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Robust Design for Crash at DaimlerChrysler Commercial Vehicles CAE

3. LS-DYNA FORUM 2004
October 14/15, Bamberg

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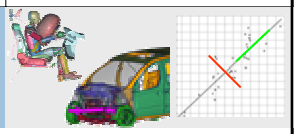
Outline



- Why is robustness important in crash?
- Meta-Modeling theory:
  Separation of deterministic and random variation
- Application (1): front impact model
- Application (2): sled test model
- Convergence studies
- Conclusions / outlook

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Real-Life Variations in Crash

- Why is robustness important in crash?
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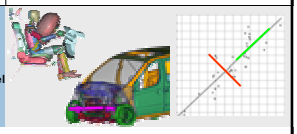

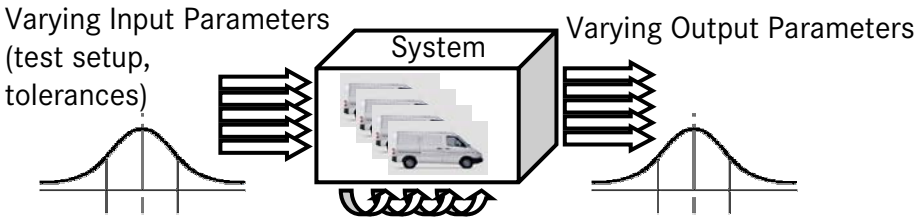

System Inherent Variations
(Bifurcations, Chaos, Unpredictable Variations)

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Example: Logistic Equation

$$x_{n+1} := a\, x_n\,(1 - x_n), \quad x_0 = 1 - 1/a$$

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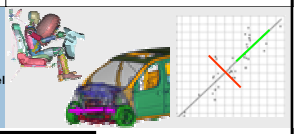
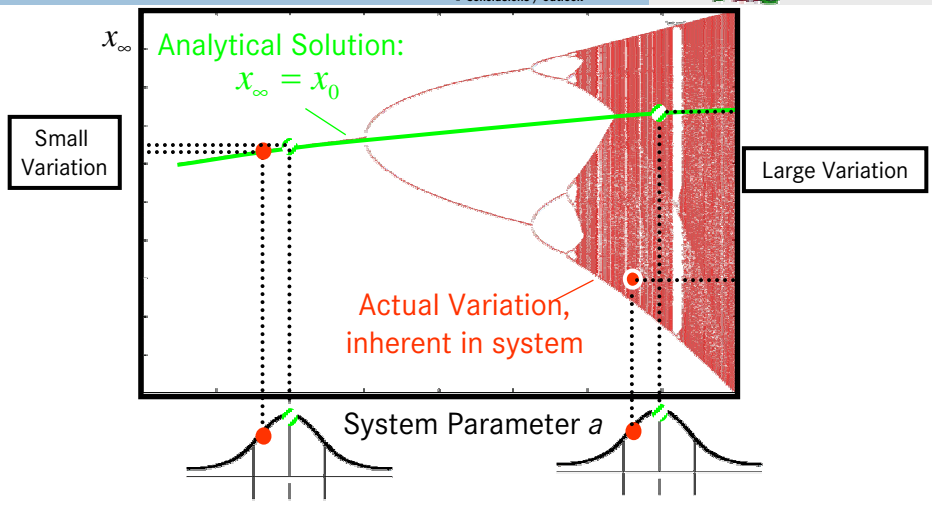
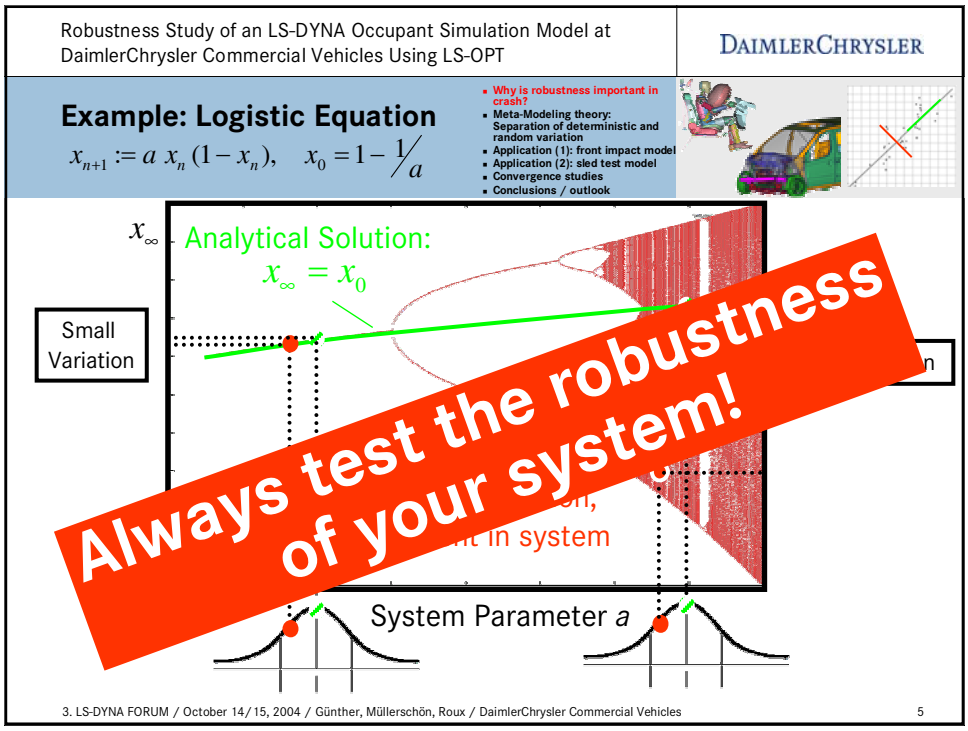
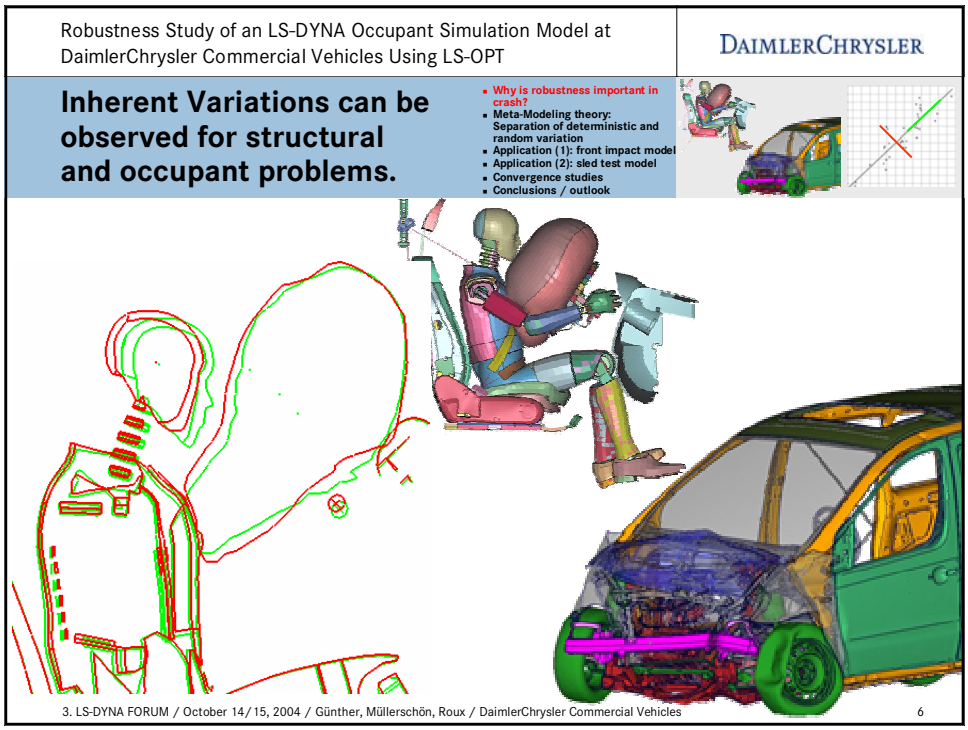
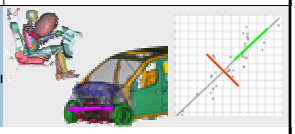




