Industrial Perspective of V&V in Engineering Decisions

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PRESENTATION OUTLINE

I. **Vehicle Development & Math-based Computer Models**

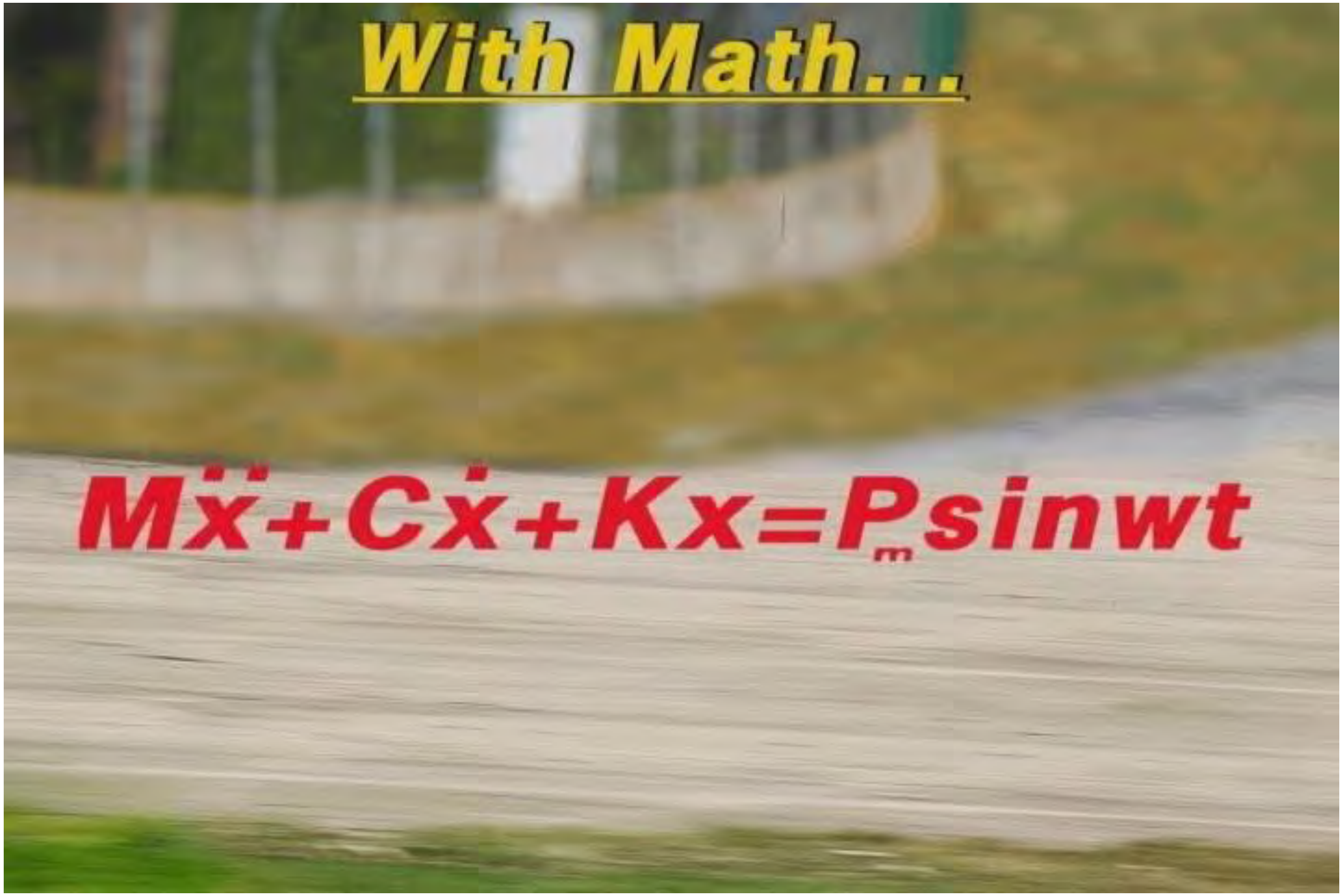
II. Decisions in Product Development

III. Model Verification and Validation

IV. Steps for Validation

V. An Example

VI. The Message

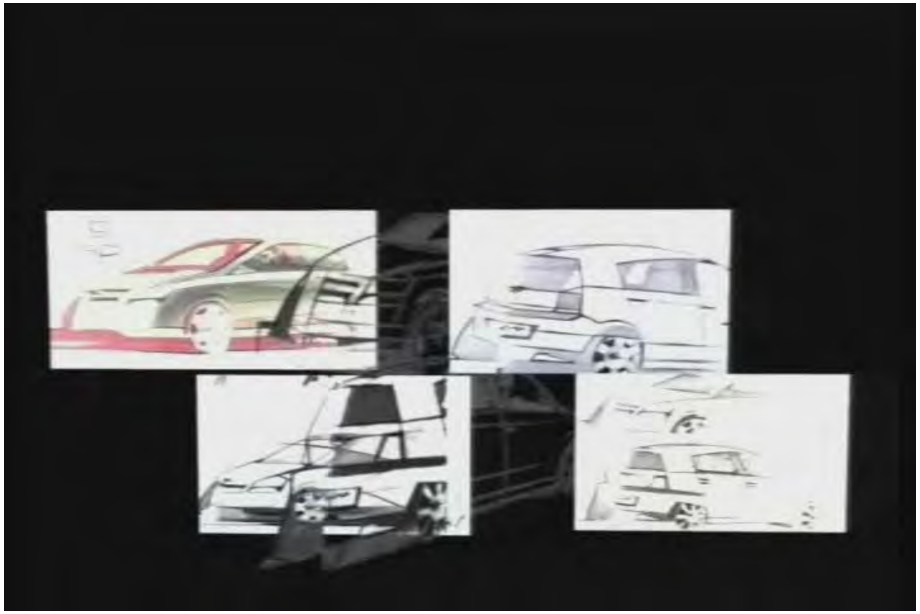


With Math...

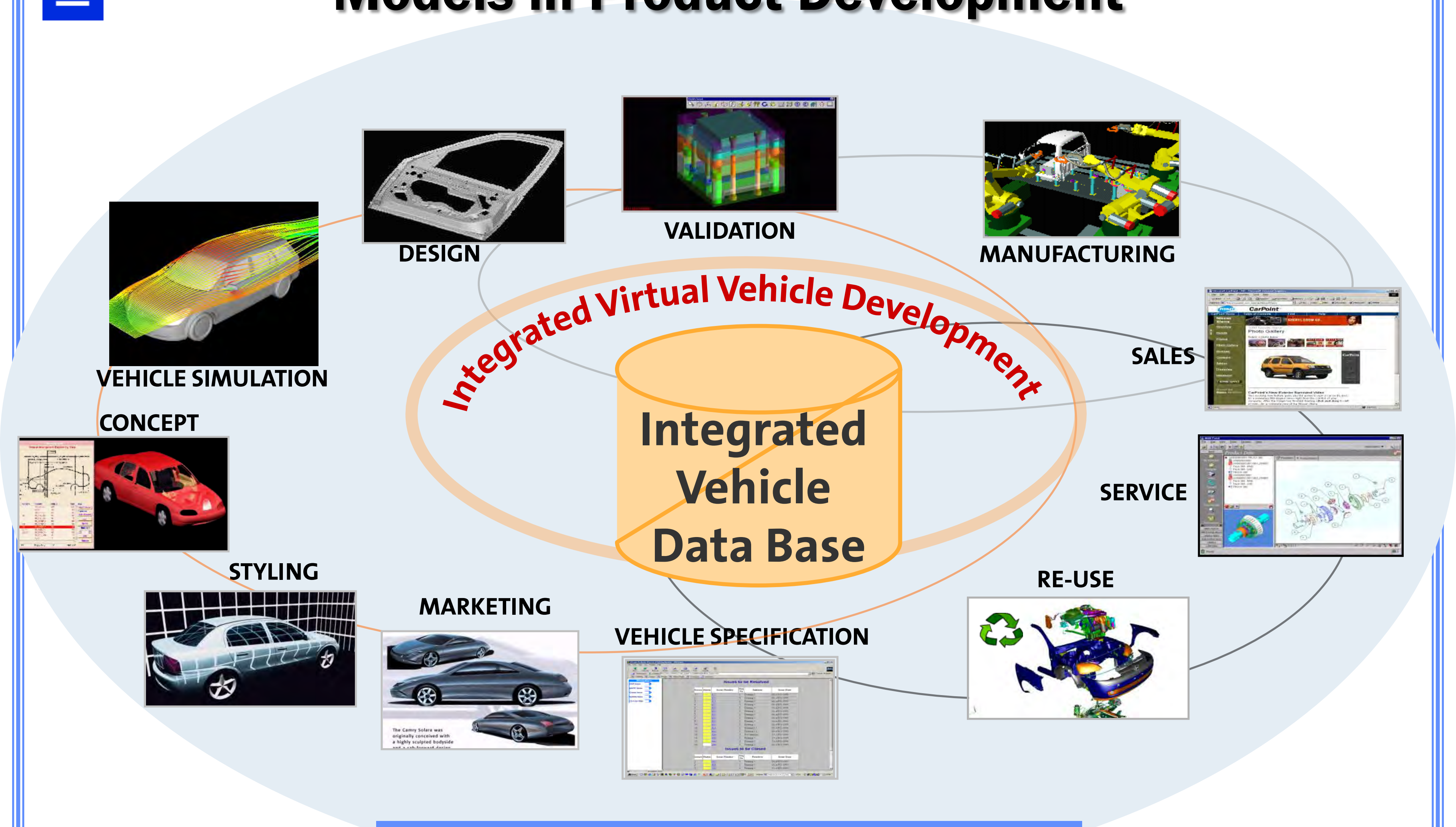
$$M\ddot{x}+C\dot{x}+Kx=P_m\sin wt$$

Why Models in Engineering?

1. **Quality Improvement** – explore more designs, eliminate early physical model uncertainty, explore variation effects.
2. **Time Constraints/Demand** – shorten time from Concept to Showroom
3. **Capital Reduction** – minimal physical costs for iteration, hardware reduction



Models in Product Development



Integrated Virtual Vehicle Development

Integrated Vehicle Data Base

DESIGN

VALIDATION

MANUFACTURING

SALES

SERVICE

RE-USE

VEHICLE SPECIFICATION

MARKETING

STYLING

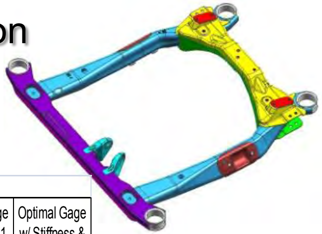
CONCEPT

VEHICLE SIMULATION

Models used to assess many types of performance in the complete vehicle life cycle

