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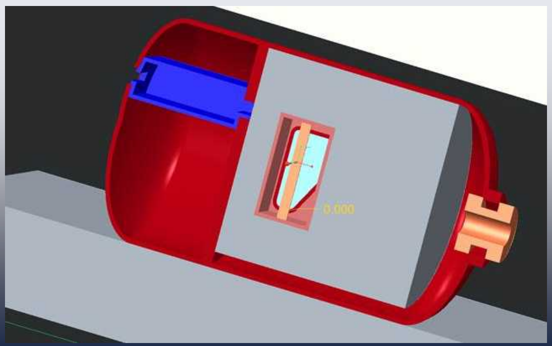

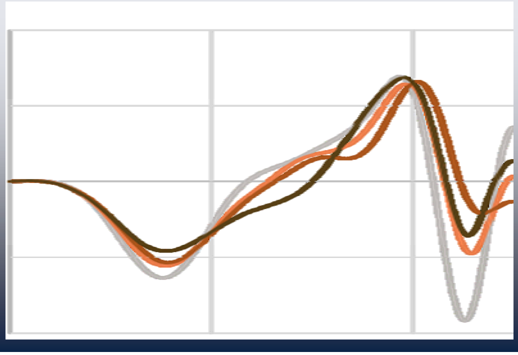

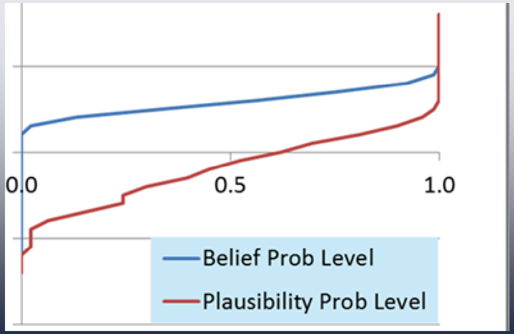

An Approach Integrating PCMM, UQ and Evidence Theory for System Requirements Verification by Analysis with Solid Mechanics Models

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2017 ASME V&V Symposium

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SM Exemplar, System Requirements

Credible Mod-Sim, Evidence Package

Deterministic Prediction of Loss of Function (LoF)

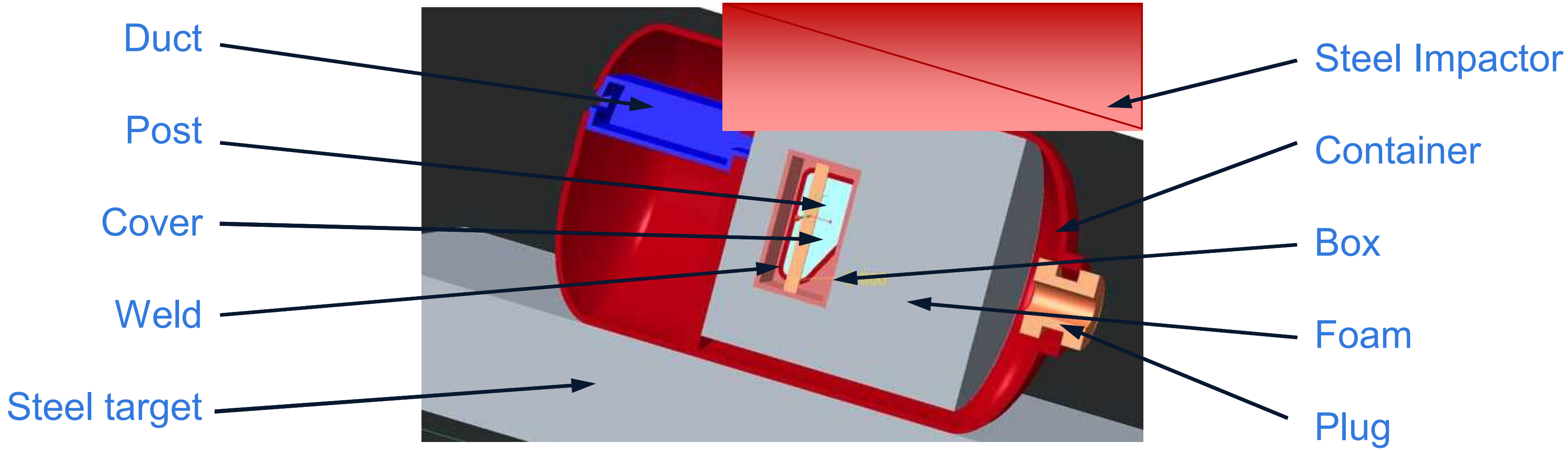
UQ based Prediction of LoF

Evidence Theory Based Prediction of LoF,
Risk Informed Program Decisions

Credible Evidence Needed to Verify System Requirement

System requirement: function of the device must be assured (open ended)

Translation: What is the maximum impactor speed without loss of function?

