Identifying a Minimal Set of Significant Characteristics from Functional Responses in Engineering Design: A Case Study

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Motivation

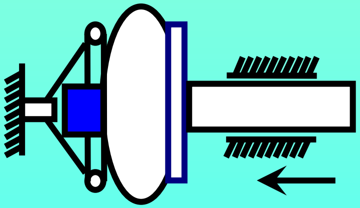
The driving force behind this project was to enhance the ability to make ***good engineering decisions*** in a ***cost efficient manner.***

Project Overview

1

Background

- New energy based test proposed for testing air bags at component level early in product development cycle
- Need to understand how to interpret the results:
  - determine key statistics to predict crash test performance



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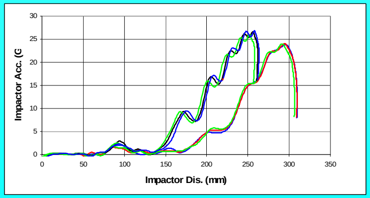
Issue

Data from test is a functional response: Acceleration versus Displacement

- Engineers' initial assumptions were max acceleration (max "g") and max displacement. This needed to be proved and correlated, or better statistics developed.



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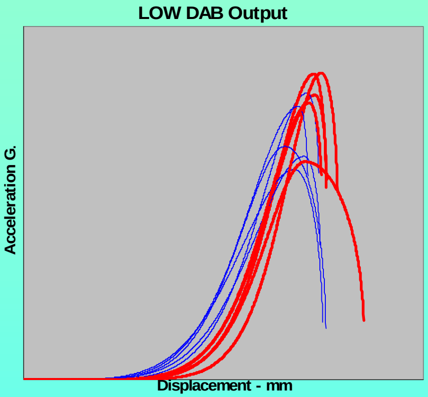
Optimize

- Tested both production designs and prototypes that had required redesign (per crash test results):
  - Blue lines: production designs
  - Red lines: prototypes which required redesign
- Developed fitting and analysis method that resulted in a minimal set of characteristics that separated the production designs from the ones that required redesign



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Verify

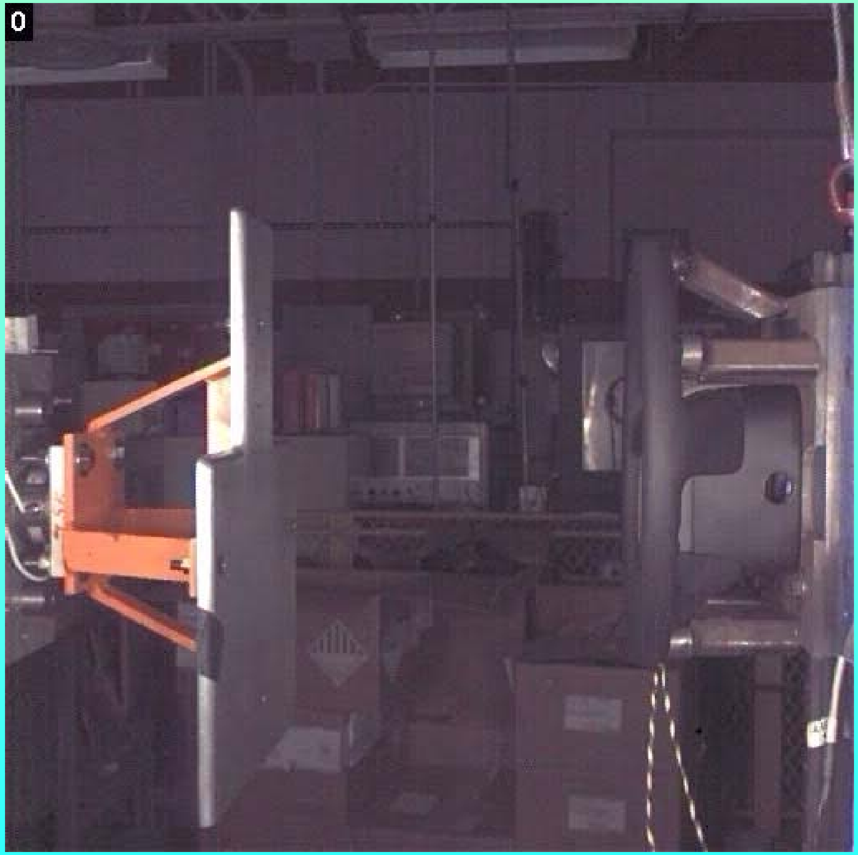
The first vehicle program that used the new test and changed design based on its results was successfully validated with crash testing.