Optimization Technique in Automotive Chassis Design

Engine Cradle Gauge Optimization



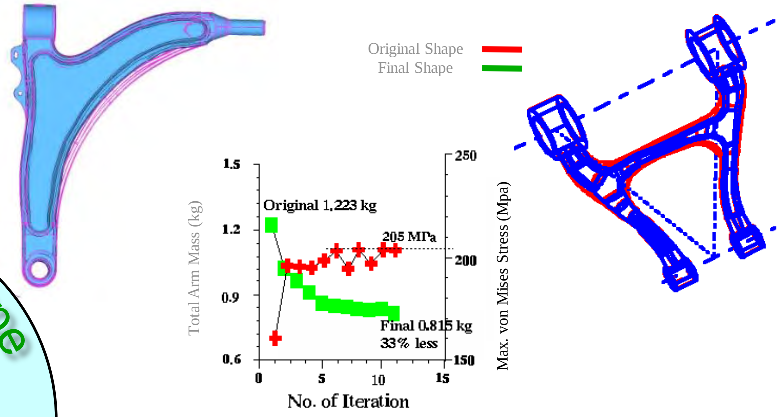
Front Cradle Gage Optimization Summary

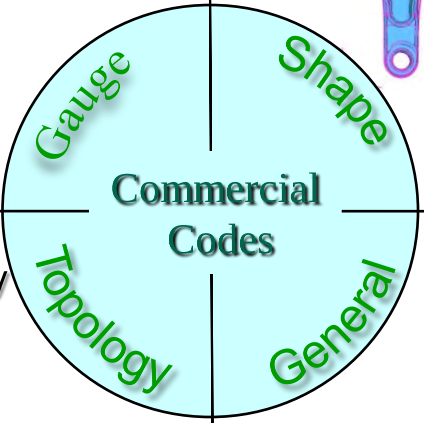
Design Gage ID	Design Variable Label	Part Mass	Lower Limit	Current IVER Design	Upper Limit	Optimal Gage w/ Stiffness Target Only	Optimal Gage w/ G0 Schedule Target Only	Optimal Gage w/ GMN9801 Schedule Target Only	Optimal Gage w/ Stiffness & G0 Schedule Target
		(kg)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	FXMEMB_Up	1.87 (7.6%)	2.0	2.0	2.8	2.0	2.0	2.0	2.0
2	FXMEMB_Lwr	2.06 (8.3%)	2.0	2.0	2.8	2.0	2.1	2.1	2.1
3	RXMEMB_Up	2.79 (11.3%)	2.0	3.0	3.3	3.2	3.0	2.7	3.0
4	RXMEMB_Lwr	2.69 (10.9%)	2.0	3.3	3.3	3.3	3.0	2.7	3.0
5	Rail	10.56 (42.7%)	2.0	2.8	3.0	2.7	2.8	2.6	2.8
6	Frt_Torq_Mnt	0.45 (1.8%)	2.0	2.3	2.8	2.0	2.3	2.1	2.3
7	LCA_Frt_Plate	1.12 (4.5%)	2.0	3.5	4.0	4.0	4.0	4.0	4.0
8	LCA_Rr_Bot	0.27 (1.1%)	2.0	2.0	2.8	2.0	2.0	2.0	2.0
9	StabBart_Brkt	0.55 (2.2%)	2.0	3.5	4.0	2.0	2.3	2.2	2.3
Total Mass		**24.71**		**24.71**		**24.27**	**24.42**	**23.00**	**24.42**
Δ Mass [Opt-Current] (kg)						**-0.44**	**-0.29**	**-1.71**	**-0.29**

Control Arm Shape Optimization

Morph

Geometry based Design Parameterization





Gauge

Shape

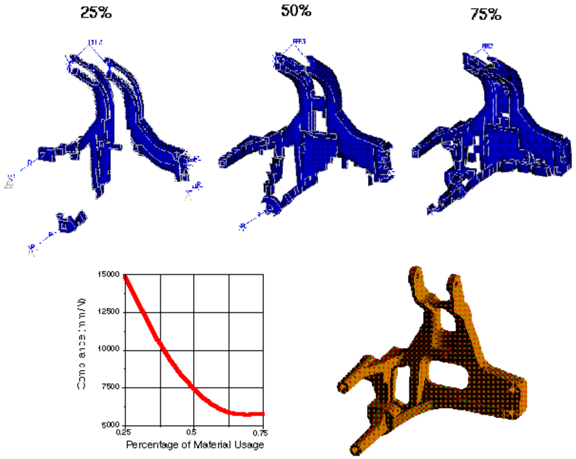
Commercial Codes

Topology

General

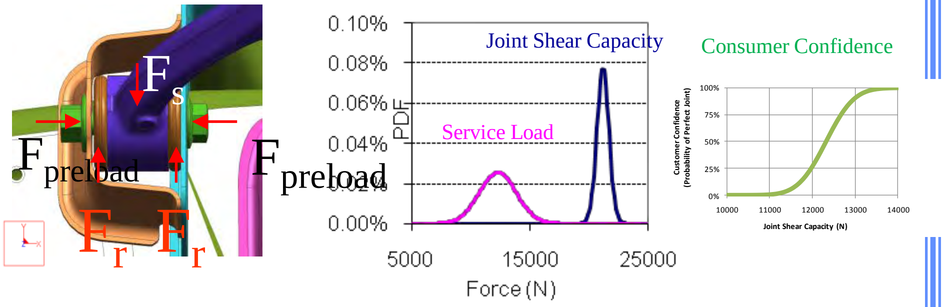
Powertrain Mount Bracket Topology Study

Material Growth Simulation



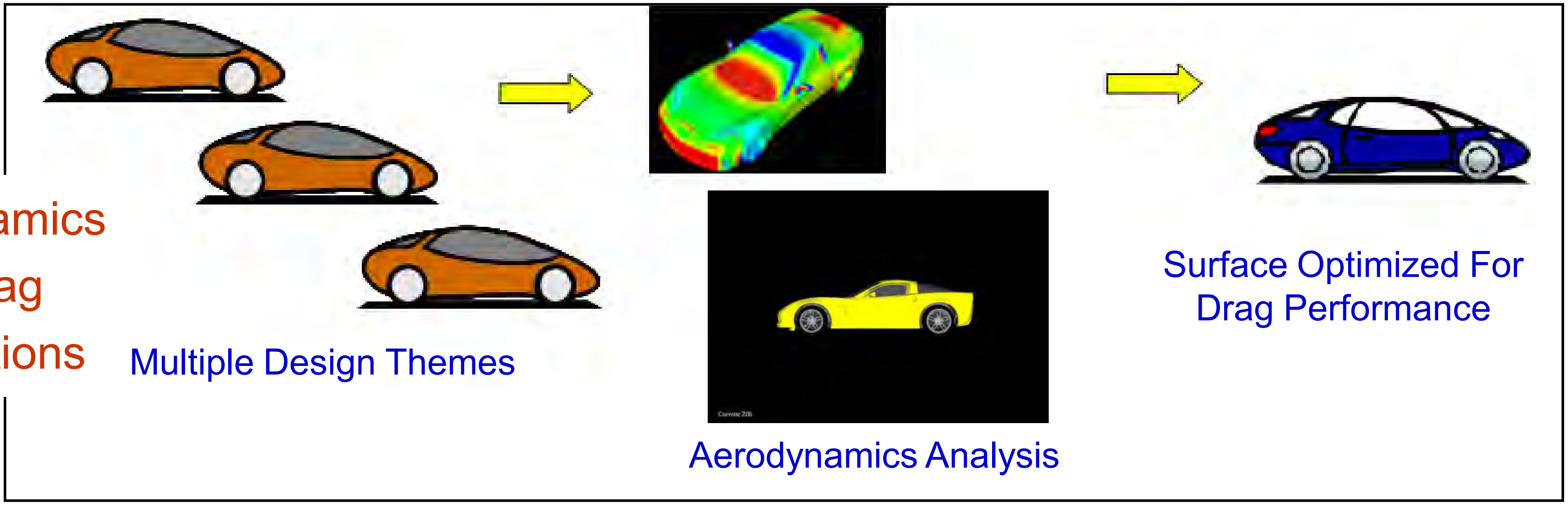
- Multi-discipline Design Optimization (MDO)
- Design of Experiment (DOE)
- Design Response Surface (DRS)
- Stochastic Design Optimization (SDO)
- Design for Six Sigma (DFSS)