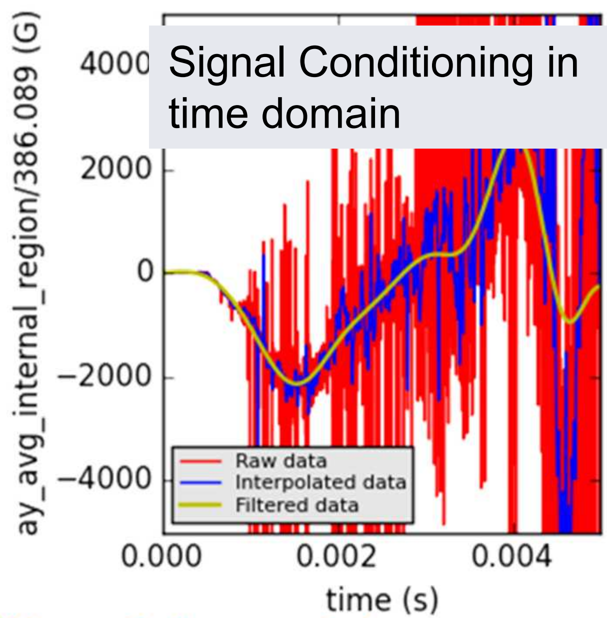


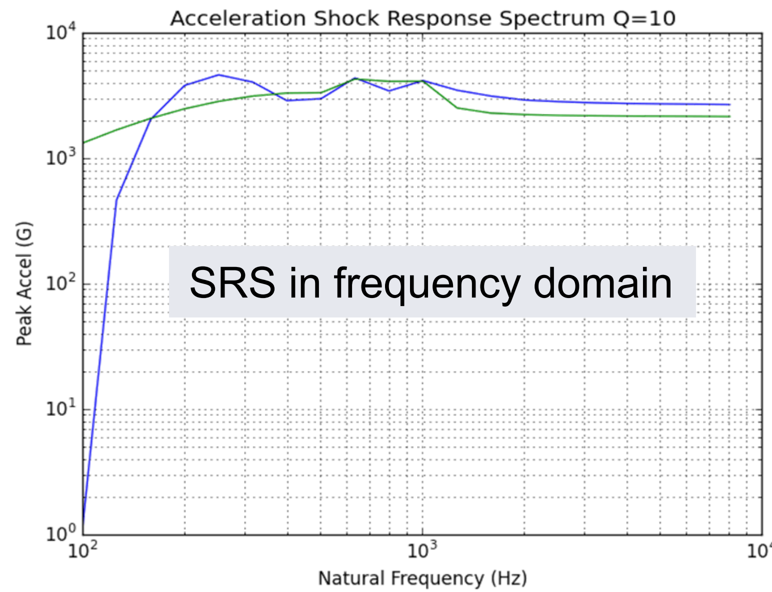
Intended use of the Comp/Sim model

- Verify system requirement
  - Uncertainties lead to unit-to-unit variation: material, interface, preload, tolerances
- Perform pre-test calculations to:
  - Determine physical testing parameters
  - Assess instrumentation requirements
- Support validation of modeling ***approach***; on-going hardware updates are likely

System Requirements and QoIs; Acceleration

- Requirement: “Post” shall not see acceleration beyond threshold of concern
- QoI: Mass averaged acceleration (must be less than threshold of concern)
  - Peak accelerations from time domain
  - Peak acceleration from Shock Response Spectra
  - Criteria negotiated with customer (high instantaneous accelerations observed but sustained consistent acceleration is considered damaging)



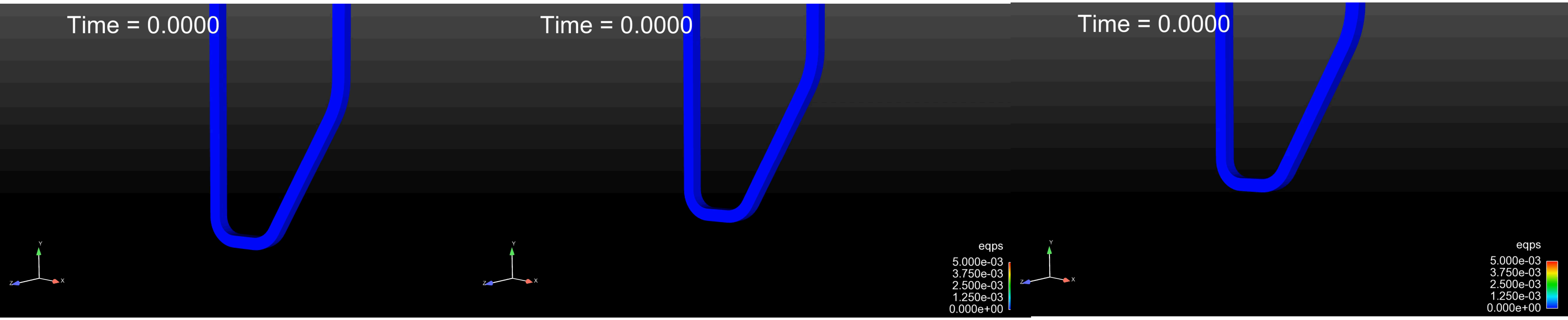


Credibility of the model to accurately evaluate this QoI is likely

Signal conditioning and SRS utilities in Engineering Sciences Tool Repository

System Requirements and QoIs; Weld Failure

- Requirement: The weld around "Cover" shall not separate
- QoI: Maximum model material failure response (must be less than calibrated material failure value); point value
  - Alternatives: Volume averaged plastic strain, tearing parameter
  - Volume averaged results from discretized models are more credible but establishing criteria will be a challenge



Credibility of the model to accurately evaluate this QoI is not known

Weld failure height and width metric evaluator in project tool repository

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Grand Challenge of Model Credibility

- Qualitative evidence
  - SME judgment, tacit organizational knowledge, past history
    - Expected predictiveness of the model for the intended use
  - PIRT (Phenomena Identification and Ranking Table) - Defines key physical phenomena ranks their importance, identifies code gaps
  - Analysis governance, peer reviews

- Quantitative evidence
  - PCMM (Predictive Capability Maturity Model) - SME elicitation process designed to characterize and communicate the completeness and rigor of the Comp/Sim process. Quantitative but "circumstantial"
    - Includes UQ and validation

- Validation at a handful conditions – mission space is large, response is nonlinear/discontinuous, test data are sparse

Need to combine qualitative and quantitative evidence to support decision making in large untested mission space

Comp/Sim Model Credibility Process

Modeling/Testing Roadmap

- Quantified System Requirements
- Negotiate Role of Comp/Sim in Decision Making
- Negotiate QoIs
- Comp/Sim Roadmap
- Phys/Sim Roadmap
- Documentation Plan

Model Development

- Model Objective
- PIRT
- Project Plan
- Analysis Governance
- Construct, Collect Models, Tools
- Implement Analysis Workflow