Business Drivers for New Test and Analysis Method

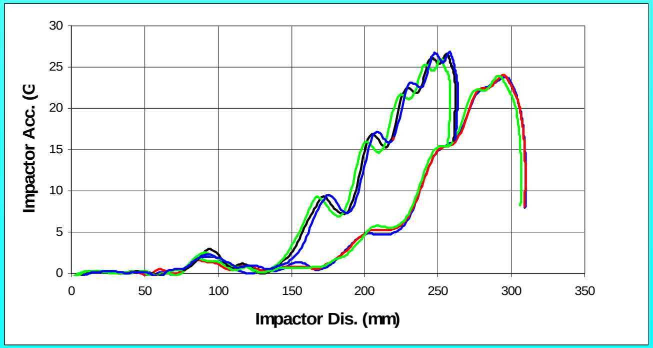
- New air bag technology had changed the relationship between existing component level tests and crash test results.
- Full vehicle barrier crash tests and crash test (sled) simulations are resource intensive with final development tests occurring later in vehicle program timing.
- Unexpected test results may require unplanned additional engineering development resources and unwanted program delays.
- Need module level test that meets following requirements:
  - Predict crash test results independent of air bag technology
  - Able to run early in the vehicle development program.

In other words – looking for *surrogate* data to predict later crash test results.

New Dynamic Air Bag Test



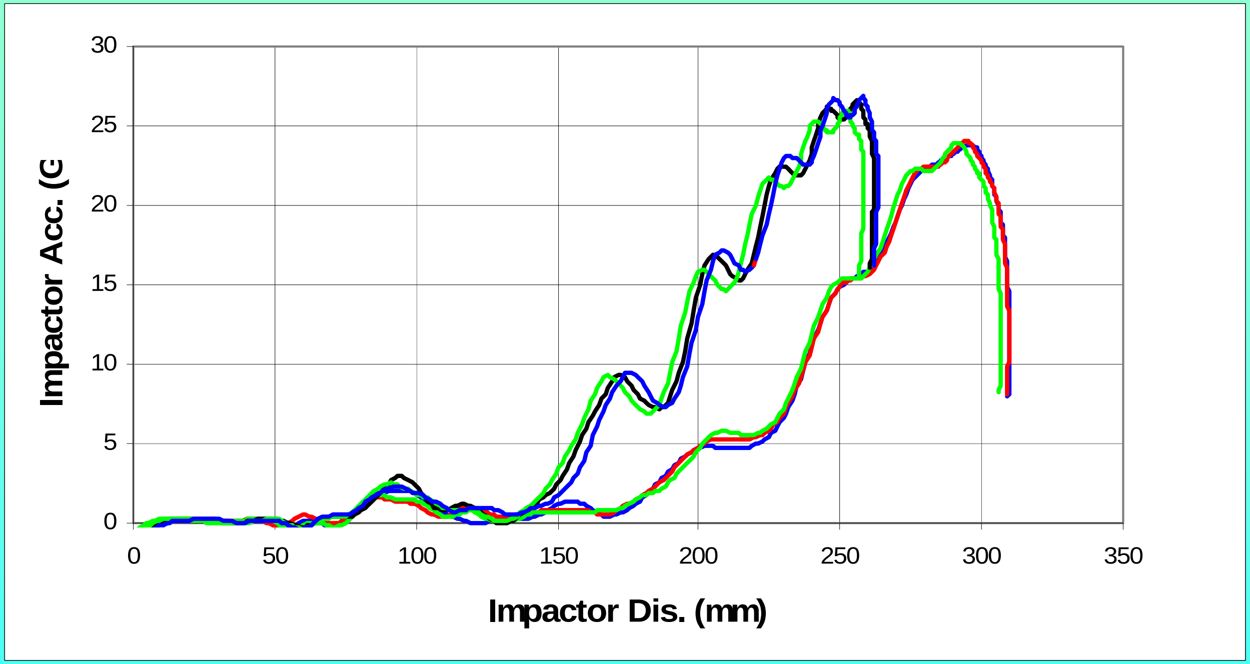
- Mass with approximately human shaped silhouette is accelerated to specified speed
- Air bag triggered at distance that corresponds to the 50% sitting distance from steering wheel
- Acceleration and displacement measured throughout test