Customer Detection of Joint Slip



Computational Fluid Dynamics (CFD) for Performance Assessments

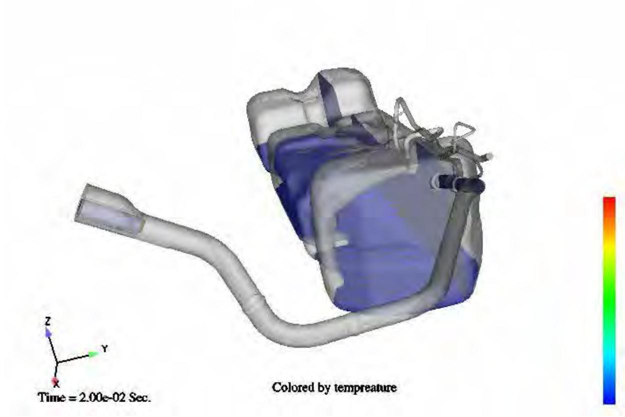
Aerodynamics for Drag Calculations



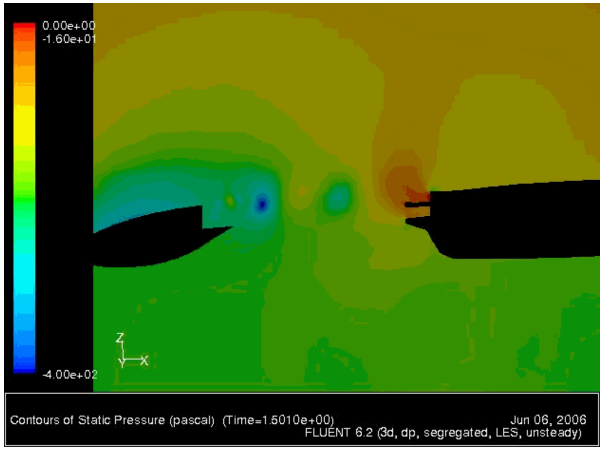
Multiple Design Themes

Aerodynamics Analysis

Surface Optimized For Drag Performance

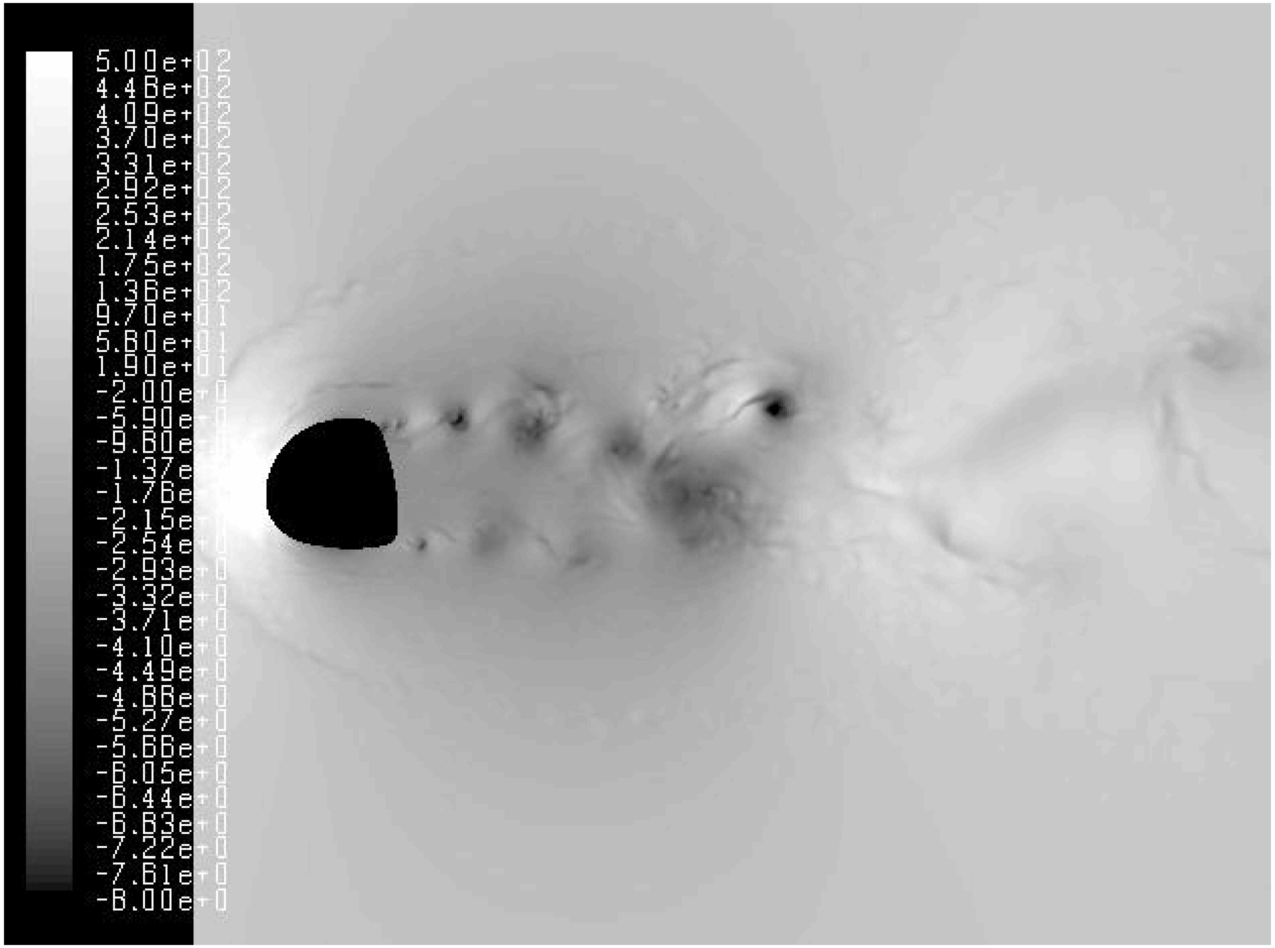


Fuel Fill & Fuel Slosh



Sunroof Helmholtz Resonator Effect

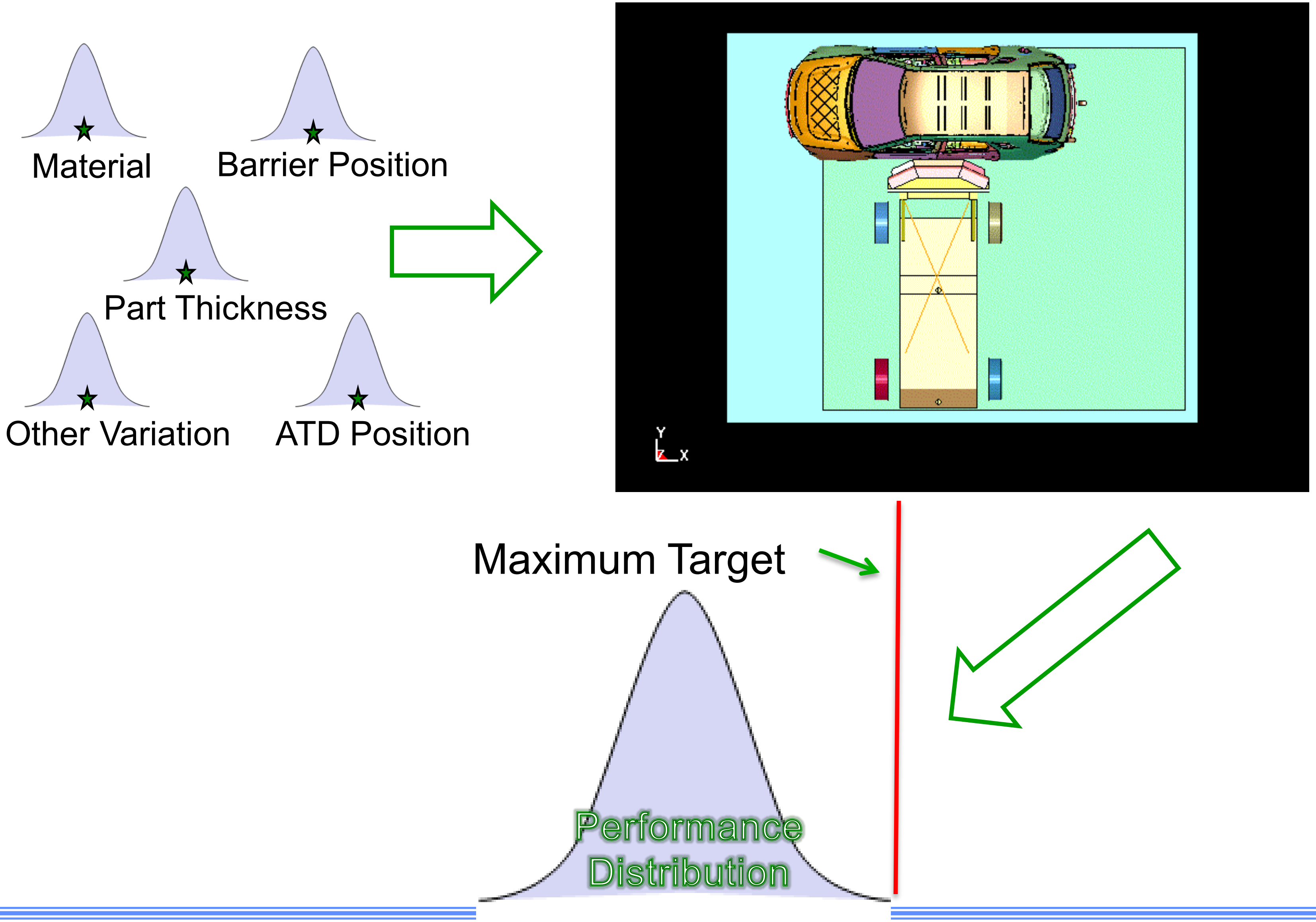
Computational Fluid Dynamics (CFD) for Performance Assessments



High Resolution Outside Rear View Mirror Flow modeling

Stochastic Methods to Enable Robust Designs

Stochastic Design Study



Material

Barrier Position

Part Thickness

Other Variation

ATD Position

Maximum Target

Performance Distribution

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MOTIVATION – WHY Verification & Validation?

Decision makers want to know:

- Can we use this model to ***predict*** frontal barrier impacts?
- What is the ***error*** between the model and tests?
- How much ***confidence*** do we have in the model predictions?
- Can we use this model to ***predict*** offset frontal barrier impacts?

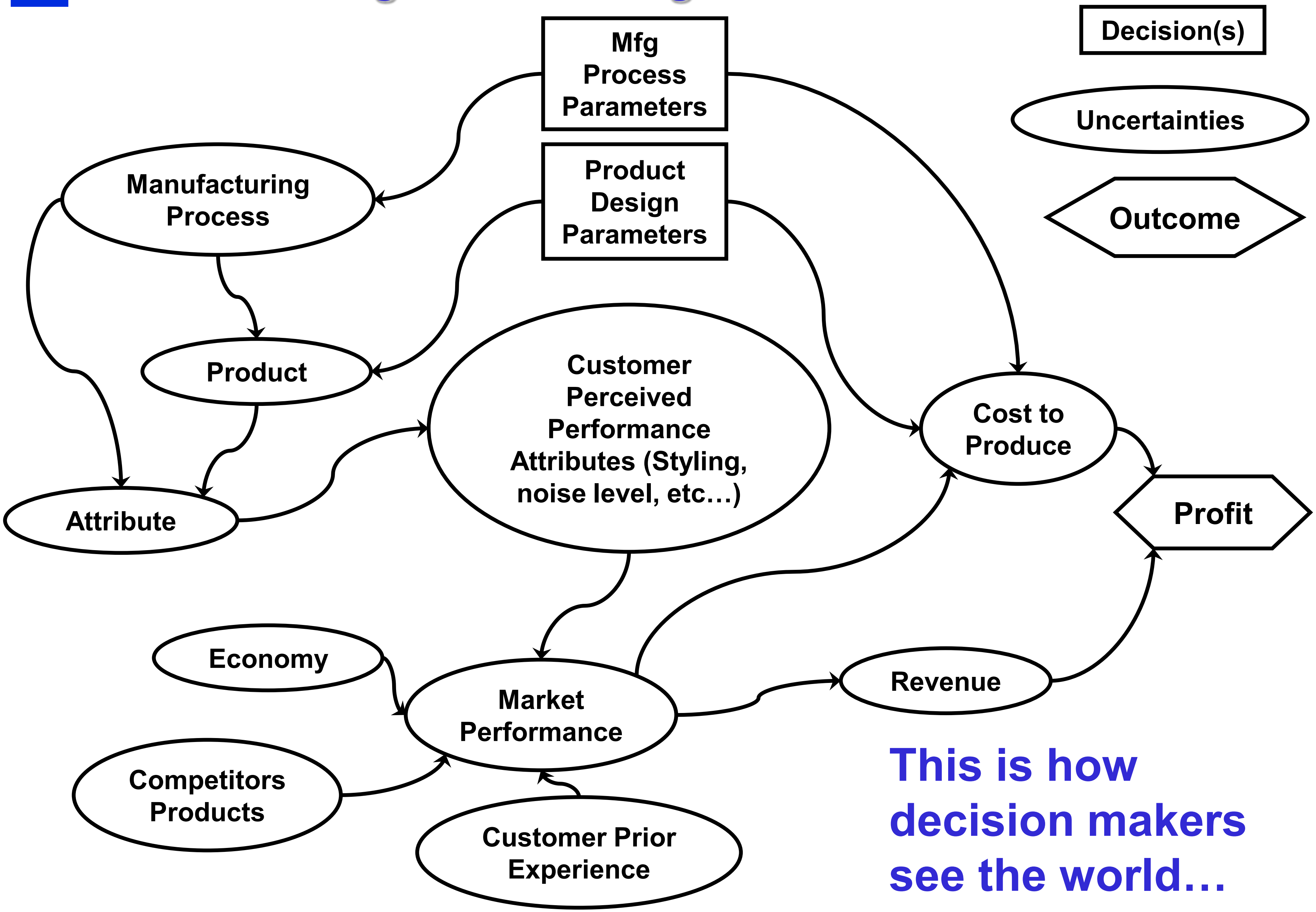
V&V can *help* answer these questions.

Decision Definition

"A decision is an irrevocable allocation of resources, in the sense that it would take additional resources, perhaps prohibitive in amount, to change the allocation." *[Matheson and Howard]*

"A good decision is based on the information, values and preferences of a decision-maker. A good outcome is one that is favorably regarded by a decision-maker. It is possible to <u>have good decisions produce either good or bad outcomes</u>. Most persons follow logical decision procedures because they believe that these procedures, speaking loosely, produce the best chance of obtaining good outcomes."

