approx. 130kPa (4psig)

Note:

•Initial Airbag Pressure has since been updated based on using a pressure relief valve, rather than a burst disk

Generation 2 System Concept