V&V

- Validation Hierarchy
- PCMM
  - Code Verification
  - Physics, Materials
  - Geometric Fidelity
  - Solution Verification
  - Uncertainty Quantification
  - Validation
- Quantitatively Pool SME and UQ info

Assessment

- Workforce Qualification
- Integrated Working Groups
- Independent Internal Peer Review
- Independent External Peer Review

Iterative (e.g. model updates after experiment data available)

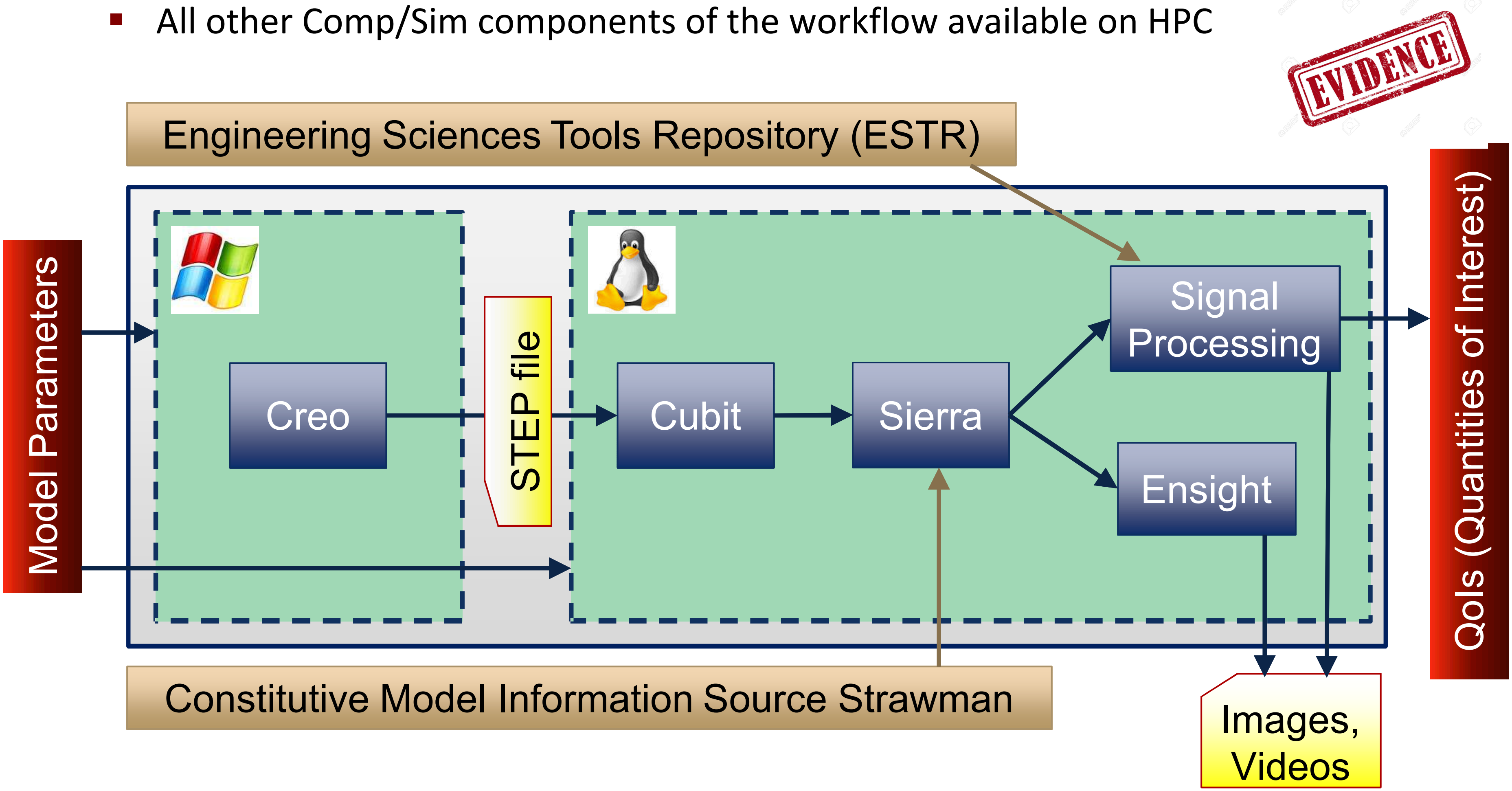
PIRT

Phenomena	Importance	Adequacy		
		Math Model	Sierra/SM Code	Validation
Large elastic-plastic deformation of metals (including strain-rate and temperature	H	H	M	L
Ductile material failure (shear, tension) of structural member	H	M	M	L
Ductile material failure (shear, tension) of tubes	H	M	M	[illegible]
Ductile material failure (shear, tension) of fasteners	H	M	M	[illegible]
Crash or drop driven puncture of ductile metal case with rails, rods, hard irregular	H	L	L	[illegible]
High velocity metal to metal impact (blast driven projectiles and case puncture)	H	H	H	[illegible]
Contact and friction between internal components (thin foam sections between hard	H	M	L	L
Crushing of rigid foam	H	H	H	L
Fracture of rigid foam	L	L	L	L
Deformation and failure of cellular silicon pads	L	L	L	L
Focused heating of metal and foams	M	M	M	M
Buckling of thin shell structures and tubes	L	M	M	L
Weld/joint failure	H	M	L	L
Adhesive bond failure	L	L	L	L
Elastomeric seal failure	L	L	L	L
Thermal expansion	L	H	M	L
Internal heat generation due to friction & plastic deformation	L	L	L	L