Decision Diagram for Design Alternatives



Decision(s)

Uncertainties

Outcome

Mfg Process Parameters

Product Design Parameters

Manufacturing Process

Product

Attribute

Customer Perceived Performance Attributes (Styling, noise level, etc…)

Cost to Produce

Profit

Economy

Market Performance

Revenue

Competitors Products

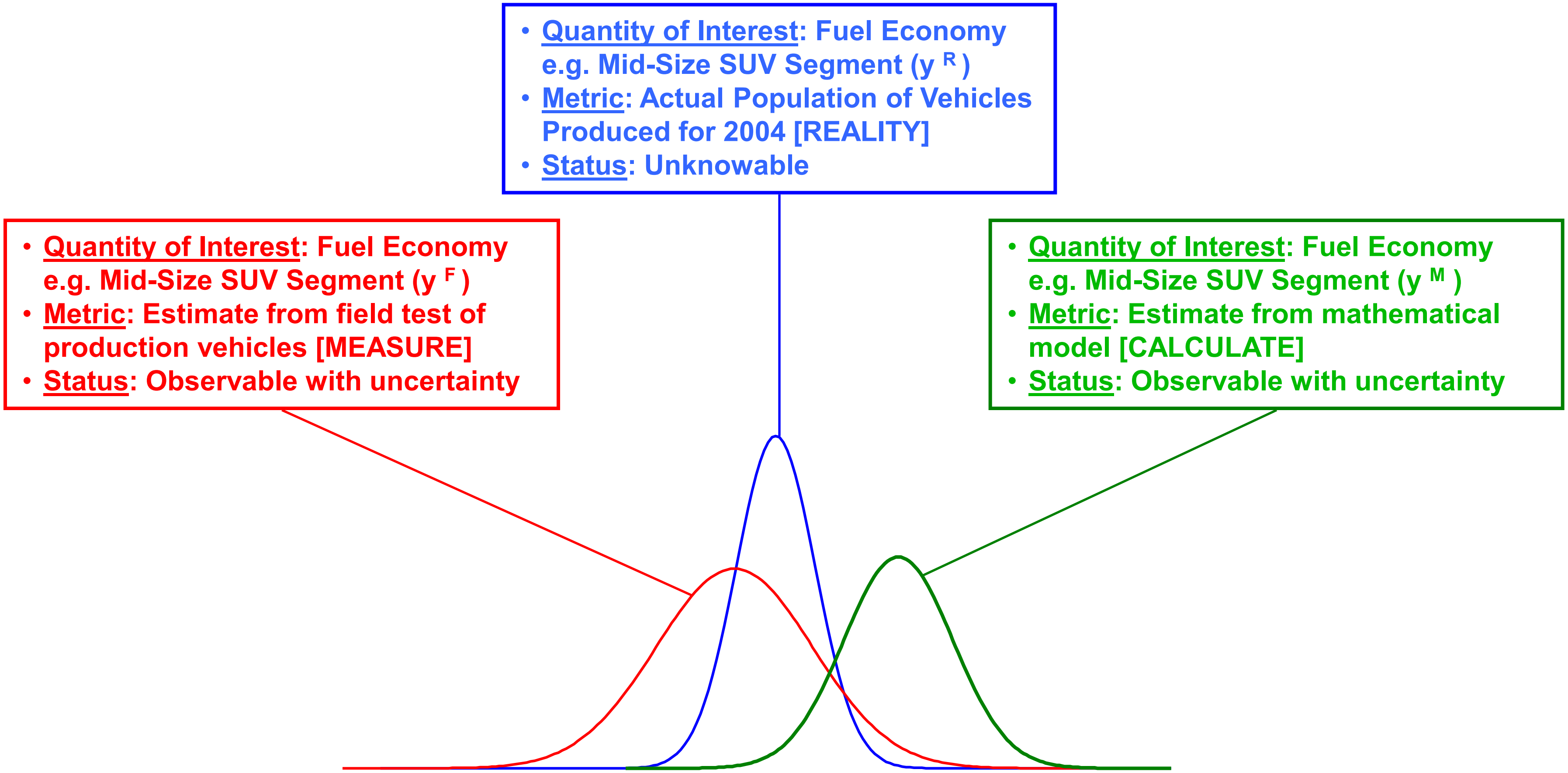
Customer Prior Experience

This is how decision makers see the world…

Product Development can be Viewed as a Temporal Set of Decisions

- Product development process is a set of decisions...
  - inevitably made under uncertainty (lack of knowledge, inherent variation) and risk (probability and consequence of failure)
  - analysts' (including engineers) role is to develop alternatives and predict outcomes
    - *Analyses should be performed when the results are relevant to the decision at hand and the value of the results exceeds the cost of obtaining them*
    - *Analysis results should include assessment of confidence* (validation)
  - product program leaders assess uncertainties and choose alternatives (make decisions) that they hope will lead to desired outcomes.

The Situation – Reality, Measurements, Simulations



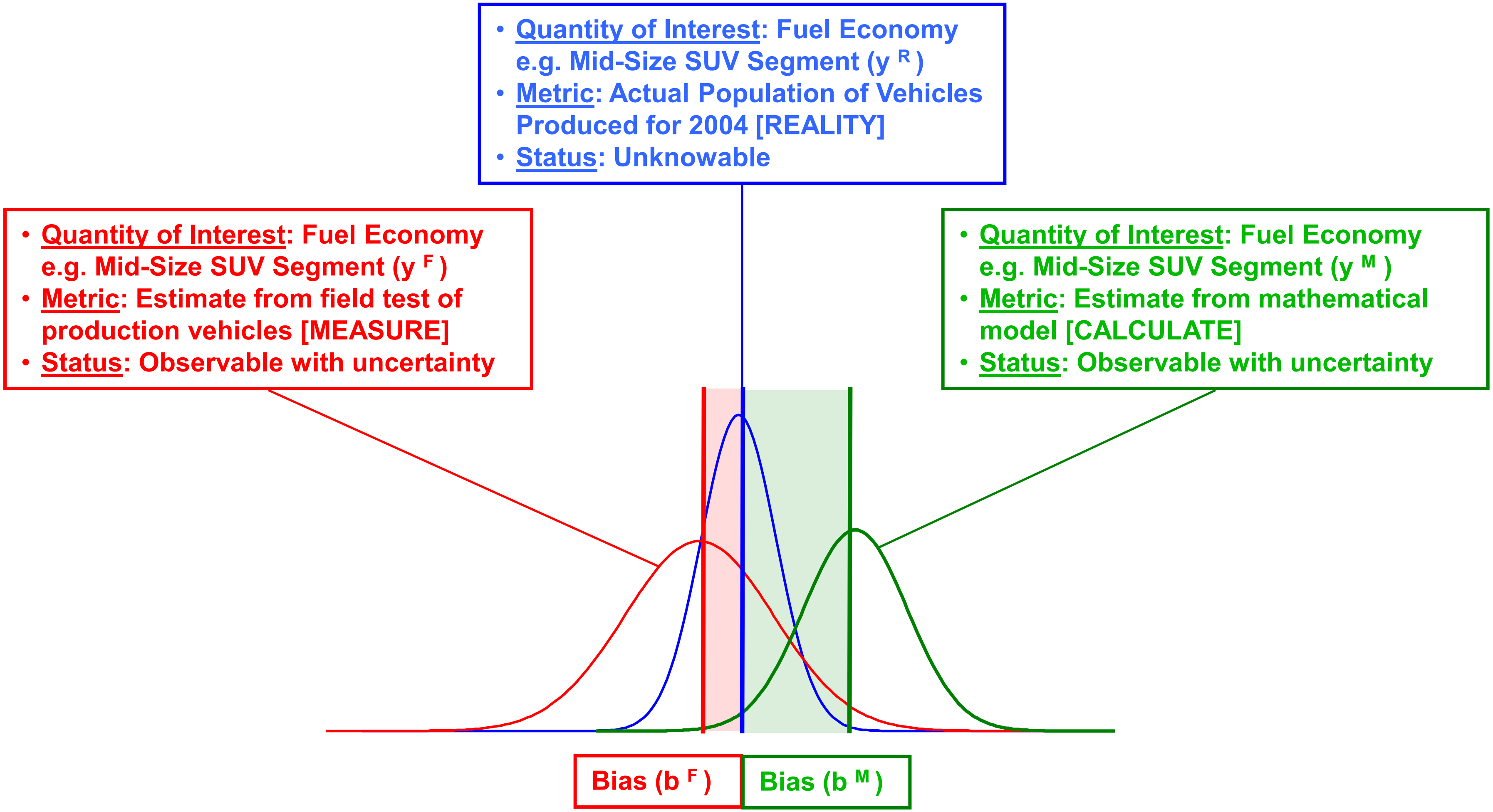
- Quantity of Interest: Fuel Economy e.g. Mid-Size SUV Segment (y^R)
- Metric: Actual Population of Vehicles Produced for 2004 [REALITY]
- Status: Unknowable

- Quantity of Interest: Fuel Economy e.g. Mid-Size SUV Segment (y^F)
- Metric: Estimate from field test of production vehicles [MEASURE]
- Status: Observable with uncertainty

- Quantity of Interest: Fuel Economy e.g. Mid-Size SUV Segment (y^M)
- Metric: Estimate from mathematical model [CALCULATE]
- Status: Observable with uncertainty

Reality is unknowable but observable either by measurement or calculation

Bias – What we would like to know



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- **Metric**: Estimate from mathematical model [CALCULATE]
- **Status**: Observable with uncertainty

Bias (b^F)

Bias (b^M)

We would like to know the difference (bias, error) between the different types of observations (measure, calculate) and reality.

Bias – What we can know

- **Quantity of Interest**: Fuel Economy e.g. Mid-Size SUV Segment (y^F)
- **Metric**: Estimate from field test of production vehicles [MEASURE]
- **Status**: Observable with uncertainty

- **Quantity of Interest**: Fuel Economy e.g. Mid-Size SUV Segment (y^M)
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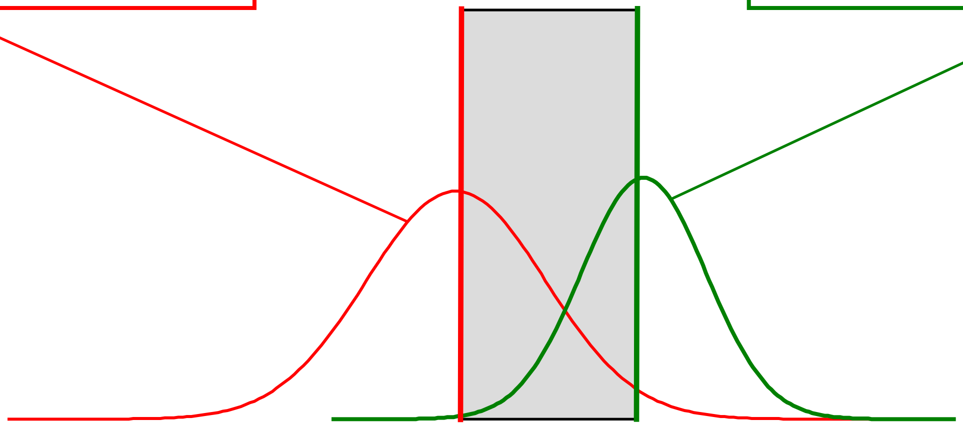
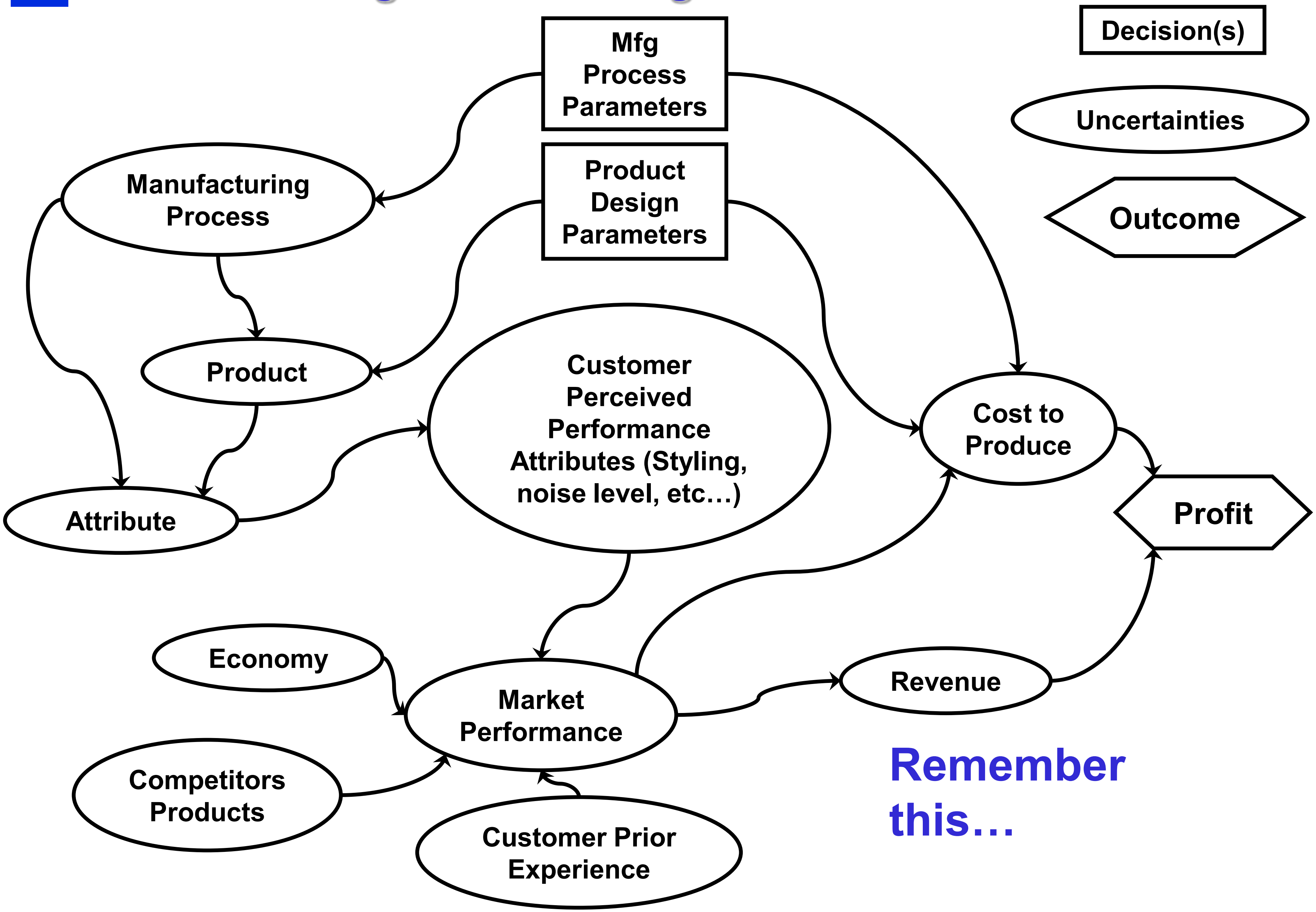