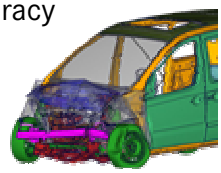


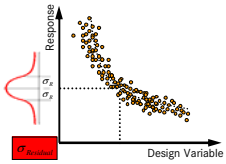


How can Meta-Modeling help us?

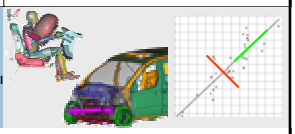


- Determine robustness of crash problems in LS-OPT based on LS-DYNA simulations
- Separate random and deterministic variation of results
- Get a better feel for the accuracy of our predictions and the repeatability of tests.
- Compute Sensitivities
- Identify influence factors on variation of results (stochastic contributions)
- More efficient alternative to standard stochastic approach (Monte-Carlo analysis)





Meta-Modeling as Projection onto a Predictable Space



$$y = \eta(\mathbf{x})$$

Scalar response variable | LS-DYNA | Vector of design variables

$$\eta(\mathbf{x}) = f(\mathbf{x}) + r(\mathbf{x}) = P\eta(\mathbf{x}) + Q\eta(\mathbf{x})$$

Meta-model | Residual | Projection onto predictable space | Projection onto residual space

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Meta-Model Characteristics

- Why is robustness important in crash?
- Meta-Modeling theory: Separation of deterministic and random variation
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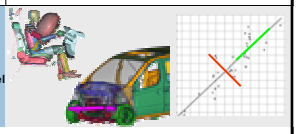

$$f(\mathbf{x}) = \sum_{\alpha=1}^{n} a_\alpha \varphi_\alpha(\mathbf{x}) = a_\alpha \varphi_\alpha = \mathbf{a}^T \varphi(\mathbf{x})$$

n coefficients

n basis functions, e.g. linear or quadratic

$$[\mathbf{x}_i] = \mathbf{X} = [\mathbf{x}_1\, \mathbf{x}_2 \ldots \mathbf{x}_m]$$

m experimental points, e.g. D-optimality criterion

$$\Phi = [\Phi_{i\alpha}] = [\varphi_\alpha(\mathbf{x}_i)]$$

$m \times n$ basis function matrix

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Fit Meta-Model to Experiments

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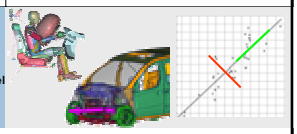

$$\mathbf{y}^T = [y_1\, y_2 \ldots y_m] \qquad \mathbf{r}^T = [r_1\, r_2 \ldots r_m] = \mathbf{y}^T - \mathbf{a}^T\Phi^T = \mathbf{y}^T - \mathbf{f}^T$$

Result vector

Residual vector

Prediction vector

$$\mathbf{a} = \left(\Phi^T\Phi\right)^{-1}\Phi^T\mathbf{y} \quad \text{minimizes} \quad \mathbf{r}^T\mathbf{r}$$

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Solution Decomposition Using the Meta-Modeling Technique

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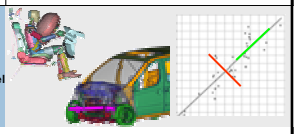

$$\mathbf{f} = \mathbf{A}\mathbf{y} \quad \text{with} \quad \mathbf{A} = \Phi\left(\Phi^T\Phi\right)^{-1}\Phi^T, \quad \mathbf{A} = \mathbf{A}^T, \quad \mathbf{A}\mathbf{A} = \mathbf{A}$$

Predictability Projection Matrix

$$\mathbf{r} = \mathbf{B}\mathbf{y} \quad \text{with} \quad \mathbf{B} = \mathbf{I} - \mathbf{A}, \quad \mathbf{B} = \mathbf{B}^T, \quad \mathbf{B}\mathbf{B} = \mathbf{B}, \quad \mathbf{A}\mathbf{B} = \mathbf{0}$$

Residual Projection Matrix

Orthogonality

Solution Decomposition

$$\mathbf{y} = \mathbf{A}\mathbf{y} + \mathbf{B}\mathbf{y} = \mathbf{f} + \mathbf{r} \quad \text{with} \quad \mathbf{f}^T\mathbf{r} = 0$$

Predictable by Meta-Model

Residual

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Metamodeling: Decomposition of Deterministic and Random Variation

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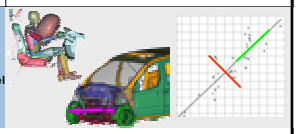

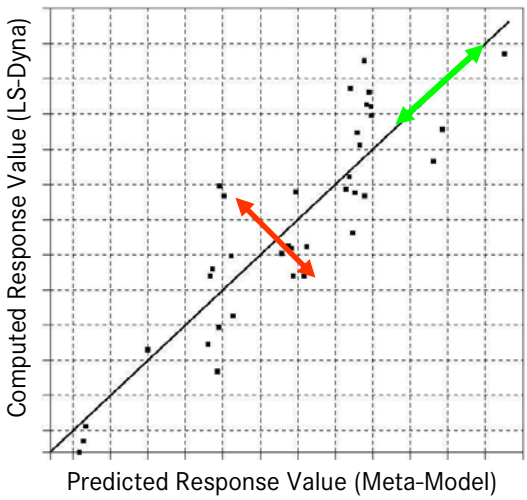

Variation of response based on variation of design variables

Random variation of response (noise, chaos, bifurcations)

We can separate deterministic variation and random variation!