Identifies validated analysis code capability gaps

SM Exemplar Analysis Workflow – Big Picture

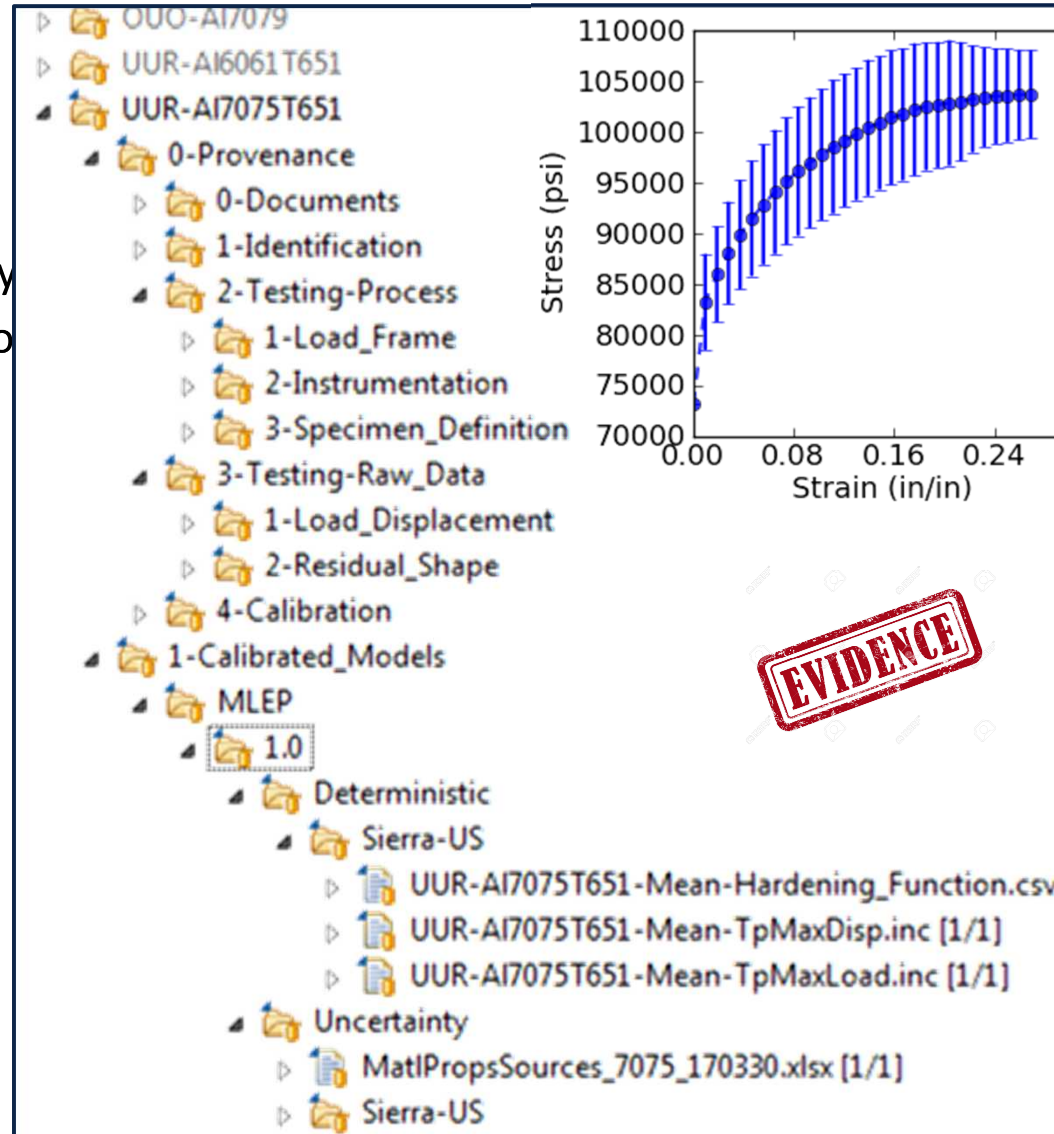
- Multi-platform analysis workflow
  - Electronic Product Definition/GD&T tolerances in PTC Creo/WindChill – Windows
  - All other Comp/Sim components of the workflow available on HPC



Credible workflow requires repositories of artifacts with demonstrated provenance

Repositories Supporting Credible Workflow

- Constitutive Model Repository Prototype
  - Full provenance
    - Material order data sheets
    - RAW Test data
    - Calibration process yielding uncertainty
      - –Different models may be calibrated to give set of test data
  - Sierra input snippets
    - Most but not all model parameters
      - –SME judgement
- Engineering Sciences Tool Repository Prototype
  - Tools developed by analysts
    - Documentation
    - Version control
    - Verification and regression tests
  - Examples: signal processing, SRS
  - Need separation of roles: author, user



PCMM

Code Verification

Analysis code reproduces closed-form results?

Physics and Material Model Fidelity

Are "closure models" (constitutive etc.) credible?

Representation and Geometric Fidelity

Is the geometric abstraction acceptable?

Solution Verification

Code solves the equations for the intended use correctly?

Uncertainty Quantification

What is the effect of input uncertainties on QoIs?

- Uncertainty inventory and characterization of input uncertainties
- Formal UQ; propagate characterized uncertainties through the model
- Experimental uncertainty

Validation

How well do model predictions match experimental data?

Collaborative Effort: Customers, Analysts, Experimentalists, Code Developers

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Metric to Measure Loss of Function (LoF)

Damage is not catastrophic in a given scenario if

$$M_{QoI}F_{Model} < \frac{R_{QoI}}{F_{Req}}$$

$$N = \frac{\frac{R_{QoI}}{F_{Req}} - M_{QoI}F_{Model}}{R_{QoI}} > 0$$

Threshold of concern

M_{QoI} : QoI from Model Response
F_{Model} : Model Confidence Factor
R_{QoI} : QoI-Specific Acceptance Requirement
F_{Req} : Requirement Derating (Confidence) Factor
N : Normalized Margin

Loss of function at N=0

- When F_{Model} or F_{Req} increases margin decreases
- Formulation is analogous to traditional margin of safety