- Bias (b)

However, we can only estimate the difference (bias, error) between the two different types of observations: 1. measure, 2. calculate.

One of these then must be the reference quantity. Because we speak of model V&V, we are choosing our test results as our referent.

Decision Diagram for Design Alternatives



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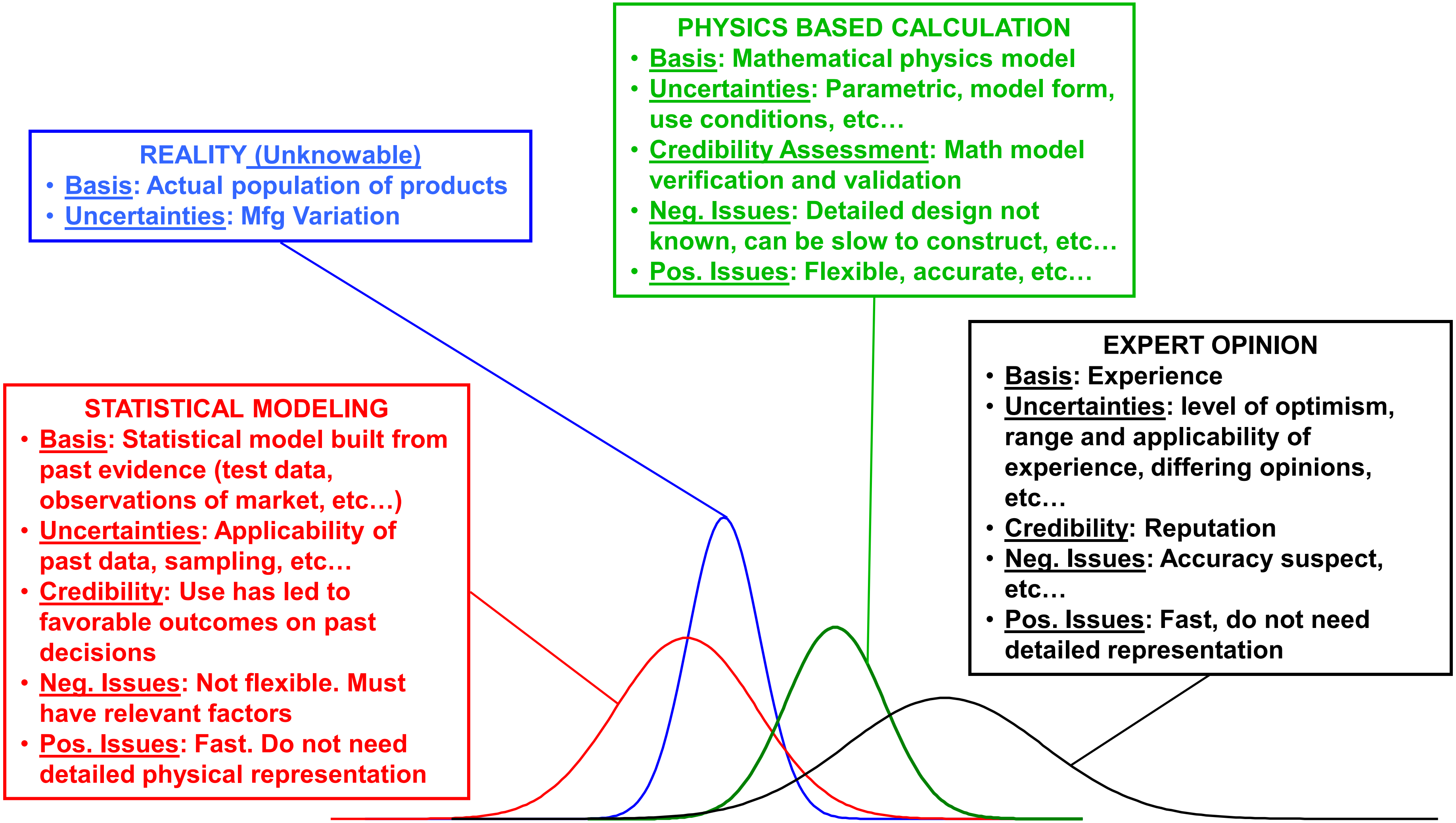
Remember this…

Evidence the decision maker uses.



REALITY (Unknowable)
- **Basis**: Actual population of products
- **Uncertainties**: Mfg Variation

PHYSICS BASED CALCULATION
- **Basis**: Mathematical physics model
- **Uncertainties**: Parametric, model form, use conditions, etc…
- **Credibility Assessment**: Math model verification and validation
- **Neg. Issues**: Detailed design not known, can be slow to construct, etc…
- **Pos. Issues**: Flexible, accurate, etc…

STATISTICAL MODELING
- **Basis**: Statistical model built from past evidence (test data, observations of market, etc…)
- **Uncertainties**: Applicability of past data, sampling, etc…
- **Credibility**: Use has led to favorable outcomes on past decisions
- **Neg. Issues**: Not flexible. Must have relevant factors
- **Pos. Issues**: Fast. Do not need detailed physical representation

EXPERT OPINION
- **Basis**: Experience
- **Uncertainties**: level of optimism, range and applicability of experience, differing opinions, etc…
- **Credibility**: Reputation
- **Neg. Issues**: Accuracy suspect, etc…
- **Pos. Issues**: Fast, do not need detailed representation

Because the decision maker is human, they must actually understand and believe in the verification and validation process.

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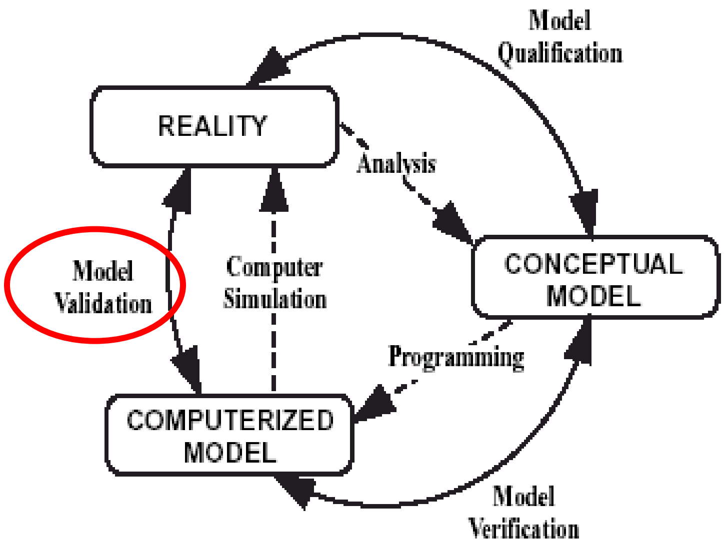
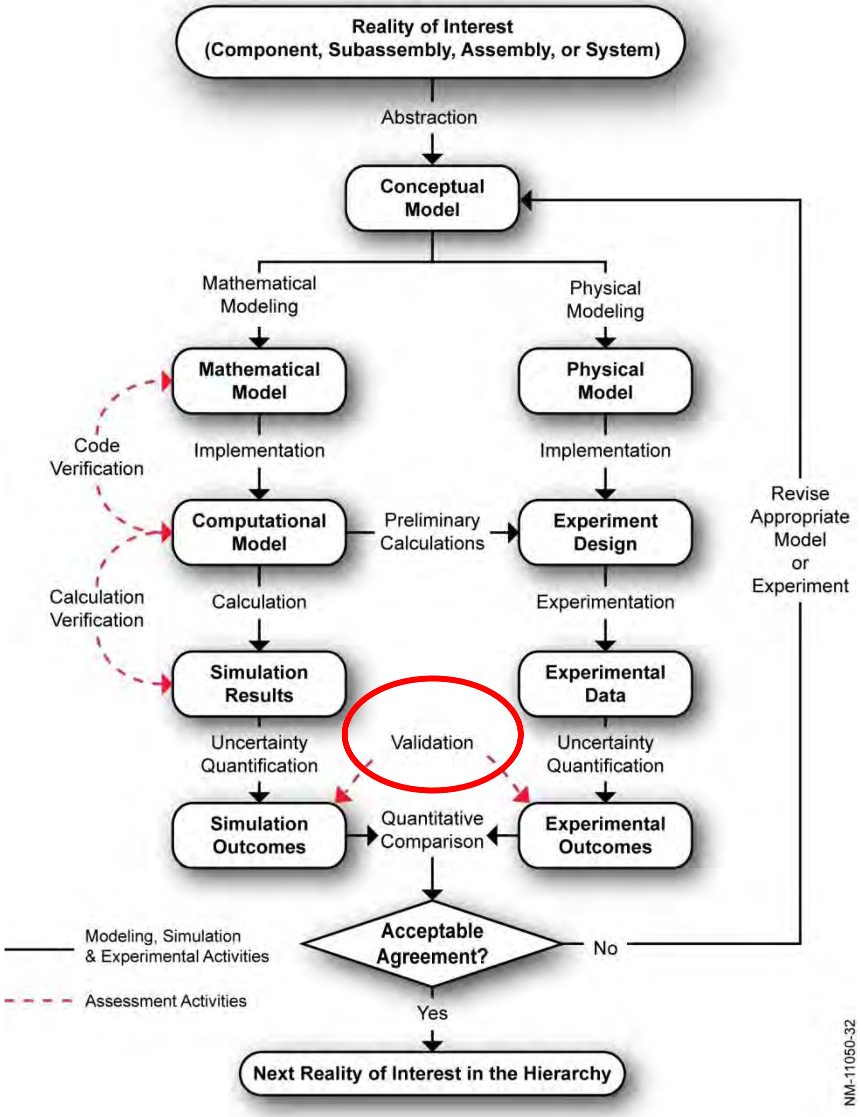
Background