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Meta-Modeling and Stochastic Contributions

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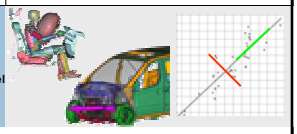
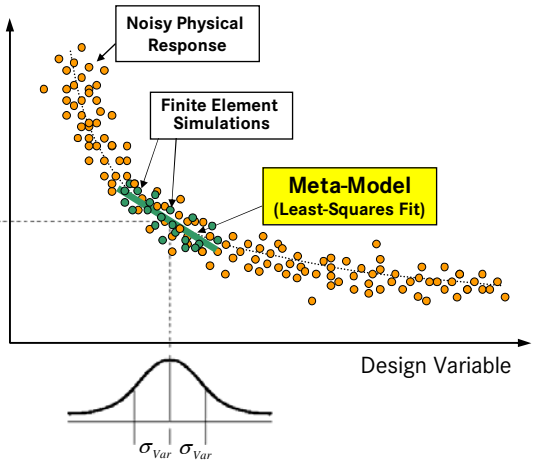


Stochastic Contributions

$\sigma_T = \sigma_R + \sigma_D$

σ^2_{Total} $\sigma^2_{Residual}$ $\sigma^2_{Determ.}$



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Application 1: Front Impact Model

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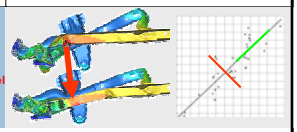

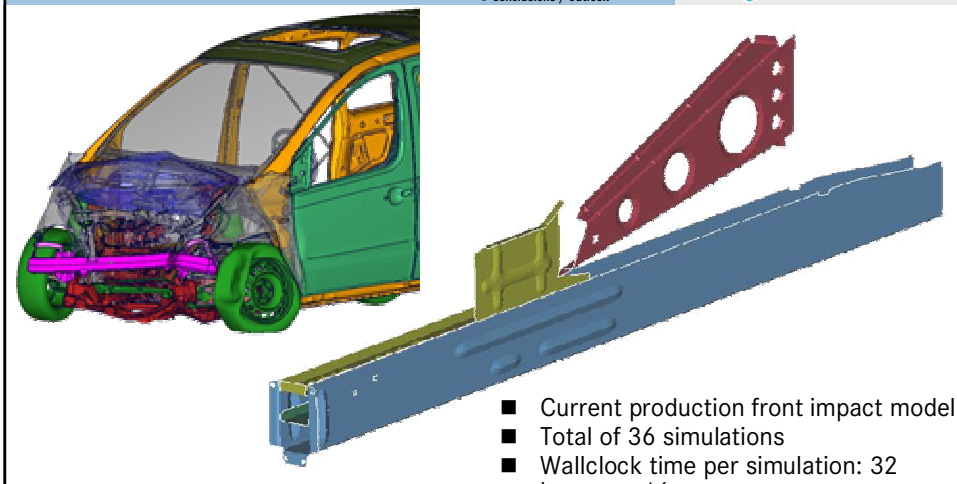

- Current production front impact model
- Total of 36 simulations
- Wallclock time per simulation: 32 hours on 16 cpus.

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Design Variables: Range/Standard Deviation

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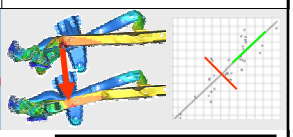

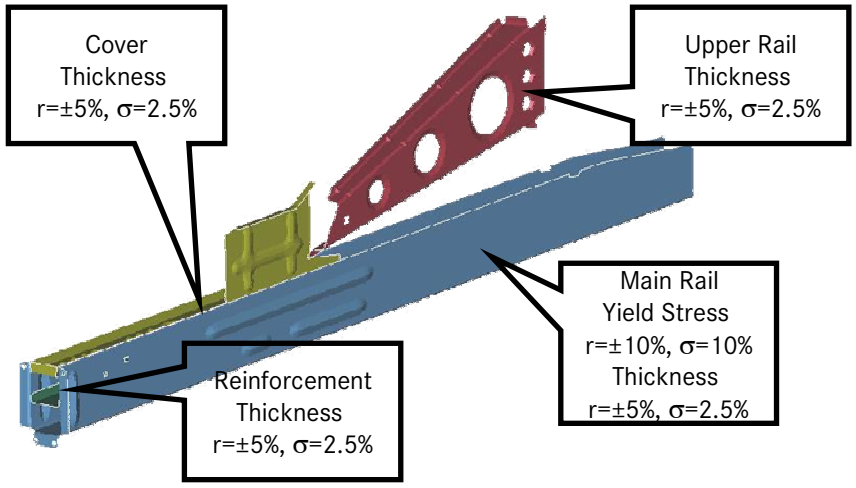

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Responses

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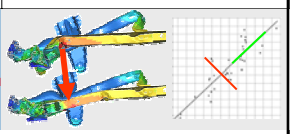

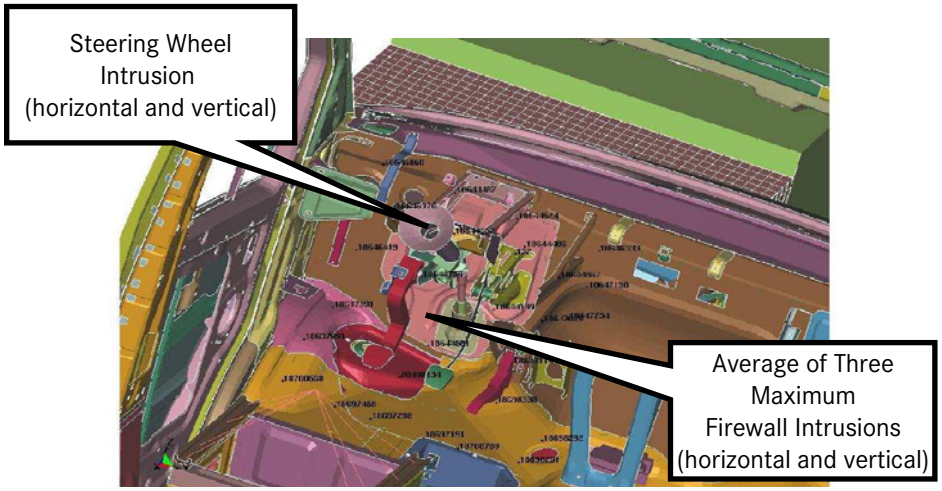

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Effect of Number of Simulations