Critical Parameters: Engineers' Prediction

- The engineers developing the test were expecting two parameters to be critical in separating designs which meet all requirements from one that require redesign:
  - Maximum acceleration ("Max G")
  - Maximum displacement

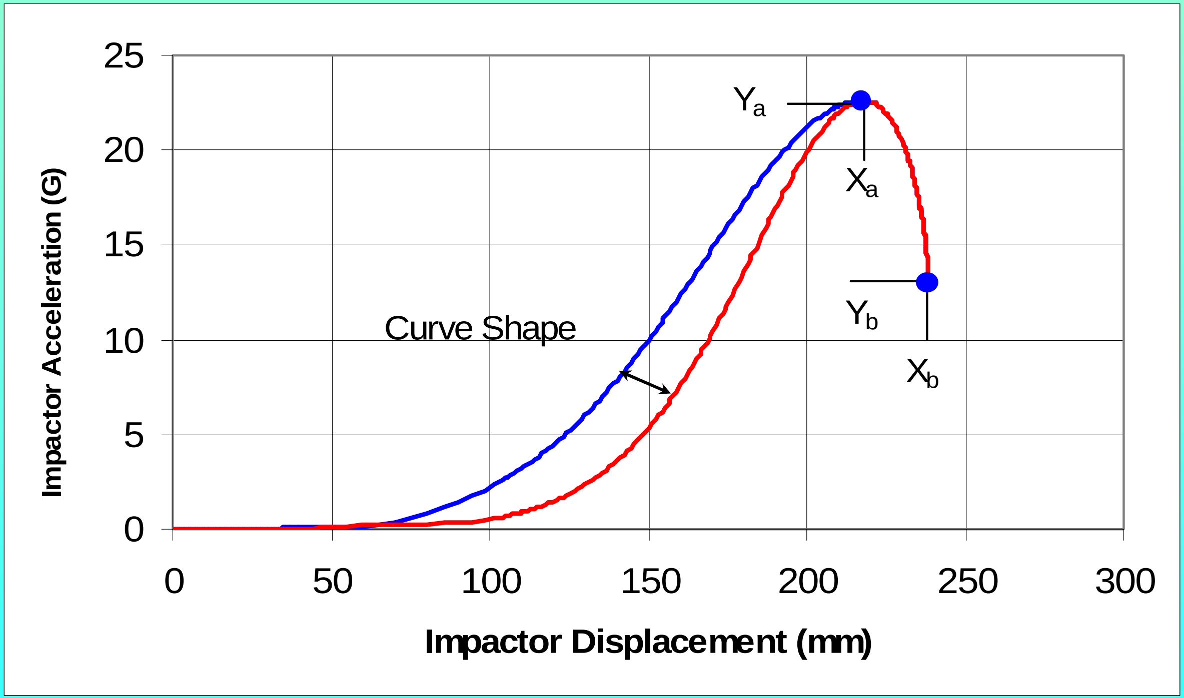
Fitting or Smoothing Data



- The shock waves in the data obscured the basic energy absorption pattern, so smoothing or curve fitting was necessary.