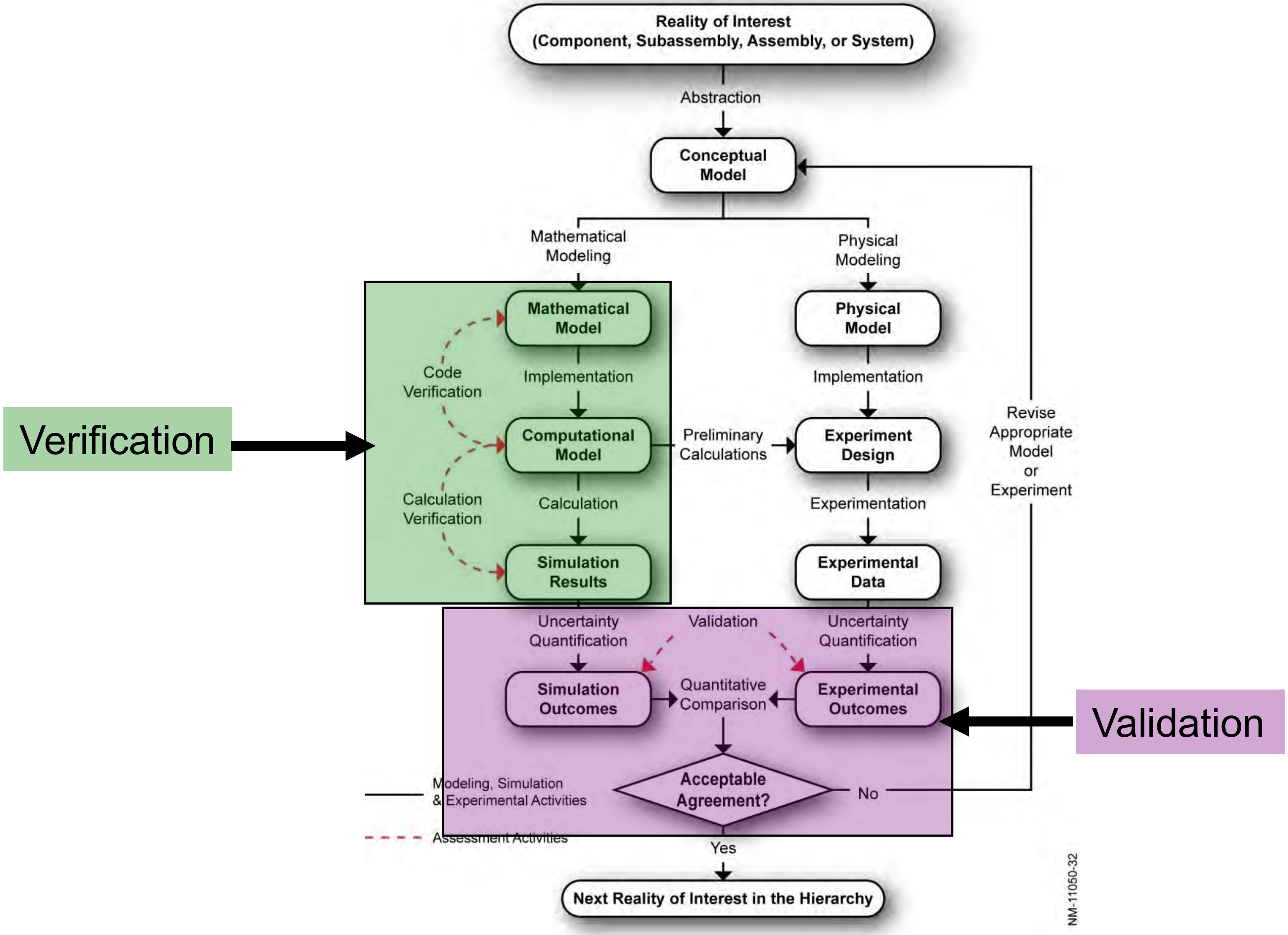


Phases of modeling & simulation (AIAA Guide – G-077-1998)



ASME Committee on V&V in Computational Solid Mechanics, PTC 60 Guide – ASME V&V 10-2006

Verification & Validation Process



Put most simply, verification is the domain of mathematics and validation is the domain of physics.

Verification

The process of determining that a computational model accurately represents the underlying mathematical model and its solution.

Code Verification – establish confidence, through the collection of evidence, that the mathematical model and solution algorithms are working correctly.

- Code Solution = Analytical Solution?
- ***Developers*** & Users

Calculation Verification - establish confidence, through the collection of evidence, that the discrete solution of the mathematical model is accurate.

- Discretization Error?
- Developers & ***Users***

Code Verification

One formal method for Code Verification is the **Method of Manufactured Solutions:**

$w(x) \longrightarrow$ **Beam Software** $EIy^{IV}=w(x)$ $\longrightarrow y(x)$

Manufacture (assume) a solution:

$$y_{MS}(x) = A\sin\frac{\alpha x}{L} + B\exp\left(\frac{x}{L}\right) + C$$

A, α, B, C constants determined from boundary conditions

Apply Differential Operator to solution:

$$EIy_{MS}^{IV} = w_{MS}(x) = EI\left\{A\left(\frac{\alpha}{L}\right)^4 \sin\frac{\alpha x}{L} + \frac{B}{L^4}\exp\left(\frac{x}{L}\right)\right\}$$

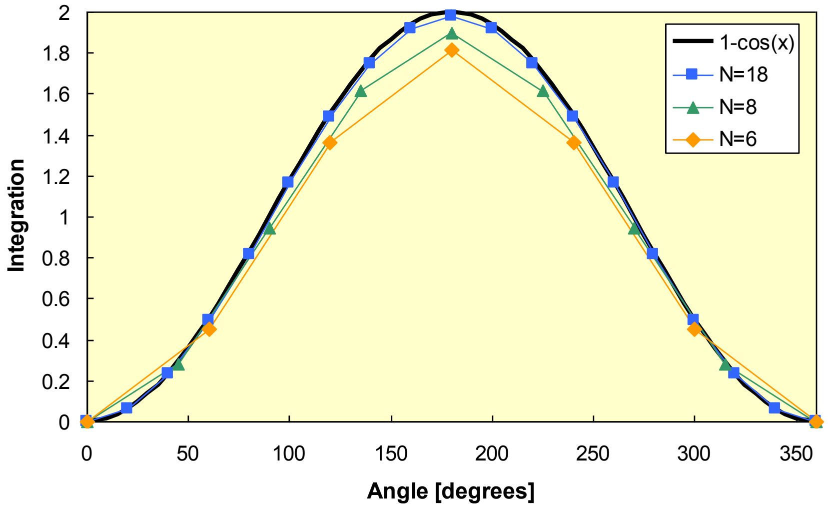
$w_{MS}(x) \longrightarrow$ **Beam Software** $EIy^{IV}=w(x)$ $\xrightarrow{?} y_{MS}(x)$

Calculation Verification

Calculation Verification – Every numerical solution contains discretization error.

$$y'(x)=\sin x \quad \Rightarrow \quad \text{Integrate using Trapezoidal Rule}$$

$$y(x)=\int_0^\theta \sin x\,dx = 1-\cos\theta \approx \frac{\theta}{2N}\sum_{i=0}^{N}\left[\sin(x_i)+\sin(x_i+\Delta x)\right] \text{ with } \Delta x = \frac{\theta}{N}$$



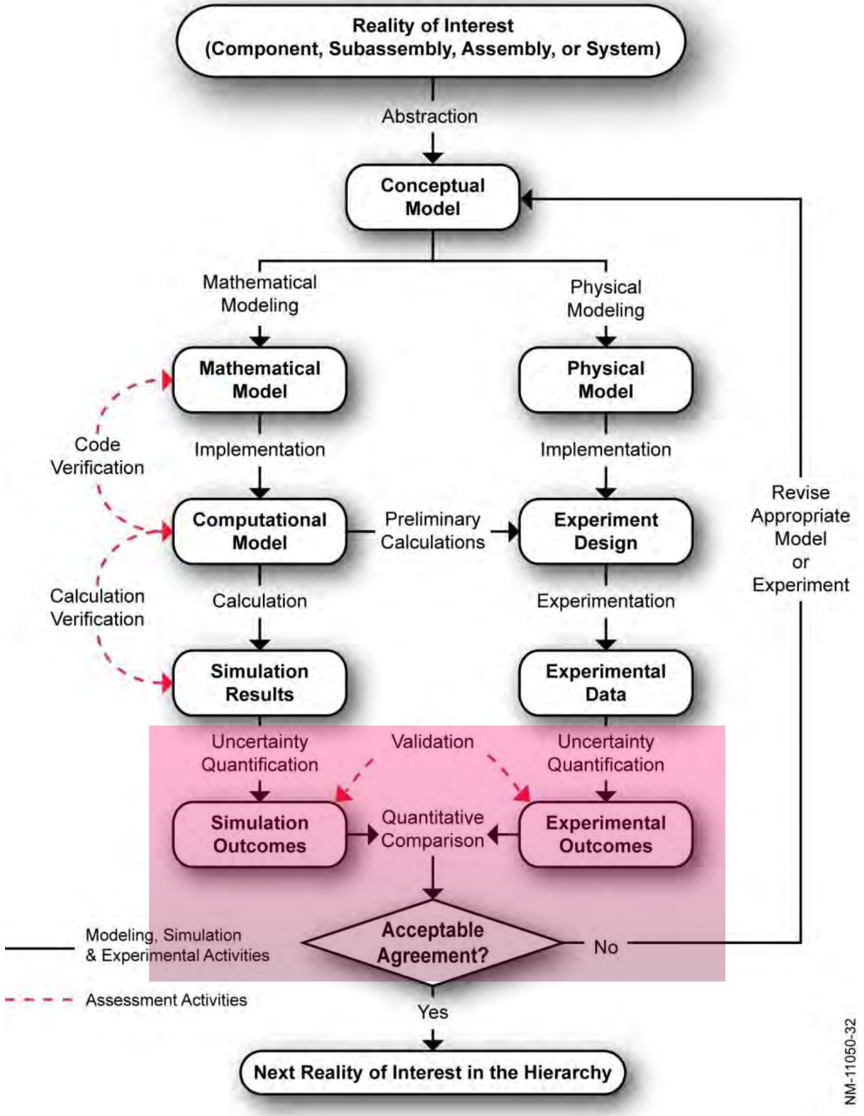
How do we quantify the discretization error when we do not know the analytical solution? One method available is the *Grid Convergence Index* (GCI) – an estimate of the percentage that the computed value is away from the ***asymptotic*** numerical value . [See: Roache, P. J., 1994, “Perspective: A Method for Uniform Reporting of Grid Refinement Studies,” *Journal of Fluids Engineering*, 116(3), pp. 405-413.]

Validation

The *validation process* has the goal of assessing the predictive capability of the model by comparing the predictive results of the model with validation experiments.