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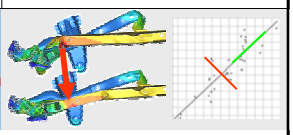

Probability of event	Required number of runs for observing 1 or more occurrences at 95% probability
0.45	5
0.26	10
0.14	20
0.095	30
0.06	50
0.03	100

In the present study, we were able to capture phenomena that occur with a probability of approx. 10% .

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Random and Deterministic Variation of Responses

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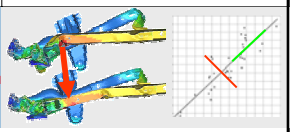

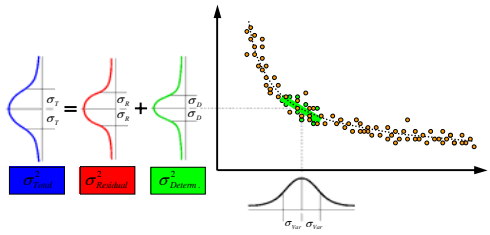

Intrusion	Reference Simulation	Mean	Deter-ministic Standard Deviation	Random Standard Deviation	Total Standard deviation
Steering X	96%	100%	13%	8%	15%
Steering Z	96%	100%	6%	11%	12%
Firewall X	93%	100%	11%	4%	13%
Firewall Z	84%	100%	16%	13%	21%

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Influence Factor Analysis

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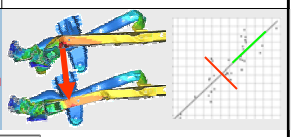

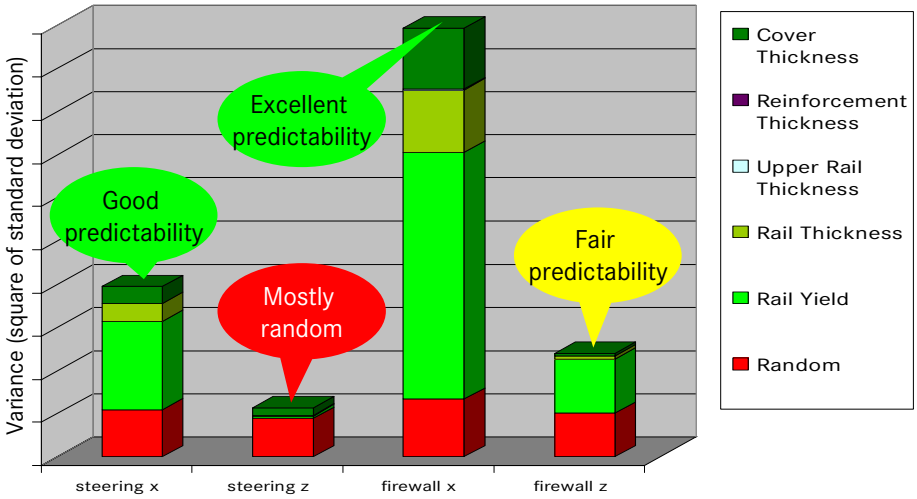

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Predictability: Influence of Design Variables

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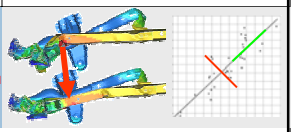

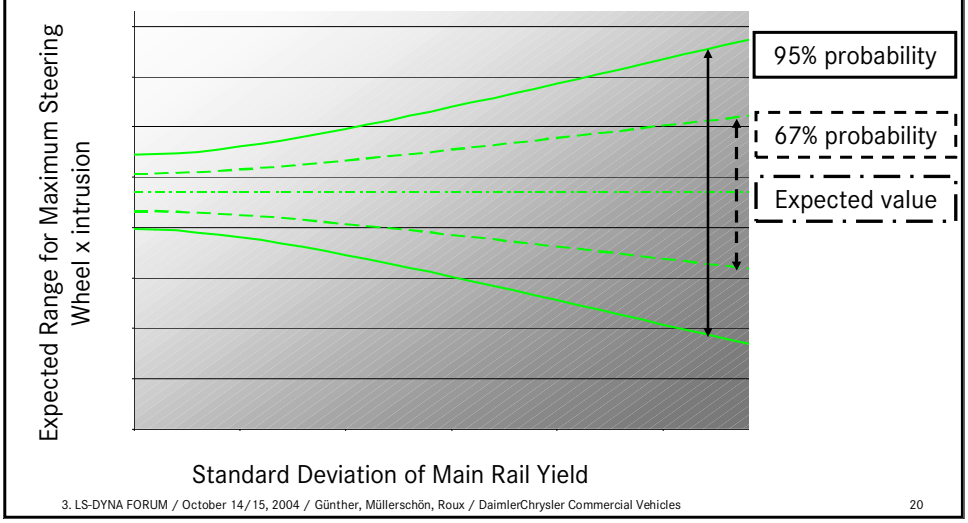

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Sensitivities

- Why is robustness important in crash?
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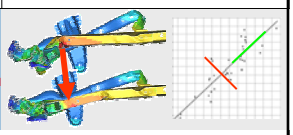

Intrusion	Normalized Derivative				
	Rail Yield	Rail Thickness	Upper Rail Thickness	Reinforcement Thickness	Cover Thickness
Steering X	-100%	-92%	Trivial	Trivial	-118%
Steering Z	Trivial	Trivial	Trivial	Trivial	-78%
Firewall X	-169%	-170%	Trivial	Trivial	-224%
Firewall Z	-80%	-40%	Trivial	Trivial	-47%

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Predicting Robustness of Mechanisms

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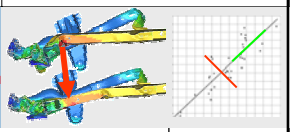

