Virtual Robustness –
Enabling new manufacturing strategies by variation-based product design

Product Development Symposium 2018

Robust Design Day
Thursday, 8th November
Technical University of Denmark

Dr. Stefan Kemmler
Knorr-Bremse makes mobility safe. By rail and road. Every day. Across the globe.

<table>
<thead>
<tr>
<th>RAIL VEHICLE SYSTEMS</th>
<th>COMMERCIAL VEHICLE SYSTEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-speed trains</td>
<td>Locomotives</td>
</tr>
<tr>
<td>Regional &amp; commuter trains</td>
<td>Passenger cars</td>
</tr>
<tr>
<td>Metros</td>
<td>Freight cars</td>
</tr>
<tr>
<td>LRVs</td>
<td>Off-train</td>
</tr>
<tr>
<td>Monorails</td>
<td>Trucks</td>
</tr>
<tr>
<td></td>
<td>Trailers</td>
</tr>
<tr>
<td></td>
<td>Buses</td>
</tr>
<tr>
<td></td>
<td>Engines</td>
</tr>
<tr>
<td></td>
<td>Special vehicles</td>
</tr>
</tbody>
</table>
## Sales by division

### Sales by division 2017

<table>
<thead>
<tr>
<th></th>
<th>2016</th>
<th>2017</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knorr-Bremse Group</strong></td>
<td>€ 5,494 million</td>
<td>€ 6,236 million</td>
<td>+13.5%</td>
</tr>
<tr>
<td><strong>Rail Vehicles Systems</strong></td>
<td>€ 2,990 million</td>
<td>€ 3,325 million</td>
<td>+11.2%</td>
</tr>
<tr>
<td><strong>Commercial Vehicle Systems</strong></td>
<td>€ 2,523 million</td>
<td>€ 2,928 million</td>
<td>+16.0%</td>
</tr>
</tbody>
</table>
From the brake system to automated driving

TODAY: 2018
- 2001 LDWS lane departure warning
- 2008 ACC adaptive cruise control
- 2015 AEBS Fusion for emergency braking behind stationary vehicles
- 2016 Yard Maneuvering (Demo)

TOMORROW: up to 2020
- 2019/20 Overvue all-round vision
- 2020 Turning Assist
- 2020 Lane Keep Assist
- 2021 Traffic Jam Assist

FUTURE: from 2020
- 2022 Truck Motion Control
- 2023 Highway Pilot
- 2024 Platooning 2.0
- Automated driving relieves the driver, saves fuel, and improves road safety
Virtual Robustness –
Enabling new manufacturing strategies by variation-based product design

Outline of the presentation

1. Introduction and motivation
2. Manufacturing and testing
3. Robust simulation and testing
4. Transfer from component to system level
5. Curb Impact Test and validation
   - Component
   - System
6. References
Virtual Robustness –
Enabling new manufacturing strategies by variation-based product design

Outline of the presentation

1. Introduction and motivation
2. Manufacturing and testing
3. Robust simulation and testing
4. Transfer from component to system level
5. Curb Impact Test and validation
   ▪ Component
   ▪ System
6. References
1. Introduction and motivation for virtual robustness

Reliability and Robustness (Robust Design) in society

Representative survey of the Center for Technology and Society (ZTG) at the TU Berlin (2017)[1]

Importance of product features when choosing a washing machine

<table>
<thead>
<tr>
<th>Feature</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>long lifetime &amp; robust</td>
<td>94%</td>
</tr>
<tr>
<td>low water/electricity cons.</td>
<td>93%</td>
</tr>
<tr>
<td>low cost</td>
<td>71%</td>
</tr>
<tr>
<td>up to date</td>
<td>70%</td>
</tr>
<tr>
<td>as quietly as possible</td>
<td>70%</td>
</tr>
<tr>
<td>good test results</td>
<td>68%</td>
</tr>
<tr>
<td>wash gently</td>
<td>61%</td>
</tr>
<tr>
<td>easy repair</td>
<td>57%</td>
</tr>
<tr>
<td>good service</td>
<td>56%</td>
</tr>
<tr>
<td>brand</td>
<td>35%</td>
</tr>
<tr>
<td>integrated dryer</td>
<td>12%</td>
</tr>
<tr>
<td>Smart-home capable</td>
<td>10%</td>
</tr>
</tbody>
</table>

Reliability and robustness describe products / processes that meet the requirements and fulfill the highest quality.