Design is acceptable if

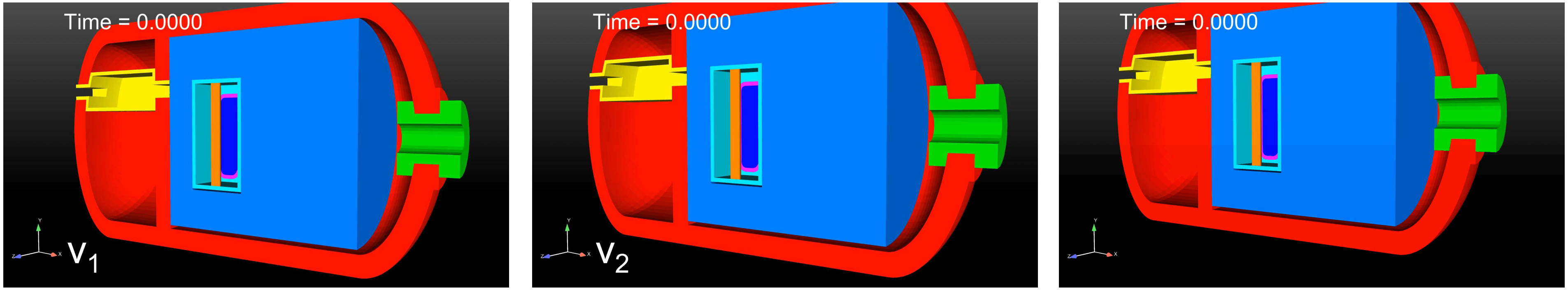
$$FS = \frac{Failure\ Load}{Working\ Load} > FS_{required} \qquad MS = FS - 1$$

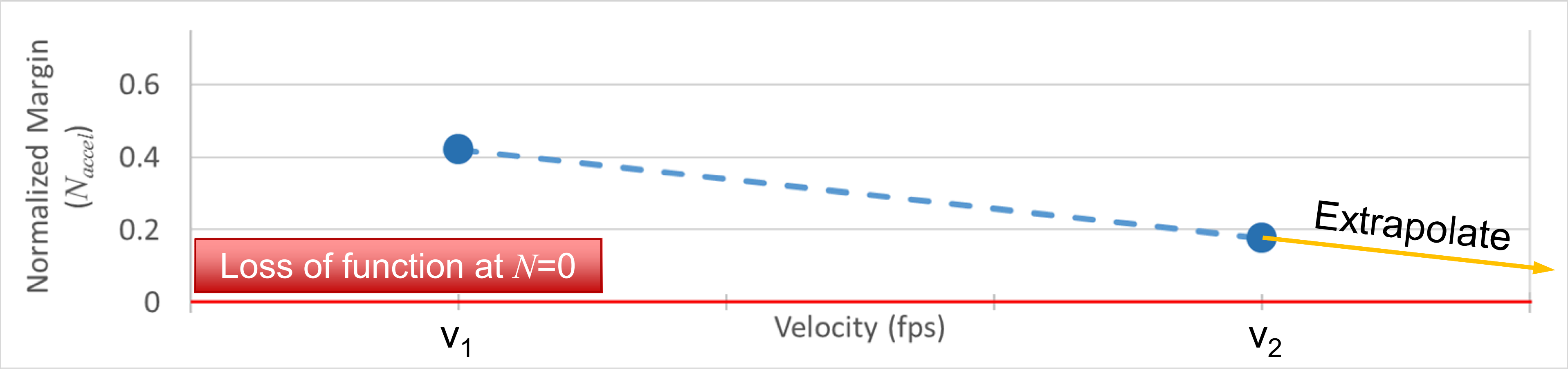
- Historical $FS_{required}$ ranges (depending on failure mechanisms)
  - Building safety: 2.0
  - Automotive, pressure vessel: 3.0-4.0
  - Aerospace: 1.1-1.4

Historical $FS_{required}$ established though decades of adjustments – **Handful of experiments in current use case**

Deterministic Prediction for Loss of Function

- Known uncertainties are not considered
- The fact that the model doesn't cover the whole physical reality not considered





Inference: The velocity for LOF is significantly larger than v_2
Useful for setting validation test conditions NOT suitable for ***credible*** decision making

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Uncertainty Inventory (Known Unknowns)

- Model feature
  - Constitutive modeling
    - Model form uncertainty (strain rate dependence, failure model)
    - Uncertainty within a model form
  - Interface conditions (friction)
  - Actual impact velocity, cylinder clocking angle
  - Signal conditioning parameters (sampling, filtering)
  - Spatial discretization (mesh)
  - Numerical uncertainty (processor count, time stepping etc.)
- NOT a model feature
  - Geometric variability within drawing tolerances (unit-to-unit variability)
  - Assembly loads
  - Residual stresses due to welding
  - Off-spec parts

Epistemic: lack of knowledge

Aleatory: Inherent variation

Bottom-Up UQ Input Uncertainties (Known and Modeled Unknowns)

- Case material constitutive model artifacts (Multi-Linear Elastic-Plastic, no model form uncertainty)

Description	Distribution
Aluminum curves	Discrete samples
Critical crack opening strain	Uniform(0.03,0.05)