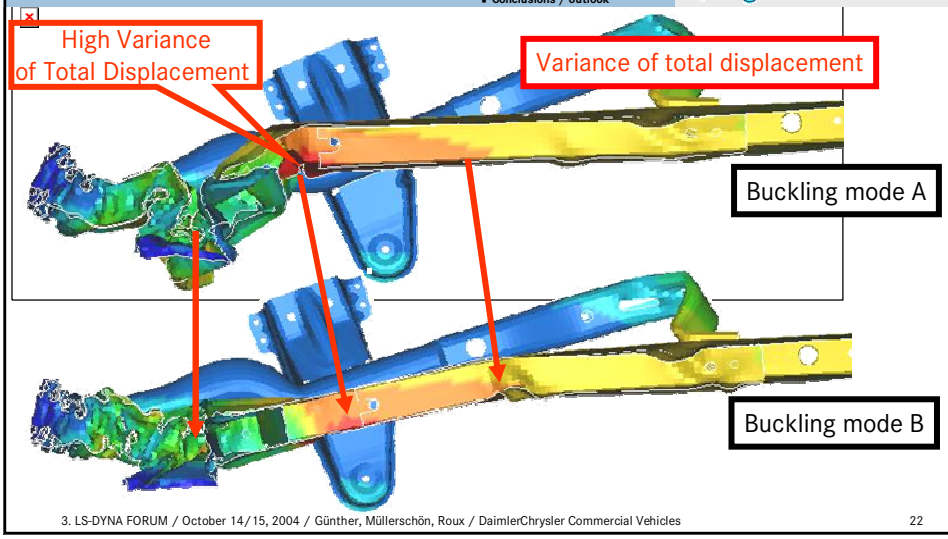

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Application 2: Occupant Simulation Model

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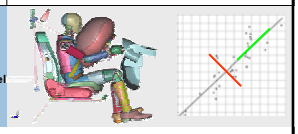
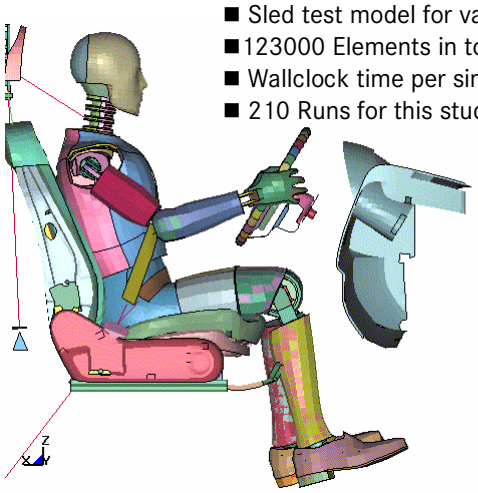
- Conclusions / outlook





- Sled test model for validation of occupant simulation
- 123000 Elements in total (Beams/Shells/Solids)
- Wallclock time per simulation: 9.5 hours on 16 cpus
- 210 Runs for this study, including 30 “pure noise” runs (only numerical parameters are modified)

x

3. LS-DYNA FORUM / October 14/15, 2004 / Günther, Müllerschön, Roux / DaimlerChrysler Commercial Vehicles 23

Robustness Study of an LS-DYNA Occupant Simulation Model at DaimlerChrysler Commercial Vehicles Using LS-OPT

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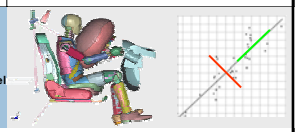
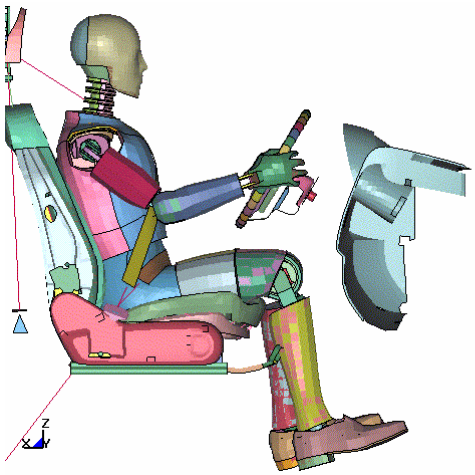
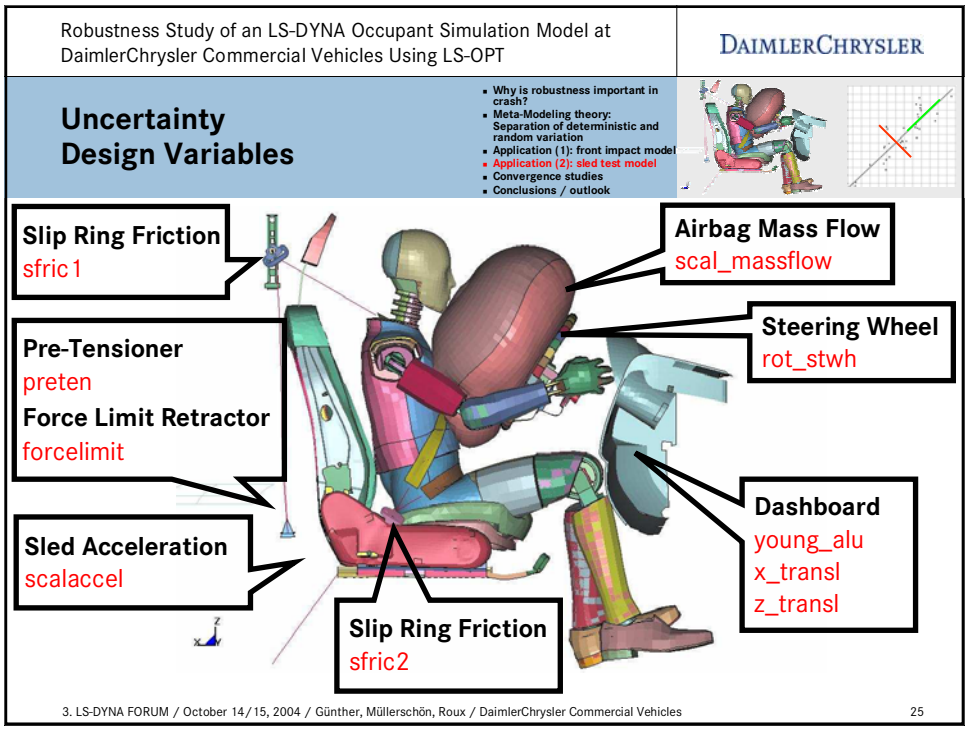
Occupant Simulation Model