Critical Information for Curve Fitting

- Maximum acceleration (Max “G”) point
  - Max “G” value
  - Displacement at Max “G”
- Maximum displacement
- Shape of curve prior to max “G”



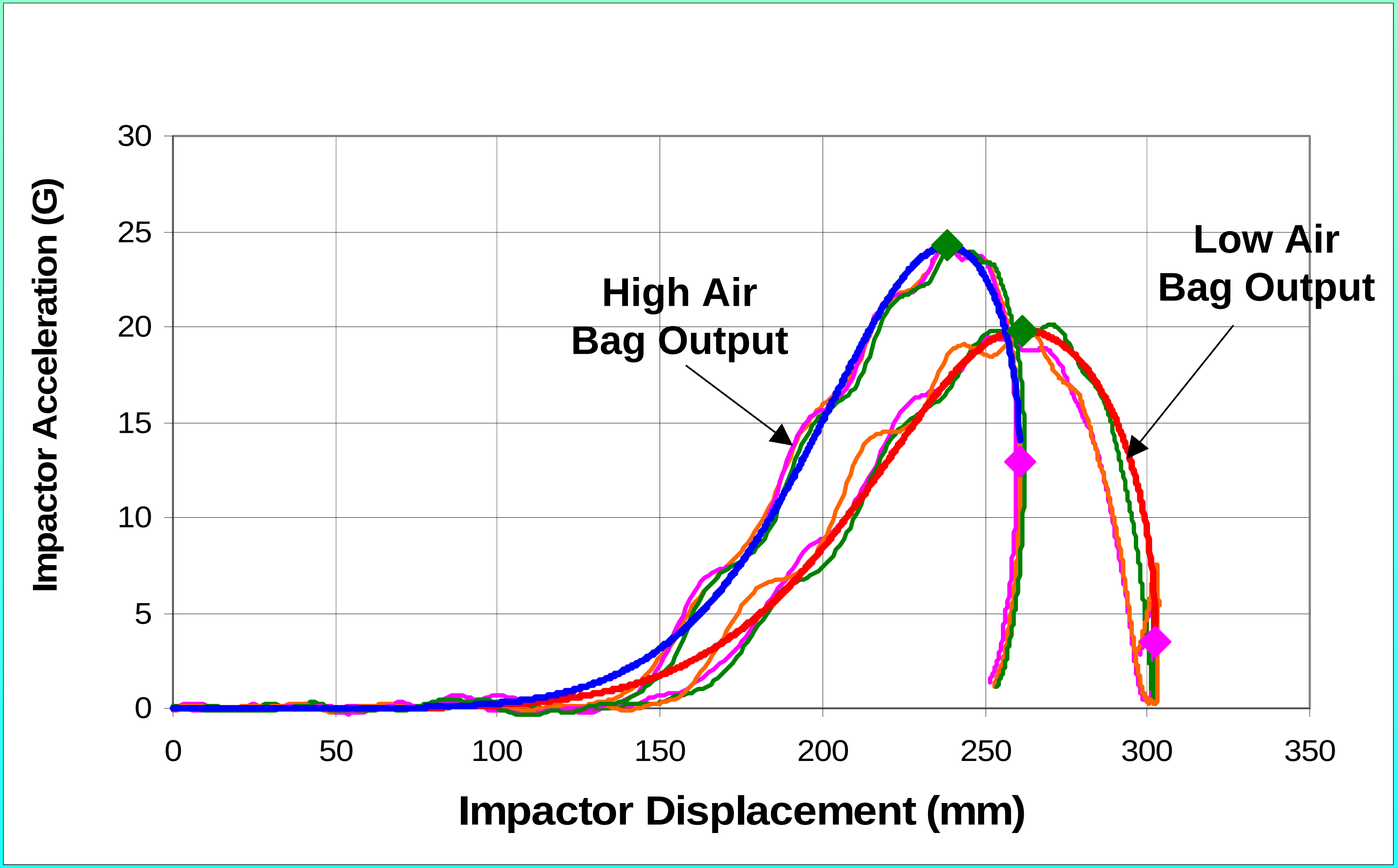
Criteria Considered for Evaluating Methods