Definition Reliability

“...ability of a unit to perform a required function under given conditions for a given period of time.”[2]

Definition Robustness

“...insensitivity of products or processes to different sources of variation.”[3]

Current state:

GM Ignition Switch Recall

GM recommends using only a single ignition key

Stop using heavy key rings immediately


1. Introduction and motivation for virtual robustness

Robust Reliability – \((R^2)\)\(^{[4],[5]}\)

Hypothesis:
- By combining both theories: **Reliability** and **Robust Design**
- in one approach, higher product quality can be achieved than by separate application.

Classic consideration and design of products and processes with regard to variation:
- in use → **Reliability**
- in the manufacturing process → **Robust Design**

Solution:
Consideration **Robustness** over time of use → **Reliability**

Definition:
**Robust Reliability** \((R^2)\) is the **probability** that a product or process will maintain its required functionality with less variance during its entire **service life**, despite all the **internal and external noises** that occur.

\(^{[4]}\)Kemmler, S.; Eifler, T.; Bertsche, B.: ROBUST RELIABILITY - Methodology for an integrated consideration of robustness and reliability in mechanical design

\(^{[5]}\)Kemmler, S.: Integral methodology for the development of robust, reliable products
1. Introduction and motivation for virtual robustness

Reliability goals from specifications – what‘s about robustness?

**What‘s about one load cycle (crash)?**
1. Introduction and motivation for virtual robustness

Reliable and robust demand for safety?

Automotive Safety Integrity Level (ASIL)

- **Hypothesis:**
  As the complexity of a system increases, the risk of systematic failures and random hardware failures increases.

Example of systems for which the standard was developed include:

**BUT:**
ISO 26262 as a functional safety standard only valid for electronic / electrical / programmable electronic safety-related systems.

**QUESTION:**
What about use case like mechanical steering knuckle?
There is no standard available for safety related development!
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

Outline of the presentation

1. Introduction and motivation
2. Manufacturing and testing
3. Robust simulation and testing
4. Transfer from component to system level
5. Curb Impact Test and validation
   ▪ Component
   ▪ System
6. Discussion and conclusion
7. References
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

Manufacturing time scale

<table>
<thead>
<tr>
<th>Driver</th>
<th>Material</th>
<th>Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effort</td>
<td>Heat-treatable steel</td>
<td>Forming</td>
</tr>
<tr>
<td>Stiffness</td>
<td></td>
<td>Pressing</td>
</tr>
<tr>
<td>Shaping</td>
<td>AFP-steel (Precipitation-hardenable ferritic-pearlitic steels)</td>
<td>Forging</td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td>Deburring</td>
</tr>
<tr>
<td>Weight</td>
<td>New: Cast iron steel</td>
<td></td>
</tr>
</tbody>
</table>

Challenges:
- No experience with cast iron in steered axles
- So far no standard load case is given.
- Safety due to over engineered components and years of experience
With which load case and proof can you ensure a robust and reliable product?

Selection of abuse scenarios[6]

<table>
<thead>
<tr>
<th>Crash-based</th>
<th>Impulse-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravel heap</td>
<td>bike</td>
</tr>
<tr>
<td>animal-vehicle crash</td>
<td>football</td>
</tr>
<tr>
<td>crash</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chassis-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>uneven road</td>
</tr>
<tr>
<td>beam crossing</td>
</tr>
<tr>
<td>edge climb</td>
</tr>
<tr>
<td>lateral jostle</td>
</tr>
</tbody>
</table>

Challenge:
No established assumption or testing method in commercial vehicle area

Reason:
Historically grown design and no explicit proof required (heat-treatable steel)
Results of curb impact test on component level\cite{7}

Assumptions:

- No real, measurable proof, based solely on simulation results (MBS model)
- AFP steel for years in field use, no feedback → engineered and designed on a save side!