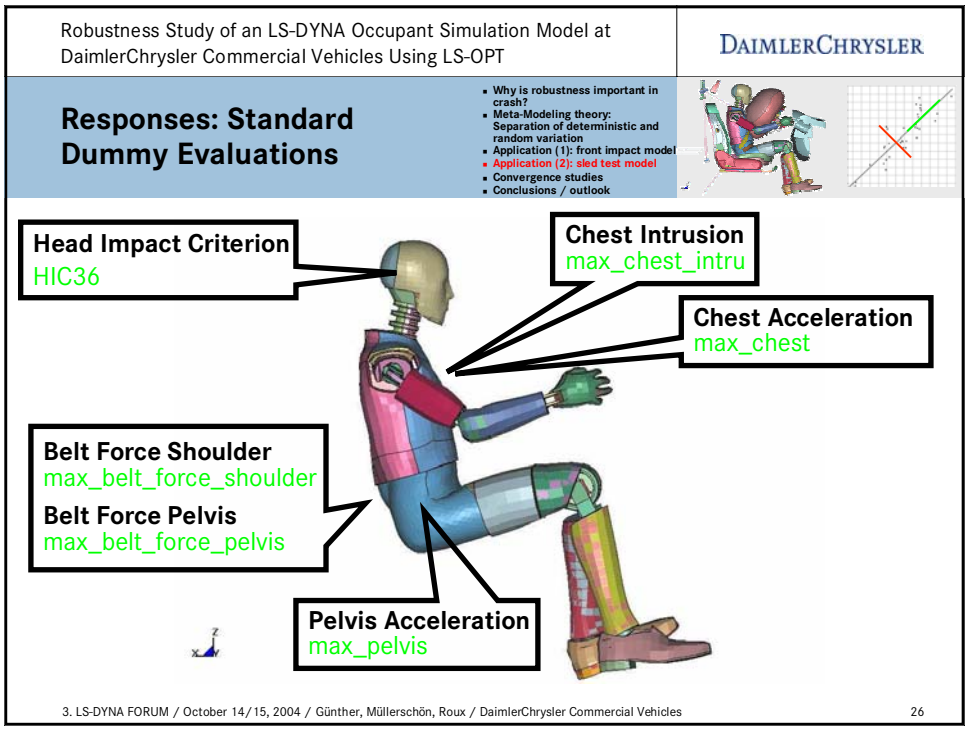
- Why is robustness important in crash?
- Meta-Modeling theory: Separation of deterministic and random variation
- Application (1): front impact model
- Application (2): sled test model
- Convergence studies
- Conclusions / outlook





3. LS-DYNA FORUM / October 14/15, 2004 / Günther, Müllerschön, Roux / DaimlerChrysler Commercial Vehicles 24





Robustness Study of an LS-DYNA Occupant Simulation Model at DaimlerChrysler Commercial Vehicles Using LS-OPT

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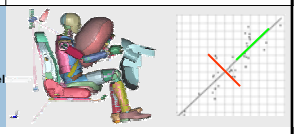
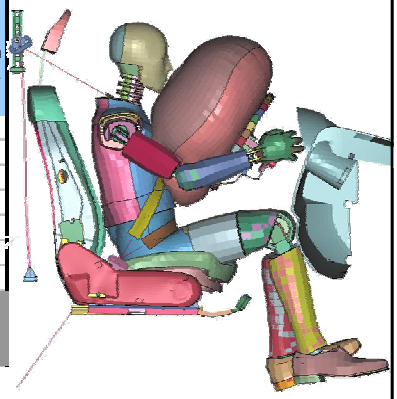
Experimental Setup of the Robustness Studies (1)

- Why is robustness important in crash?
- Meta-Modeling theory: Separation of deterministic and random variation
- Application (1): front impact model
- Application (2): sled test model
- Convergence studies
- Conclusions / outlook



Variable	Nominal Value	Setup 1 Range for Response Surface Min	Setup 1 Range for Response Surface Max	Setup 1 Standard Deviation for Meta-Model	Setup 2 Range for Response Surface Min	Setup 2 Range for Response Surface Max	Setup 2 Standard Deviation for Meta-Model
scalaccel	1,00	0,95	1,05	0,03	0,90	1,10	0,05
sfric1	1,00	0,50	1,50	0,25	0,00	2,00	0,50
sfric2	1,00	0,50	1,50	0,25	0,00	2,00	0,50
preten	1,00	0,91	1,09	0,04	0,82	1,18	0,09
forcelimit	1,00	0,89	1,11	0,06	0,78	1,22	0,11
rot_stwh	-1,00	-1,10	-0,90	0,05	-1,19	-0,81	0,10
transl_x	0,00	-1,00	1,00	0,50	-2,00	2,00	1,00
transl_z	0,00	-1,00	1,00	0,50			
scalmassflow	1,00	0,90	1,10	0,05			
young_alu	1,00	0,90	1,10	0,05			



3. LS-DYNA FORUM / October 14/15, 2004 / Günther, Müllerschön, Roux / DaimlerChrysler Commercial Vehicles 27

Robustness Study of an LS-DYNA Occupant Simulation Model at DaimlerChrysler Commercial Vehicles Using LS-OPT

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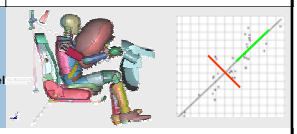
Experimental Setup of the Robustness Studies (2)

- Why is robustness important in crash?
- Meta-Modeling theory: Separation of deterministic and random variation
- Application (1): front impact model
- Application (2): sled test model
- Convergence studies
- Conclusions / outlook



Name of Robustness Study	Number of Experiments	Experiment Selection	Design Variables and Ranges	Meta-Model
L1-30	30	*D-optimal for linear response surface*	setup 1	linear
L1-60	60		setup 1	linear
L1-90	90		setup 1	linear
L1-120	120		setup 1	linear
L2-30	30		setup 2	linear
L2-60	60		setup 2	linear
Q1-90	90		setup 1	quadratic
Q1-120	120		setup 1	quadratic
Q2-60	60		setup 2	quadratic
Pure Noise	30	random	numerical parameters only (number of cpus, soft constraint, etc.)	none

3. LS-DYNA FORUM / October 14/15, 2004 / Günther, Müllerschön, Roux / DaimlerChrysler Commercial Vehicles 28

Robustness Study of an LS-DYNA Occupant Simulation Model at DaimlerChrysler Commercial Vehicles Using LS-OPT

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Stochastic Contribution Results for 30 Experiments (Linear Meta-Model)