- Provide “reasonable” fit - enable solid engineering decisions
- Parameters of fit related to engineering parameters
- Minimal number of parameters in fit
- Engineers (including suppliers) able to perform the fit with software already on their computers

Evaluation of Alternatives

	Fit	Engineering Interpretation of terms	Number of Terms	Soft-ware
Modified Weibull	Fit poor after maximum	missing information	too few	**Excel**
Modified Weibull plus ellipse	**Best Fit**	**good**	**5**	**Excel**
Half Normal plus ellipse	Close	average	**5**	**Excel**
Polynomial	Requires lots of terms	weak	too many	Minitab
MARS	Requires lots of terms	weak	too many	Special
Gamma	------------	*too intractable to estimate*	------------	Special

Sample Fit of Test Data



Modified Weibull Formula: Rescaled to Force Curve Through Maximum Acceleration Point

$$A = k \cdot \left(\frac{\beta}{\alpha}\right) \cdot D^{\beta-1} \cdot \exp\left[-\left(\frac{D}{\alpha}\right)^{\beta}\right]$$

The factor *k* rescales the classic Weibull function so that the area under the curve no longer equals 1, thus enabling forcing the function through the maximum acceleration point.

Where:

A Acceleration

D Displacement

α Weibull Characteristic Life

$$\alpha = D_{AM}\left(\frac{\beta}{\beta-1}\right)^{\left(1/\beta\right)}$$

β Weibull Shape

k Rescaling constant (converts to acceleration units)

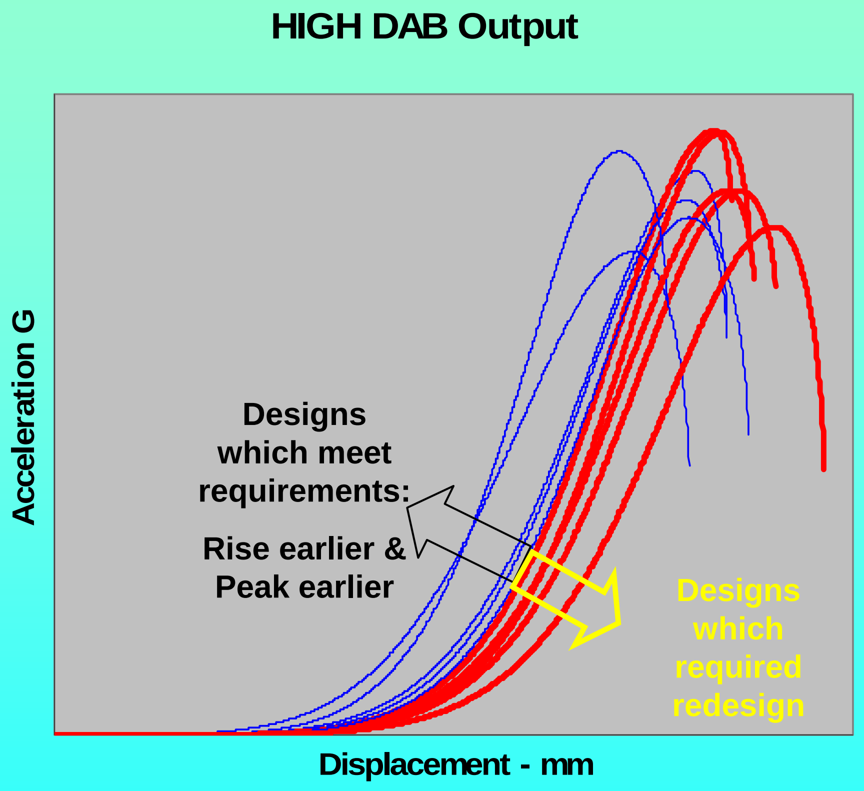
$$k = \frac{A_{\max} D_{AM}}{(\beta-1)e^{\left(\frac{1}{\beta}-1\right)}}$$