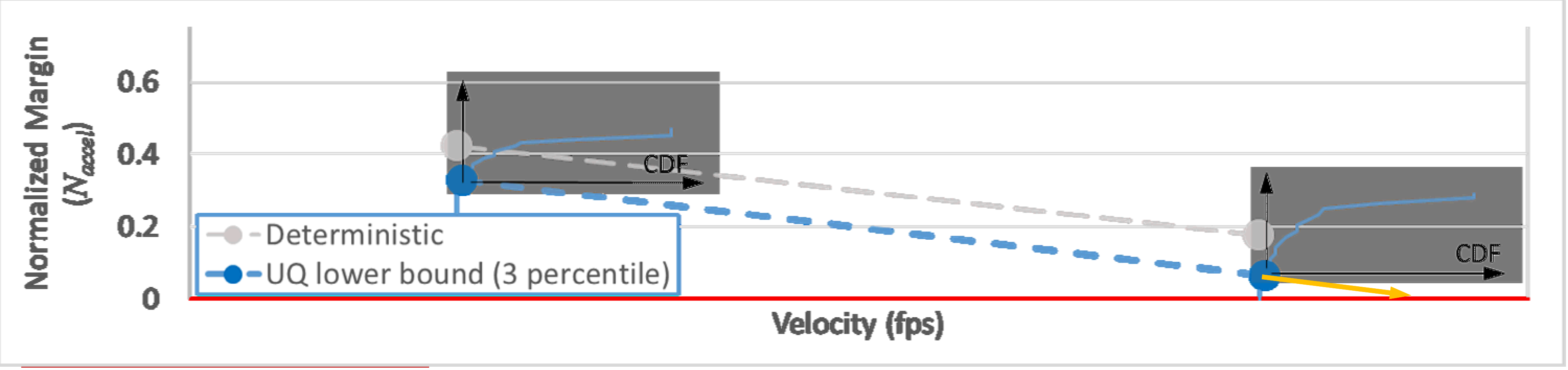
- Interface friction coefficient multiplier

Description	Distribution
Impactor-Cylinder	Uniform(0.9,1.1)
Cylinder-Foam	Uniform(0.9,1.1)
Foam-Box	Uniform(0.9,1.1)

- PMDI Foam model

Description	Distribution
Density Multiplier	Uniform(0.85,1.10)

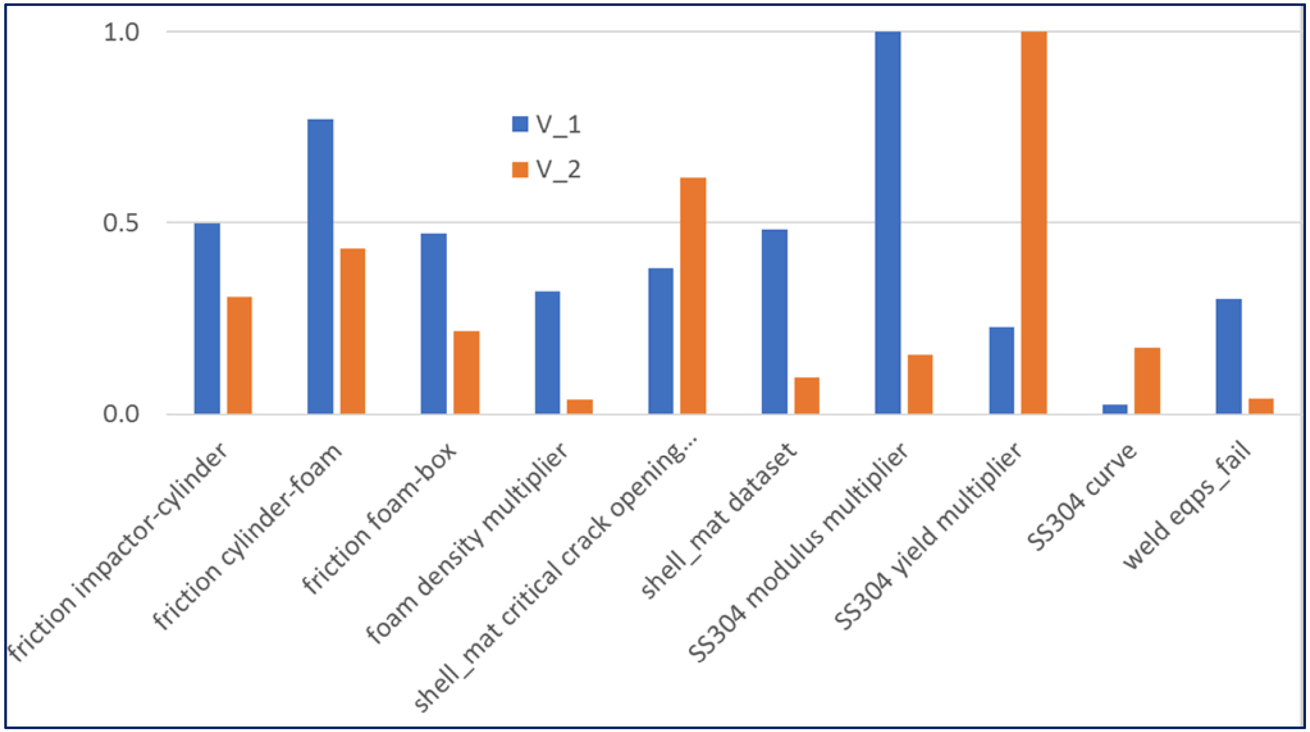
UQ Based Prediction for Loss of Function



- 30-60-120 sample incremental LHS (Latin Hypercube Sampling) in Dakota
- At higher velocity the response distribution is more dispersive
  - C. o. V. of stress-strain curves is higher at higher strains
  - Complex nonlinear structural response