Requirements:

- No breakage failure,
- Controllable control of the vehicle to a stop, with permissible deformation on the chassis

Results or damage with the same design:

1. Impact test successful with AFP-steel
2. Impact test not successful with cast iron

Question:

How to protect cast iron knuckle against this impact load?

\cite{7} Kaufmann, M.; Küppers, M.: Höheres Leichtbau- und Einsatzpotential praxisrelevanter Schmiedewerkstoffe

\cite{8} Küppers, M.; Streicher, M.; Herbert, A.; Schönborn, S.: Betriebssichere Auslegung von Fahrwerksbauteilen aus AFP-Stahl am Beispiel eines Nfz-Achsschenkels

Figure\cite{8}:
AFP-steel (left) vs. heat-treatable steel (right) after impact test

Note: Knuckle and values are standardized

Figure:
Cast iron steel broken after impact test (virtual and real)
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

Outline of the presentation

1. Introduction and motivation
2. Manufacturing and testing
3. Robust simulation and testing
4. Transfer from component to system level
5. Curb Impact Test and validation
   - Component
   - System
6. References
Define new test environment for a holistic consideration

Based on question:

- Why does the cast knuckle break?
- Was the test interpreted correctly?
- Is there a test that is more representative?

Tasks:

- Extend component test to module test for consideration of interaction effects
- Respect stiffness and damping effects at the system boundary

Vorhaben 1635 BG: Betriebssichere Auslegung von Fahrwerkssicherheitsbauteilen aus AFP-Stahl.
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

Map of Variation – Virtual testing

- Load
- Weather conditions
- Velocity
- Angle
- Position
- Tire
- Surface
- ... (additional variables)

Figure: see reference [7]
Map of Variation in test environment – component

- Temperature
- Velocity
- Mass
- Height
- Position
- Energy
- Design
- Stiffness
- Damping

Virtual Robustness – Enabling new manufacturing strategies by variation-based product design
Map of Variation in test environment – system
Virtual design development based on considered map of variation

4 steps to robust, reliable knuckle design

Prior knowledge

<table>
<thead>
<tr>
<th>Load definition</th>
<th>Material properties</th>
<th>Damage</th>
<th>Lifetime behavior</th>
<th>Failure behavior</th>
</tr>
</thead>
</table>

Improvement of topology based on variation

Variation simulation

Parameter optimization

Parameter set:
- Design
- Material
- Ext-/internal load
- ...

Virtual Robustness – Enabling new manufacturing strategies by variation-based product design
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

All-in-one Simulation – system- and component level

Shown is the setup of component level

Note: Knuckle and values are standardized

Conclusion:
Based on the simulations and design studies
- Tendency to damage: the pin and on the inside
- but not a complete rupture of the steering knuckle.
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

Parameter analysis and Robust Design Optimization (RDO)

Parameter analysis

- Identify significant factors via sensitivity study

- Get the parameter behavior via correlation matrix

Robust Design Optimization (RDO)

- Using different optimization methods
- Identification of global and local models of robustness
- Usage of expected value as robust value

Target:
Parameter-Optimization based on merged mean value and corresponding variance.

![Parameter analysis diagram](image)

![Robust Design Optimization diagram](image)
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

**Definition of system- and component-test based on robustness consideration**

- **Impact load by drop hammer test on component level**
- **Impact load by pendulum impact test on system level**

**Conclusion:**
- Component test is a release for each design level and finally for the system test.
- System test gives more information about the other components and their interaction(s).
- Component test setup is much more efficient than the single component test.
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

Outline of the presentation

1. Introduction and motivation
2. Manufacturing and testing
3. Robust simulation and testing
4. Transfer from component to system level
5. Curb Impact Test and validation
   - Component
   - System
6. References
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

Simulation – component level

Consideration of energy in wheel end and knuckle (casting)

With the given condition and the potential energy:

\[ E_{\text{pot}} = m \cdot g \cdot h \]

the energy for the drop hammer test is given.