Fitting Steps for Modified Weibull with Ellipse

- Determine the average “Max G” point for the multiple runs.
- Fit β by minimizing the sum of squared error term from zero through the “Max G” point.
- Determine the average maximum displacement point for the multiple runs.
- Calculate ellipse portion from the coordinates of the “Max G” point and the maximum displacement point.

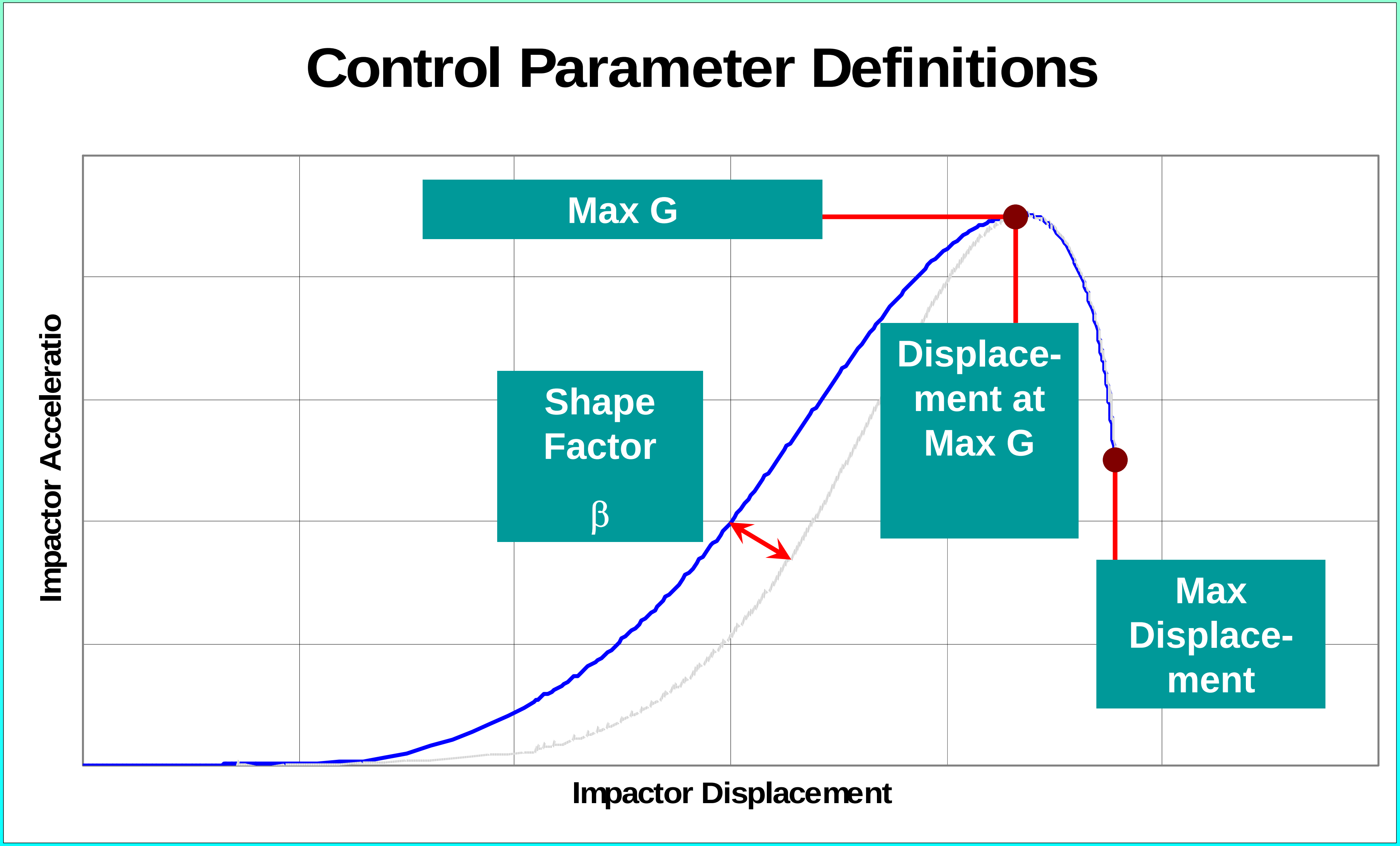
Test Results

- Tested driver air bag modules of both preliminary prototype and production level designs of several vehicle lines.