- Why is robustness important in crash?
- Meta-Modeling theory: Separation of deterministic and random variation
- Application (1): front impact model
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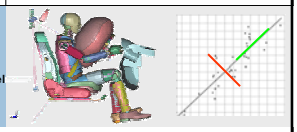
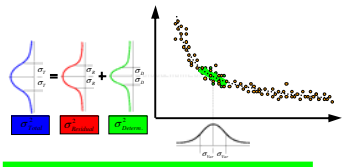
- Conclusions / outlook



Design Variable	Standard Deviation of Design Variable	Standard Deviation Contribution					
		HIC36	max_chest_intru	max_b_f_shoulder	max_bf_pelvis	max_chest	max_pelvis
scalaccel	2,5%	3,1%	1,5%	0,1%	2,3%	1,9%	2,9%
sfric1	25,0%	1,3%	0,6%	4,1%	1,8%	0,7%	0,7%
sfric2	25,0%	0,5%	0,6%	0,1%	3,7%	0,1%	0,1%
preten	4,4%	0,0%	0,5%	0,0%	1,1%	0,3%	0,2%
forcelimit	5,6%	1,3%	0,4%	4,4%	0,6%	1,4%	0,2%
rot_stwh	4,8%	0,5%	0,1%	0,1%	0,0%	0,1%	0,1%
transl_x	50,0%	0,1%	0,1%	0,7%	4,5%	0,5%	0,8%
transl_z	50,0%	1,2%	1,0%	0,3%	1,6%	0,2%	0,9%
scalmassflow	5,0%	1,8%	1,8%	0,6%	2,2%	0,6%	0,9%
young_alu	5,0%	0,3%	0,3%	0,0%	0,5%	0,1%	0,1%
all variables		4,3%	2,8%	6,1%	7,2%	2,6%	3,4%
residuals		4,7%	1,9%	1,8%	6,0%	3,5%	2,3%
Total		**6,4%**	**3,4%**	**6,3%**	**9,4%**	**4,3%**	**4,1%**



Contribution of Variation of design variables to variation of results.

Meta-model space

Residual space

Total Variation

3. LS-DYNA FORUM / October 14/15, 2004 / Günther, Müllerschön, Roux / DaimlerChrysler Commercial Vehicles 29

Robustness Study of an LS-DYNA Occupant Simulation Model at DaimlerChrysler Commercial Vehicles Using LS-OPT

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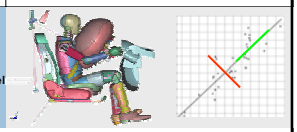
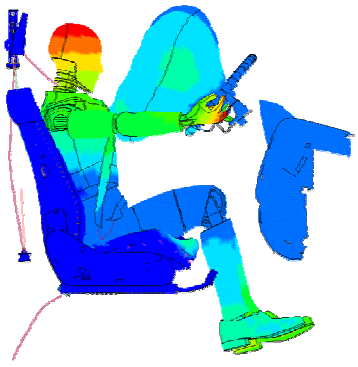
Displacement Statistics - Meta-Model vs. Outliers

- Why is robustness important in crash?
- Meta-Modeling theory: Separation of deterministic and random variation
- Application (1): front impact model
- Application (2): sled test model
- Convergence studies
- Conclusions / outlook

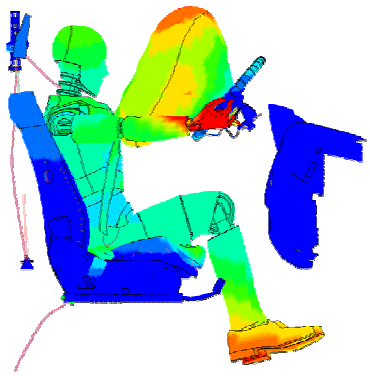


Standard deviation of x-displacements of each node (120 runs)

(a) Deterministic (Meta-Model)



(b) Residual (Outliers)



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Robustness Study of an LS-DYNA Occupant Simulation Model at DaimlerChrysler Commercial Vehicles Using LS-OPT

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Stochastic Contribution Plot for 30 Runs (Linear Meta-Model)

- Why is robustness important in crash?
- Meta-Modeling theory: Separation of deterministic and random variation
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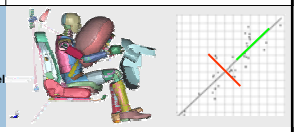

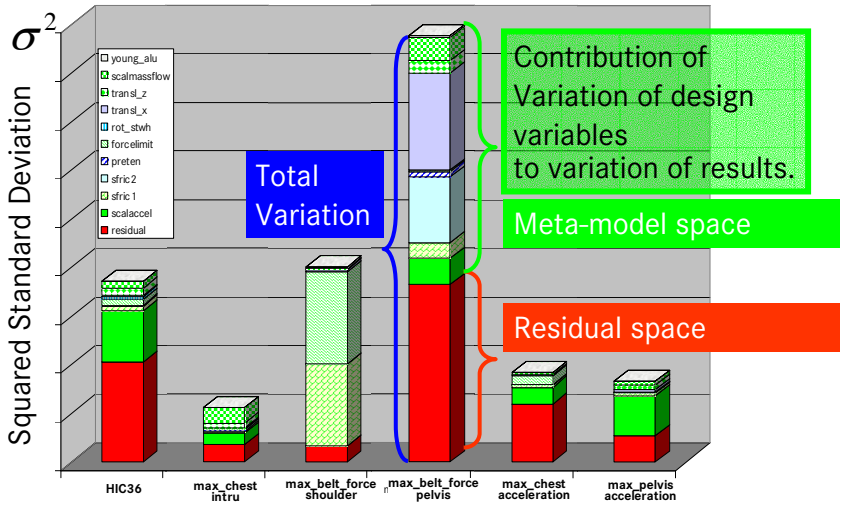

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Robustness Study of an LS-DYNA Occupant Simulation Model at DaimlerChrysler Commercial Vehicles Using LS-OPT

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Convergence Study of Stochastic Contributions and Residual for HIC36