Three key elements of Validation:

1. Precision Testing
2. Uncertainty Quantification
3. Comparative Metrics



Reality of Interest (Component, Subassembly, Assembly, or System)

Abstraction

Conceptual Model

Mathematical Modeling

Physical Modeling

Mathematical Model

Physical Model

Code Verification

Implementation

Implementation

Revise Appropriate Model or Experiment

Computational Model

Preliminary Calculations

Experiment Design

Calculation Verification

Calculation

Experimentation

Simulation Results

Experimental Data

Uncertainty Quantification

Validation

Uncertainty Quantification

Simulation Outcomes

Quantitative Comparison

Experimental Outcomes

Modeling, Simulation & Experimental Activities

Acceptable Agreement?

No

Assessment Activities

Yes

Next Reality of Interest in the Hierarchy

NM-11050-32

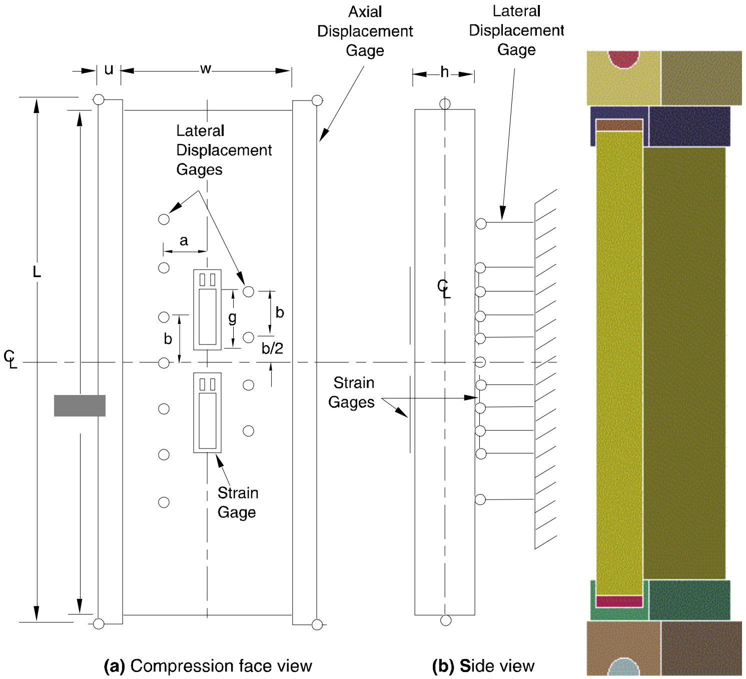
Validation

The goal of a ***validation experiment*** is to be a physical realization of an initial boundary value problem, since an initial boundary value problem is what the computational model was developed to solve.

Redundancy of the Data – repeat experiments to establish experimental variation.

Supporting Measurements - not only are measurements of the important system response quantities of interest recorded, but other supporting measurements are recorded. An example would be to record the curvature of a beam to support a strain gauge measurement.

Uncertainty Quantification - errors are usually classified as being either random error (precision) or systematic error (bias).



(a) Compression face view

(b) Side view

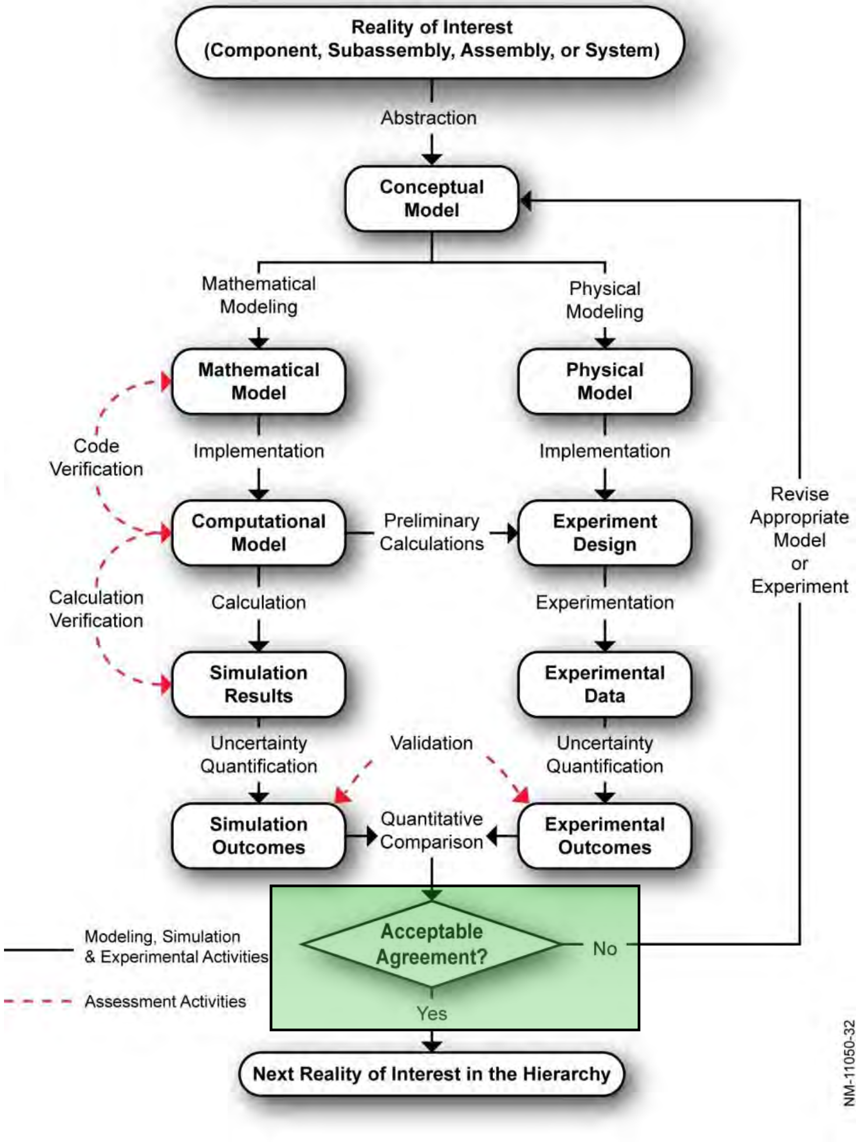
Gran, J.K. and Senseny, P.(1996) "Compression Bending of Scale-Model Reinforced-Concrete Walls," Journal of Engineering Mechanics, American Society of Civil Engineers, Volume 122, Number 7, pages 660-668, July.

What is a validated model?

If the model passes the comparison tests in the ***V&V Plan***, then it can be used to make the desired predictions with confidence.

When it is said that the ***model is validated*** for the intended use, it is not the just the ***Computational*** model, which likely will have to change for the predictions of interest, but the ***Mathematical*** and ***Conceptual*** models upon which the Computation model was built that have been validated.

It is through the ***Validation*** of the ***Conceptual*** model that confidence is gained that the correct physics (mechanic) were included in the model development.



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Six-Step Process

1. **Specify an input/uncertainty map**

   Identify and quantify the important parameters and inputs to the model that are believed to be potentially significant contributors to error and uncertainty in model predictions. Assess their impact. During the validation process this map is revisited, revised and updated.

2. **Determine evaluation criteria**

   Specification of what physical quantities or system response measures are being chosen for validation purposes.

3. **Design of validation experiments**

   This includes both designed computer and designed field or laboratory experiments. Explore range-of-use and range-of-uncertainty. DOE deals with controllable and uncontrollable factors.

4. **Data collection and generate model outcomes**

   Approximate fast running surrogate models are usually key for enabling the analyses carried out in Step 5.

5. **Compare computer model output with field output**

   Calculate bias, variance and (potentially) model tuning/calibrating parameters. Simple (algebra with normal dist) to complex (Bayesian) techniques can be used.

6. **Feedback information into current validation exercise and feed-forward information in future validation activities**

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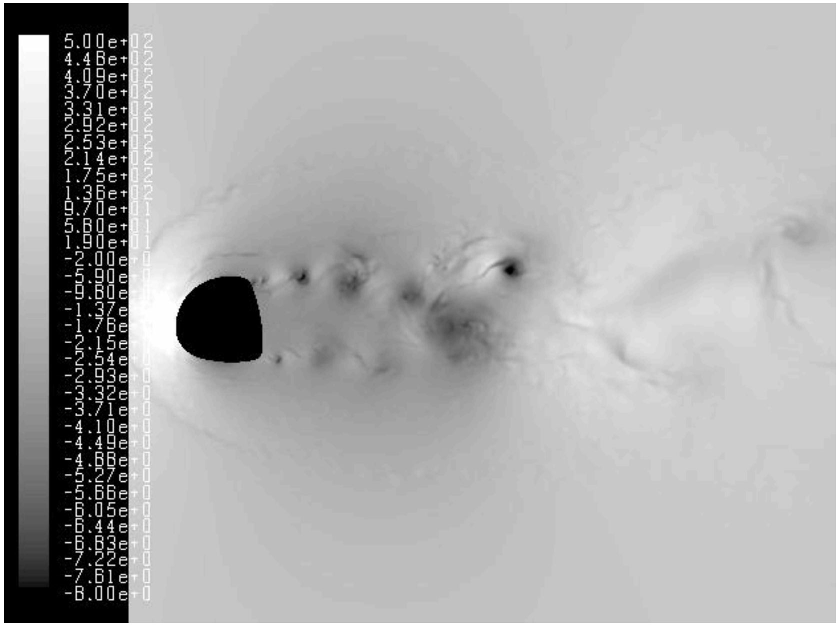
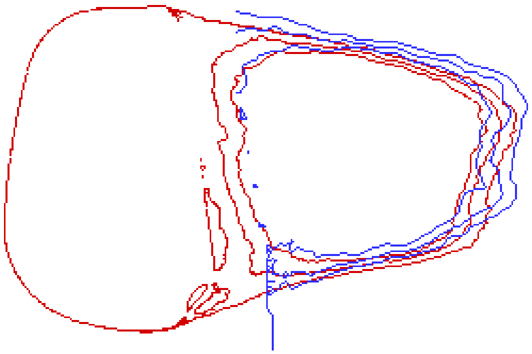
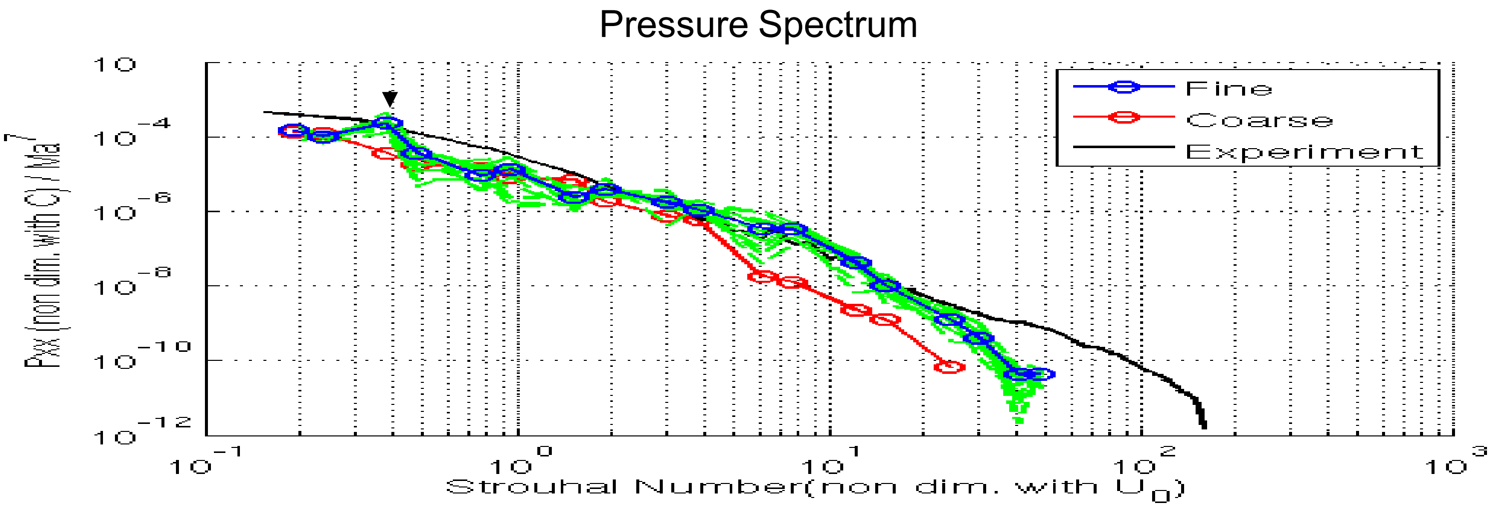