  - The preliminary prototype designs were ones that required redesign determined by crash test results.
- Test distinguishes between production quality designs and ones that required redesign.
  - Blue lines: production designs which meet all requirements.
  - Red lines: prototype designs which required redesign



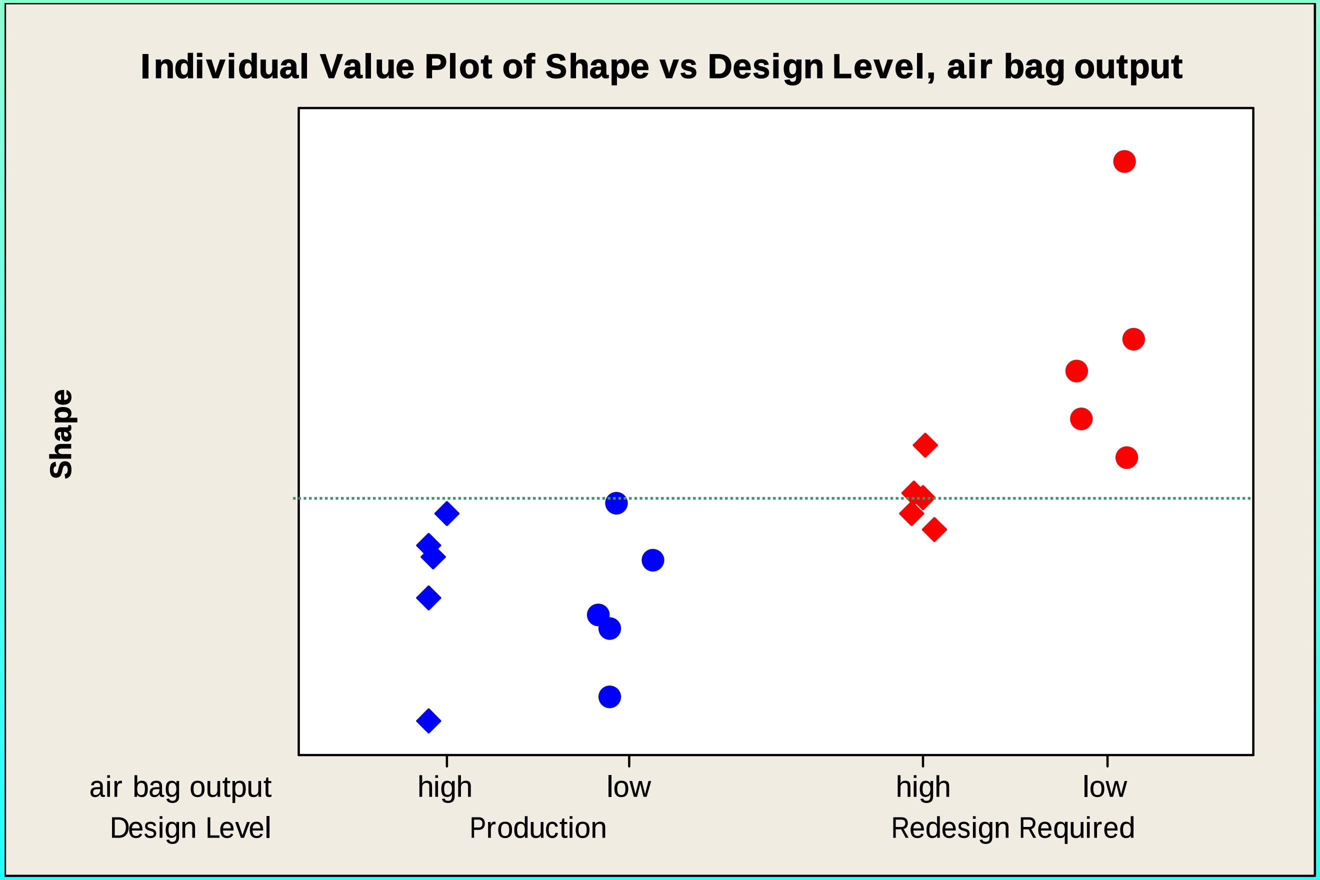
Surprise finding: The displacement of the "Max G" point was more important than the magnitude. The designs which required redesign picked up slower and peaked later. This was true on both high and low output.

