Model-Based Testing of Driver Assistance Systems for Counterbalance Forklift Trucks
Motivation for the Introduction of Model-Based Testing at Linde Material Handling

Linde Safety Pilot Driver Assistance System

Modeling Requirements for Testing the Linde Safety Pilot Driver Assistance System

Model Validation

Model-Based Testing Framework
Evolution of Software-Testing at LMH

Electronic Control Unit (ECU) Testing

<table>
<thead>
<tr>
<th>Vehicle-Based</th>
<th>Model-Based</th>
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</thead>
<tbody>
<tr>
<td>Manual Testing</td>
<td>Fully Automated Testing</td>
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<tr>
<td>Reporting -</td>
<td>Reporting +</td>
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<tr>
<td>Time -</td>
<td>Time ++</td>
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<td>Quality -</td>
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<td>Flexibility -</td>
<td>Flexibility +</td>
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Main Drivers to Introduce Model-Based Testing

- More projects
- More variants
- Higher function complexity
- Shorter development cycles
- Stricter regulations e.g. functional safety
- Increased test effort to validate future assistance systems e.g. LSP
Outline

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Linde Safety Pilot Driver Assistance System
Modeling Requirements for Testing the Linde Safety Pilot Driver Assistance System
Model Validation
Model-Based Testing Framework
Accidents with Counterbalance Forklift Trucks Happen – And Often the Drivers are not Aware Why
### Who is Responsible?

**Operator**

BGV D27- § 8 Stability Against Collapse:
"Counterbalance trucks have to be operated in a way, that stability against collapse is preserved."

**Driver**

**Responsibility of the Forklift Driver**
- Load?
- Load center of gravity?
- Maximal allowed lifting height?

**Producer**

Producers are liable to indicate the stationary carrying capacity in each truck.

![Diagram showing load capacity chart](image)
Stationary Carrying Capacity
Stationary Carrying Capacity is Often Hard to Determine
Linde Material Handling

Linde Safety Pilot - Active
Measured Quantities and Sensors

Axle-Force Sensor

Pressure Sensor

Load Force

Wire-Actuated Encoder

Rear-Axle Force

Lifting Height

Lifting Height
Video LSP-WOM
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- Model-Based Testing Framework
HIL Design
HIL Design – Modeling World
Modeling, Data Acquisition

Responsibility Linde

- Mast+Attachment Data
- Working Hydraulics Model
- Sensor Characteristics
- Steering Model
- Brake Model
- CAN Restbus
- Powertrain Models
  - electric
  - hydraulic
- Powersource Models
  - Battery
  - ICE

Responsibility IPG

DUT

Road Environment
Chassis
Tires
Vehicle dynamics
+ Mast dynamics
## Huge Truck Variety

**Actual Series BR387/388**

<table>
<thead>
<tr>
<th>Capacity</th>
<th>F20</th>
<th>F25</th>
<th>E30</th>
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- **387**
- **388**

**Trucks:** 34

**Masts:** 4

**Height Range:** 3-7m

**LSP500**

**LSP600**

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<tr>
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### Actual Series BR387/388

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- Masts: 4
- Height Range: 3-7m

LSP500 LSP600
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Hardware In The Loop – HIL Validation Process

- Data Acquisition
- System Modeling
- Test Execution
- Setup HIL Environment
- Model Validation
- Discussion of Results
- Approved Model

Discussion of Results

Approved Model
Vehicle Dynamics Validation
Test Execution - Validation Driving Maneuvers

Quelle: Schyr, Fa IPG
Real Input

Pedal

Steering wheel

Real vs Simulated Results

- Speed
- $a_x$
- $a_y$
Lifting Dynamics Validation
Forklift z Coordinate

Mast Stage Transition

Measurement
Simulation

z in m

p oil in bar

F in dN

Time in s
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### 1. Requirement

„Drive speed shall be reduced smoothly when forklift condition is potentially dangerous e.g. lifted load while driving...“

### 2. Setup Model

**Physically:**
- Inertia of Vehicle
- Center of Gravity
- Mast type and data
- Mast attachment
- Geometries
- Powertrain
- Hydraulics
- Tires

**Electrically:**
- Additional sensors
- Additional control units
- Additional data and teaching effort for ECU operability

### 3. Test case generation

- Define maneuver
- Define various conditions in which to test:
  - Loads
  - Load center of gravity
  - Mast type + attachment
  - Vehicle variant
  - Environment (Road inclination, surface...)
- Program test script
- Decide on which physical quantities to focus for automated test case evaluation → Criteria!

### 4. Test case execution on Hil

- Execute test scripts + store results
- Check if specified boundaries have been violated
- Automated protocol with highlighted deviations including illustrations
- No user interaction required
- Remote usage of analyzing tools (e.g. Matlab)
Hardware In The Loop – HIL
State Diagram & Electrical Failure Testing

1. Requirement

2. Test case
   - Straightforward
   - Mouse click programming
   - Predefined macros
   - Configurable macros

3. Test case schedule

4. Test case execution on Hil with test manager software

- Collect test cases A, B, ...
- Specify expected behavior
- Review previously generated result files and re-specify behavior

- Load schedule + execute test cases A, B, ...
- Store results
- Compare to expected behavior given by test case schedule (automated/interactively)
- Highlight deviations
Linde Safety Pilot
Go to your limits. But never beyond!

Linde Material Handling