Note: Knuckle and values are standardized

Maximum of the total energy of the wheel end at 25 kJ

~25 kJ

Setting balance

Maximum of the total energy of the wheel end at 100 kJ

~100 kJ

Energy \( \rightarrow \) Simulation time \( \rightarrow \)

Energy \( \rightarrow \) Simulation time \( \rightarrow \)

With the given condition and the potential energy:

\[ E_{\text{pot}} = m \cdot g \cdot h \]

the energy for the drop hammer test is given.

Note: Knuckle and values are standardized
### Simulation – system- and component level

Energy-comparison of both levels

<table>
<thead>
<tr>
<th>Component</th>
<th>IE</th>
<th>KE</th>
<th>PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel End</td>
<td>0.95</td>
<td>0.11</td>
<td>0.72</td>
</tr>
<tr>
<td>Knuckle</td>
<td>0.16</td>
<td>0.09</td>
<td>0.13</td>
</tr>
</tbody>
</table>

**System level 100 kJ**

**Component level 25 kJ**

**Conclusion:**

Identical damage distribution and similar energy balance between system and component test; Same behavior with the knuckle forging material → Component test illustrates the behavior of the system test very well.

Note: Knuckle and values are standardized.
Virtual Robustness –
Enabling new manufacturing strategies by variation-based product design

Outline of the presentation

1. Introduction and motivation
2. Manufacturing and testing
3. Robust simulation and testing
4. Transfer from component to system level
5. Curb Impact Test and validation
   ▪ Component
   ▪ System
6. References
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

Drop hammer test

Velocity of the impact

Deformation in x-direction

<table>
<thead>
<tr>
<th>Impact</th>
<th>Velocities</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 6.8 m/s</td>
<td></td>
</tr>
<tr>
<td>~ 24.5 km/h</td>
<td></td>
</tr>
</tbody>
</table>

Gauge bar

Rim

Axle

Total Energy amount ~25 kJ

Δ ~10 mm
Post processing and validation – component level

Comparison of the deformed rim and the introduced energy

- ~ 10 mm deformed rim after impact test
- ~ 25 kJ introduced energy
→ Matched validation in both values

First time right:
- Cast iron knuckle doesn’t break!
- Predicted deformation and energy impact match!
- Optimized, robust and reliable design is developed!
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

Post processing and validation – system level

Comparison of the deformed rim and the introduced energy

- No broken location is identified.
- Based on simulation a robust, reliable design is given.

Note: Knuckle and values are standardized
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

First time right:
- Cast iron knuckle doesn’t break!
- Predicted deformation and energy impact match!
- Optimized, robust and reliable design is developed!
- Transfer from component to system level is valid!
The word "coincidence" is only the expression of our ignorance.

*Pierre Simon Marquis de Laplace (1749 – 1827)*
Virtual Robustness –
Enabling new manufacturing strategies by variation-based product design

Outline of the presentation

1. Introduction and motivation
2. Manufacturing and testing
3. Robust simulation and testing
4. Transfer from component to system level
5. Curb Impact Test and validation
   ▪ Component
   ▪ System
6. References
Virtual Robustness – Enabling new manufacturing strategies by variation-based product design

References


[2] VDI 4002-2:
Reliability Engineer – Requirements for qualification. Verein deutscher Ingenieure, 2011.

[3] Taguchi, G.; Chowdhury, S.; Wu, Y.:


[6] Engelmann, S.:
Simulation von fahrwerkdominierten Misuse–Lastfällen zur Unterstützung der virtuellen Crashsensorik. Helmut Schmidt University Hamburg, 2013


[9] IGF-Vorhaben 1635 BG:
Betriebssichere Auslegung von Fahrwerkssicherheitsbauteilen aus AFP-Stahl. Forschungsvereinigung Forschungsgesellschaft Stahlverformung (FSV) in Kooperation mit Forschungsvereinigung Stahlanwendung e.V. (FOSTA) – Gefördert durch AiF im Rahmen der IGF.
For more questions, comments and / or idea, don’t hesitate to contact me.

Knorr-Bremse SfN GmbH
Dr. Stefan Kemmler
Moosacher Strasse 80
D-80809 Munich

Tel.: +49 89 3547-183492
Email: stefan.kemmler@knorr-bremse.com
www.knorr-bremse.com