Inference: The velocity for LOF is larger than v_2

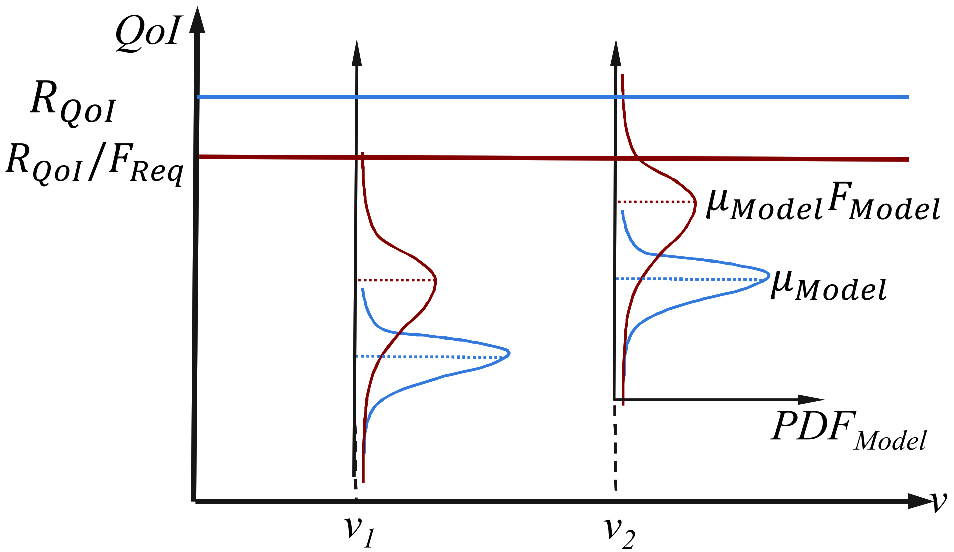
Bottom-Up UQ: Output (QoI) Sensitivities



- Linear partial correlation coefficients (absolute value)
- Conclusions
  - Importance ranking varies with impact velocity
  - **Defining "Upper Bound" deterministic parameter set for all velocities difficult**

Information aids resource allocation: which input variables are candidate for more accurate characterization?

Effect of Credibility Confidence and Requirement Derating Factors on LoF



Notes:

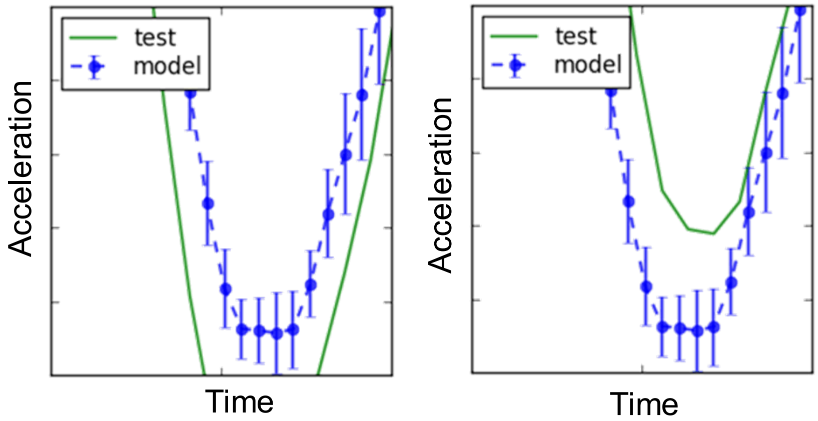
- μ denotes mean value
- When confidence factors are =1.0 impacts at v_2 are admissible
- When confidence factors are >1.0 impacts at v_2 are NOT admissible

- This approach doesn't account for
  - ***All uncertainties*** model captures only a subset
  - ***Diversity*** in SME judgement
  - ***Interval*** type uncertainties (parallel consistency, mesh sensitivity, etc.)
- Elicit confidence factors from both requirements (customers) and Comp/Sim (analysts)

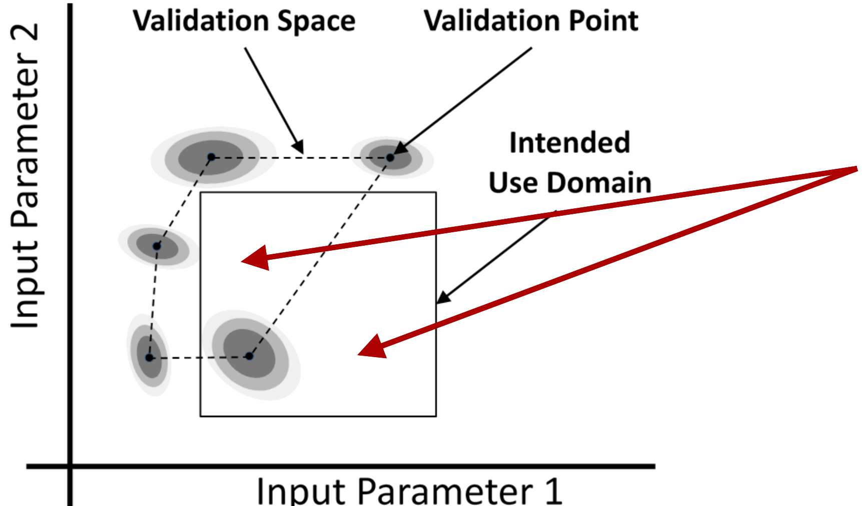
NOT yet suitable to make ***credible*** programmatic decision

Validation Evidence with Sparse Data

- Two destructive tests performed, response uncertainty from model UQ doesn't explain discrepancy



- Unit-to-unit variation likely – NOT modeled
- **Challenge**: Selection of validation metric, defensible acceptance criteria
- **Grand Challenge**: Sparse set of system tests, large mission space



- Ask the SMEs; expert elicitation
- Quantify answers
- Document evidence

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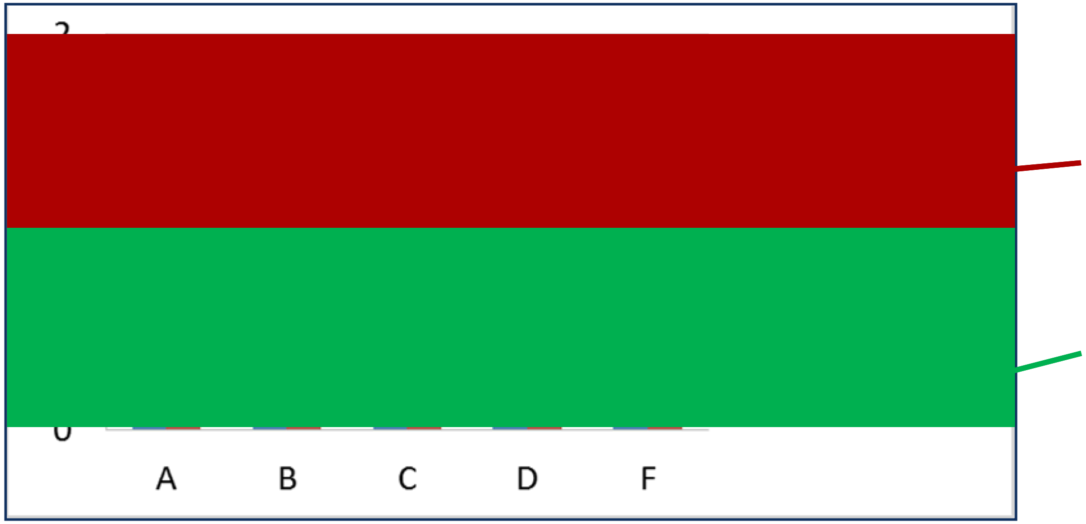
SME Elicitation to Quantify Mod/Sim Confidence