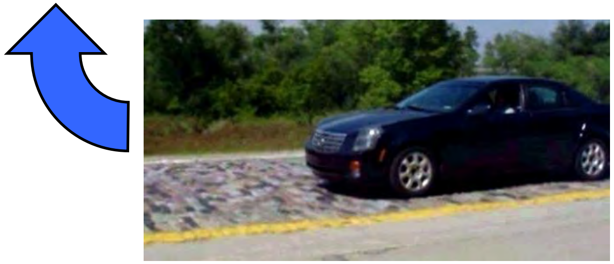
LES Experiment(PIV)
Recirculation Area

High Resolution Outside Rear View Mirror Flow Modeling for Noise



Multi-body Dynamics (MBD) Math Model

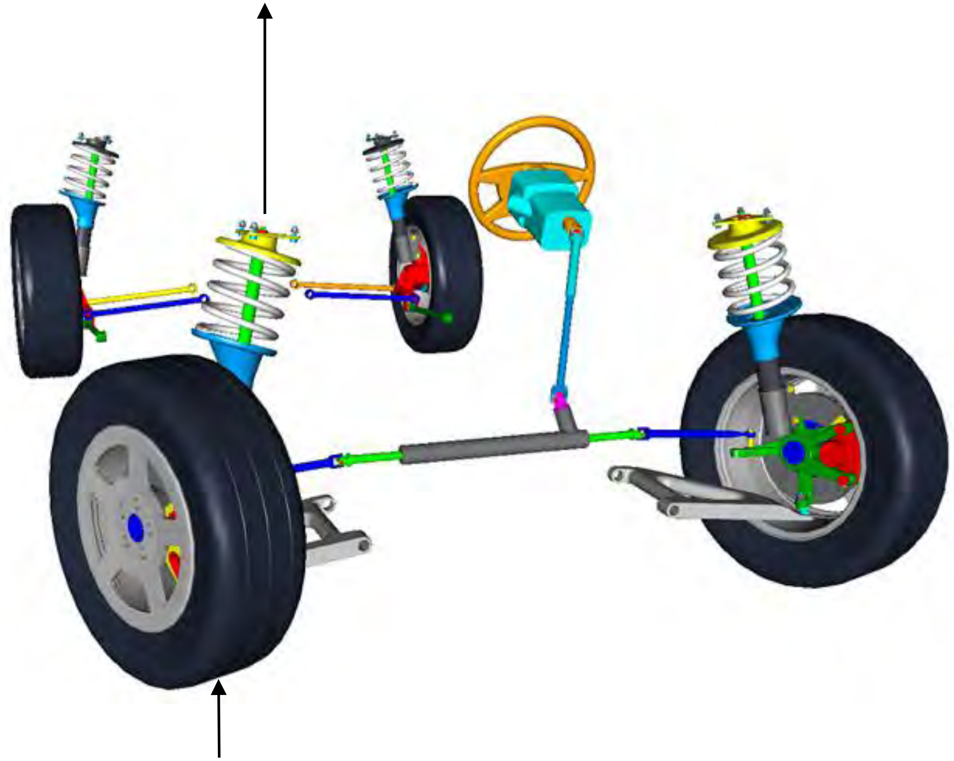
Replacement of Road Load Data
Acquisition with Analytical Loads



Simulation:
- Multi Body Dynamics models of vehicles built in math
- Digital road profiles are used as loads
- Response calculated at spindles, suspension-body interfaces

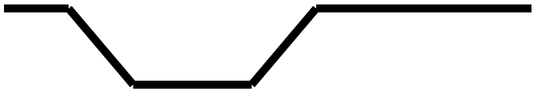
Typical measurements:
- force
- moment
- acceleration
- displacement

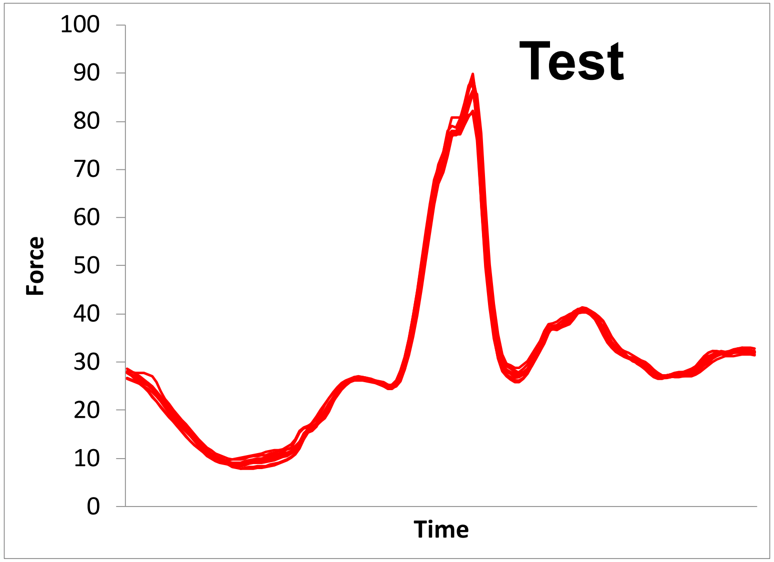
Road Load Prediction – Pot Hole Event

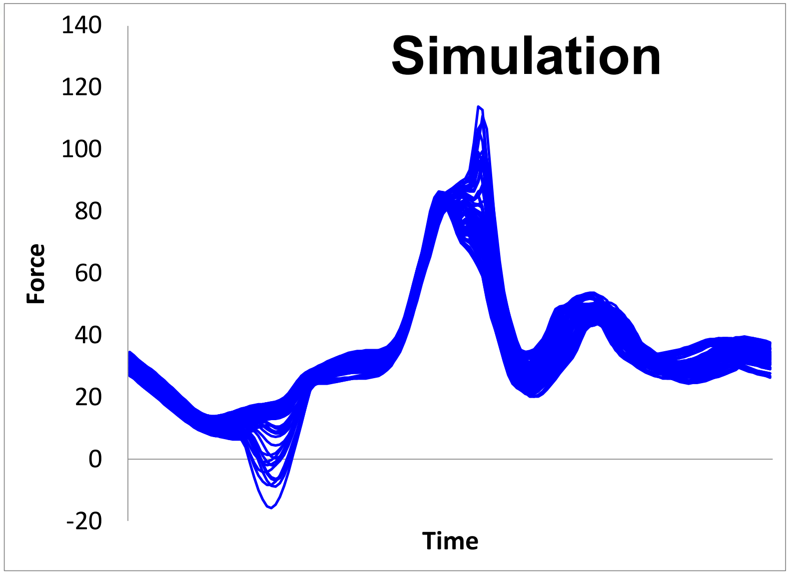


Load (FORCE) response at the shock-to-body interface

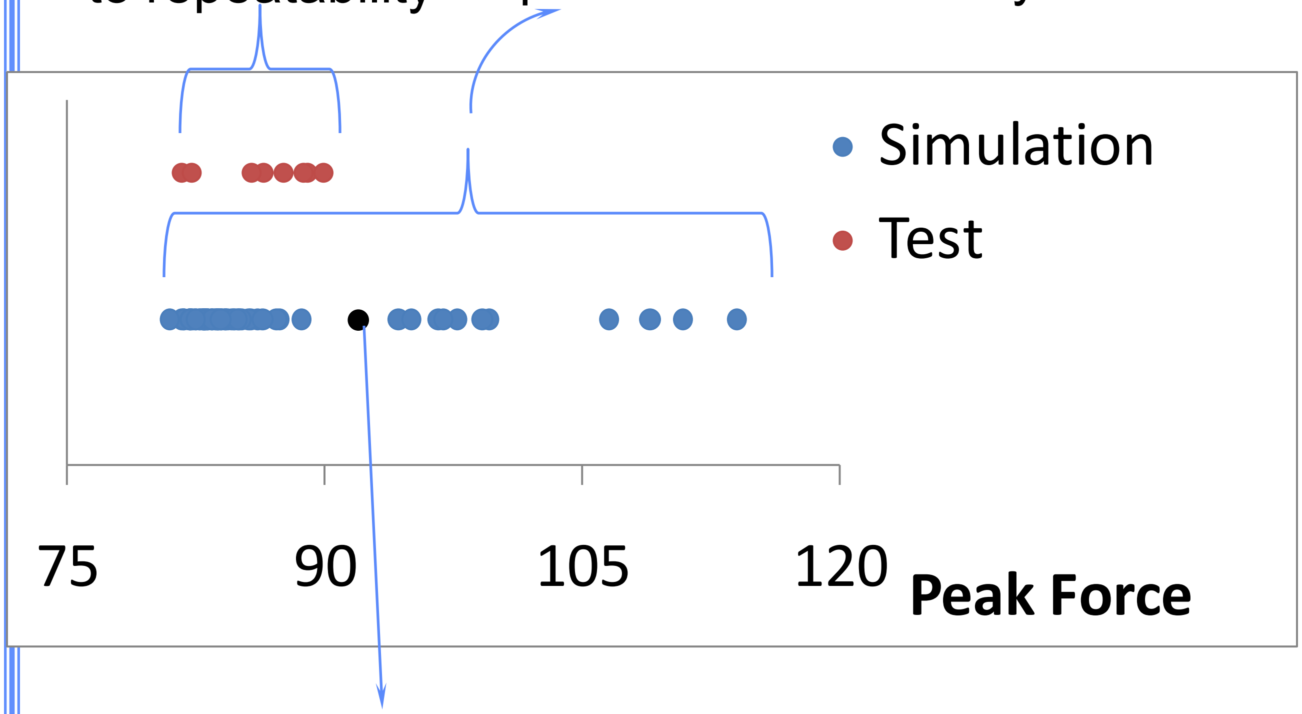
Pothole event road input at the tire







Road Load Prediction – Pot Hole Event



Variability due to repeatability

Variability due to parameter uncertainty

Nominal Simulation

Simulation

Nominal = 92.1
Average = 86.7
Std. dev = 7.47
Samples = 65

Test

Average = 86.4
Std. dev = 3.08
Samples = 9

- *Do simulation and test come from same population?*
- *What is the bias between simulation & test?*
- *Statistical comparison of results*

PRESENTATION OUTLINE

I. Vehicle Development & Math-based Computer Models

II. Decisions in Product Development

III. Model Verification and Validation

IV. Steps for Validation

V. An Example

VI. The Message

Messages

- The value of simulation results often exceeds the cost of obtaining them.
- Rigorous V&V can establish credibility in math models. Credibility is essential for use.
- Uncertainty Quantification as a language of V&V and so this means that statisticians and engineers will need to team up and work together to accomplish V&V.
- Effective communication of validation results to the decision makers is key. The decision makers must understand and buy-in to the V&V process.
- Decision making is done by humans – not computers!

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