- Why is robustness important in crash?
- Meta-Modeling theory: Separation of deterministic and random variation
- Application (1): front impact model
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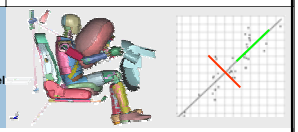
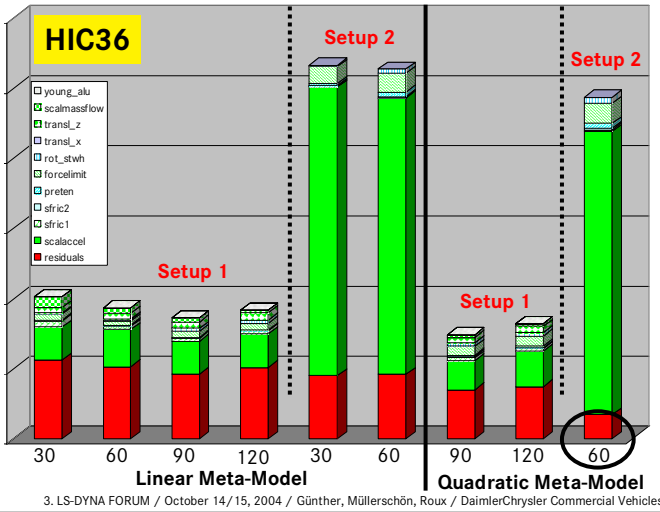
- Convergence studies
- Conclusions / outlook





- Good agreement of residual for different meta-models
- Small oversampling for Q2-60 => small residual
- Good agreement of stochastic contributions within experimental setup

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Robustness Study of an LS-DYNA Occupant Simulation Model at DaimlerChrysler Commercial Vehicles Using LS-OPT

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Convergence Study of Residual and Comparison to Pure Noise Residual

- Why is robustness important in crash?
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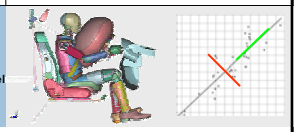

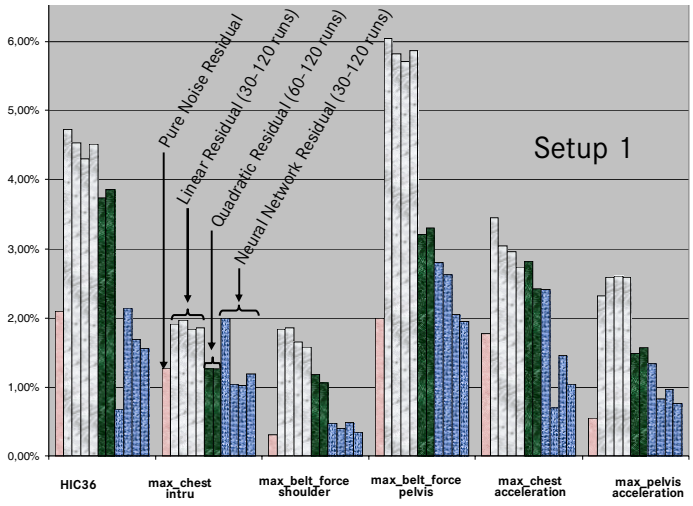

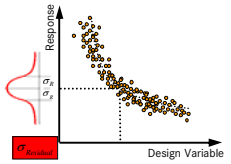

- Good agreement of residual for different meta-models
- Neural Network residual shows best agreement with Pure Noise residual => worth investigating
- Question: similar noise in hardware tests?

Robustness Study of an LS-DYNA Occupant Simulation Model at DaimlerChrysler Commercial Vehicles Using LS-OPT

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Conclusions/Outlook

- Why is robustness important in crash?
- Meta-Modeling theory: Separation of deterministic and random variation
- Application (1): front impact model
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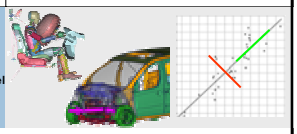

- Meta-Modeling shows great promise to be used in all stages of the vehicle development process to test for robustness of crash relevant components. Random an predictable variation can be separated.
- Is the variation we found inherent in the physics of the problem, or in finite element modeling? Difficult to say, unless we conduct a statistically significant number of identical hardware tests.
- Choice of response surface merits further investigation. Neural networks seem quite promising.
- Additional information: Talk by Dr. Stander (LSTC) on Friday, “Application of Neural Networks in LS-OPT”. References in conference proceedings

Thank you for your attention!

- Why is robustness important in crash?
- Meta-Modeling theory: Separation of deterministic and random variation
- Application (1): front impact model
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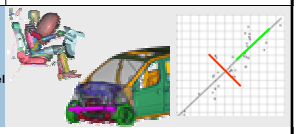
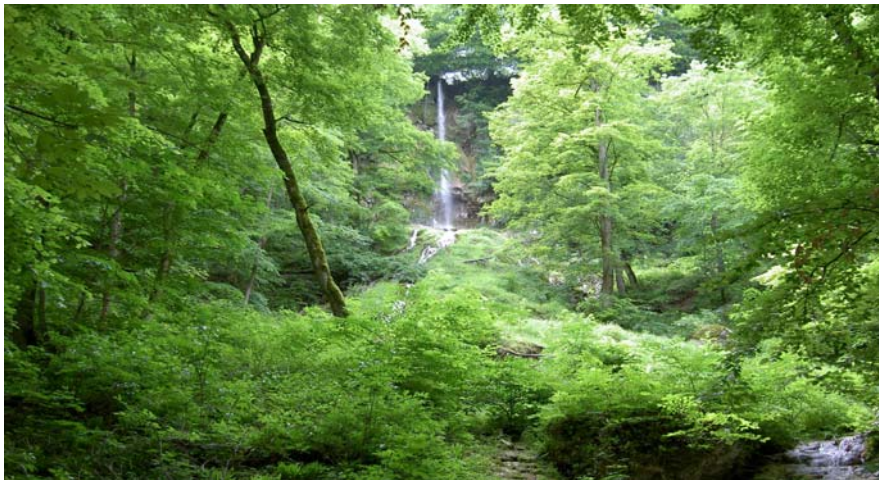
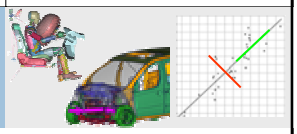




References



- *Nondeterministic Analysis of Highly Nonlinear Structural Problems* Roux W., Stander N., Günther F., Müllerschön H., in preparation.
- *Robustness Study of an LS-DYNA Occupant Simulation Model at DaimlerChrysler Commercial Vehicles using LS-OPT* Günther F., Müllerschön H., Roux W., LS-DYNA World Conference 2004, Dearborn, USA
- *Robustness Study of a Front Impact Model* Günther F., Müllerschön H., Roux W., JAPAN LS-DYNA Users Conference 2003, Tokyo
- *LS-OPT User's Manual Version 2* Stander N., Eggleston T., Craig K., Roux W.