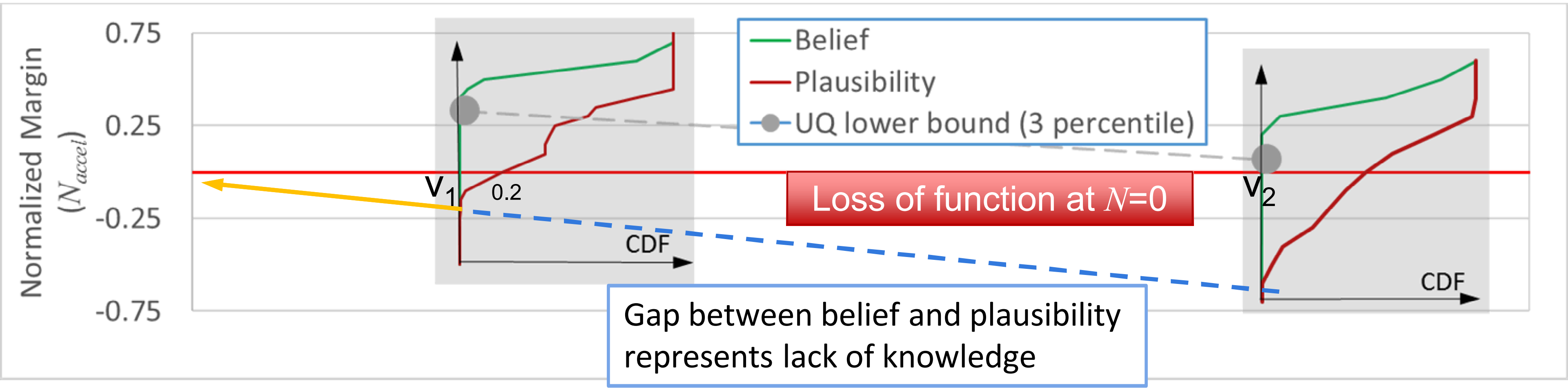
State of knowledge for peak acceleration



- Five Comp/Sim SMEs provided input on model confidence factors for
  - Quantified factors: mesh sensitivity, parallel consistency, model form error
  - Qualitative factors: experience base with similar devices
- SMEs review all evidence: validation, previous programs, SVER,
- Equal weighting for now (B and C are hands-on analysts)
- Similar elicitation is needed on the requirements side

Evidence Theory Based Prediction for Loss of Function

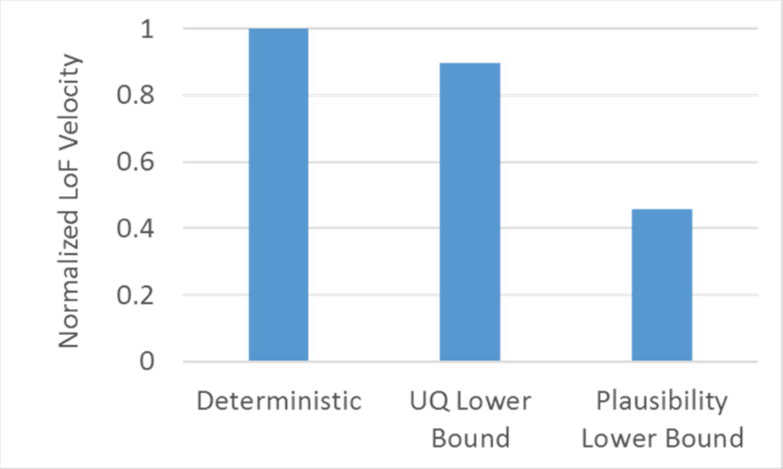
- Evidence Theory: general framework for reasoning with uncertainty; results expressed in terms of belief and plausibility. It combines
  - Customer SME judgement regarding acceptance criteria
  - Comp/Sim SME judgement regarding model credibility
  - Bottom-up UQ accounting for known unknowns propagated through the model
  - Other uncertainties expressed as intervals (numerical uncertainties)
- Implemented in Dakota (Dempster-Shafer method)



Inference 1: At v_1 there is a plausibility (~0.2) of Loss of Function
Inference 2: The velocity where there is no plausibility of Loss of Function is less than v_1

Credible Decision Making Based on Convolved UQ and SME Judgment

- Necessary conditions for credibility
  - Comp/Sim Model Credibility Process; Customer Comp/Sim, Experiment partnership
  - PIRT - Defines key physical phenomena and ranking their importance
  - PCMM – SME elicitation process designed to characterize and communicate the completeness and rigor of the Comp/Sim process
- Sufficient conditions for credibility
  - SME elicitation of quantitative model confidence and requirement derating factors
  - SME judgement and bottom-up UQ quantitatively convolved



- Risk of making program decisions based on deterministic models is high
- Risk-informed decisions from belief-plausibility
  - Accept the risk of plausible negative margin
  - Redesign
  - Re-evaluate acceptance criteria

Model credibility is defined in the context of intended use
Qualitative and quantitative body of evidence compiled by customer-analyst team