Statistics/Parameters that Distinguish Design Levels



Example: Shape factor β versus Barrier Results

- For each parameter, dot plots were examined to see if there were levels that separated acceptable designs from ones that needed redesign.



Ability of Parameters to distinguish between classes

	vehicle	A		B		C		D		E	
	Air Bag Output Level	low	high	low	high	low	high	low	high	low	high
Prototypes: Design Change Required	Max G: $\boldsymbol{A_{MAX}}$	X	X	OK	OK	OK	OK	X	X	OK	OK
	Max Displacement: $\boldsymbol{D_{MAX}}$	X	OK	X	OK	X	OK	X	OK	OK	OK
	Displacement at Max G: $\boldsymbol{D_{AM}}$	X	X	OK	X	X	X	X	X	X	X
	Shape Factor: β	X	OK	X	X	X	X	X	X	X	OK
Production Designs	Max G: $\boldsymbol{A_{MAX}}$	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Max Displacement: $\boldsymbol{D_{MAX}}$	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Displacement at Max G: $\boldsymbol{D_{AM}}$	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	Shape Factor: β	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

The 5th parameter, acceleration at max displacement, does not distinguish the design levels. It is only needed to plot the functions.

While none of these parameters by themselves distinguish the classes of design level, the set does.

Results

- Have parameterized model for fitting the data
  - The set of parameters can distinguish designs that will pass barrier crash tests from ones that need redesign
  - Univariate statistical methods can be applied to the model parameters:
    - DOE's can be run using the parameters as response statistics – enabling future optimization
    - Part to part variation can be quantified

Tips for Determining Engineering Parameters from Surrogate Functional Responses

1. Plot the data – the human eye may pick up patterns from graphs that would not be visible in tables
2. Color code the curves by classifications of results, and overlay the results
3. Build on engineering (or subject matter) knowledge
4. Use data from the full range of ultimate responses in trying to determine the significant parameters (the subject matter experts may have to be educated on this point)

Conclusions

- Traditional statistical fitting methods for Y=f(X) were developed to be able to predict “y” given a new “x” value. They may or may not be useful when Y is an intermediate or surrogate response, and the shape of the function impacts the final results:

  Z=g(Y) where Y=f(X), or Z=g(f(X)) … but … Y=f(X) is being modeled.

- The ability to collapse a function into a minimal set of statistics such that the set of statistics can be used to predict the ultimate results is critical for good engineering decision making.
  – One key is to be able to link the parameters to important engineering (or subject matter) features in the function

- A modification of the Weibull proved useful in modeling THIS application of energy absorption from a trigger point to the point of maximum energy absorption
  – UNKNOWN: Applications in other fields: medical, chemical, other engineering applications

Questions?

Comments?