Prepared for

CAR2017

International Congress of Automotive and Road Transport Engineering, University of Pitesti, Romania

Pitești, November 9th, 2017
S. Herrmann, Dr. M. Nijs, H. Lehn, D. Guse, Dr. J. Scharf, J. Berquez, R. Wellers
Engine-in-the-Loop Testing
Simulation of Real Driving Scenarios at the Engine Test Bench

- Challenges
- Virtualization Choices
- FEV Solution for Engine-in-the-Loop Testing
- Engine-in-the-Loop Use Case
- Engine-in-the-Loop Benefit in Calibration Projects
- Conclusion
Engine-in-the-Loop Testing
Simulation of Real Driving Scenarios at the Engine Test Bench

CHALLENGES

- Virtualization Choices
- FEV Solution for Engine-in-the-Loop Testing
- Engine-in-the-Loop Use Case
- Engine-in-the-Loop Benefit in Calibration Projects
- Conclusion
Limits of Vehicle Testing
Increased Set of Challenges as Motivation for Virtual Environments

**CHALLENGES**

- Calibration engineers need to change conventional calibration approach

- Lack of prototype vehicles and increased text matrix for vehicle derivate validation

- Various environment conditions (high altitude, summer/winter tests) cause high cost

- Increasing complexity of powertrain

**Virtualization as a relevant mean for calibration projects**
Engine-in-the-Loop Testing
Simulation of Real Driving Scenarios at the Engine Test Bench

CONTENT

- Challenges

- Virtualization Choices
  - FEV Solution for Engine-in-the-Loop Testing
  - Engine-in-the-Loop Use Case
  - Engine-in-the-Loop Benefit in Calibration Projects
  - Conclusion
Virtualization Options
Various Degrees of Freedom & Precision Depending on Chosen Solution

**MULTIPLE POSSIBILITIES**

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>EiL</th>
<th>HiL</th>
<th>MiL</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Prototype vehicle / Cost intensive</td>
<td>+ Real engine + aftertreatment system with target SW ECU</td>
<td>+ Fully automated testing 24/7</td>
<td>+ No hardware required / Full-Virtualization of target powertrain</td>
</tr>
<tr>
<td>- Limited availability</td>
<td>+ Reproducibility</td>
<td>+ Reproducibility</td>
<td>+ Cost benefit</td>
</tr>
<tr>
<td>+ Target system</td>
<td>+ Emission</td>
<td>+ Testing in extended environments</td>
<td>+ Physical models</td>
</tr>
<tr>
<td></td>
<td>+ Physical real-time capable models</td>
<td>+ Physical real-time capable models</td>
<td>- Challenging for building of virtual ECU (model)</td>
</tr>
<tr>
<td></td>
<td>- Extended test bench equipment</td>
<td>- Model calibration + HiL HW set-up</td>
<td>- Model calibration</td>
</tr>
</tbody>
</table>

**Intelligent combination and selection of vehicle calibration task based on x-in-the-Loop limits and benefits**
FEV Solution for XiL Calibration Environment
XiL Based Virtual Calibration Process
# Substituting Vehicle Testing

## Identifying the Key Technology to Address Today's Challenges

<table>
<thead>
<tr>
<th>Road trial</th>
<th>Chassis dyno</th>
<th>Powertrain test bed</th>
<th>Engine test bed</th>
<th>HiL</th>
<th>MiL</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Road trial image" /></td>
<td><img src="image2.png" alt="Chassis dyno image" /></td>
<td><img src="image3.png" alt="Powertrain test bed image" /></td>
<td><img src="image4.png" alt="Engine test bed image" /></td>
<td><img src="image5.png" alt="HiL image" /></td>
<td><img src="image6.png" alt="MiL image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Real Environment</th>
<th>Vehicle Environment</th>
<th>Vehicle Environment</th>
<th>Vehicle Environment</th>
<th>Vehicle Environment</th>
<th>Vehicle Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image7.png" alt="Real Environment image" /></td>
<td><img src="image8.png" alt="Vehicle Environment image" /></td>
<td><img src="image9.png" alt="Vehicle Environment image" /></td>
<td><img src="image10.png" alt="Vehicle Environment image" /></td>
<td><img src="image11.png" alt="Vehicle Environment image" /></td>
<td><img src="image12.png" alt="Vehicle Environment image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Real Vehicle</th>
<th>“Vehicle Model”</th>
<th>Vehicle Model</th>
<th>Vehicle Model</th>
<th>Vehicle Model</th>
<th>Vehicle Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image13.png" alt="Real Vehicle image" /></td>
<td><img src="image14.png" alt="“Vehicle Model” image" /></td>
<td><img src="image15.png" alt="Vehicle Model image" /></td>
<td><img src="image16.png" alt="Vehicle Model image" /></td>
<td><img src="image17.png" alt="Vehicle Model image" /></td>
<td><img src="image18.png" alt="Vehicle Model image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Real Driver</th>
<th><img src="image19.png" alt="Real Driver image" /></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Real Transmission</th>
<th><img src="image20.png" alt="Real Transmission image" /></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Real Engine</th>
<th><img src="image21.png" alt="Real Engine image" /></th>
</tr>
</thead>
</table>

---

\[ F_{R,t} = F_{R,t} + F_{R,L} + F_{R,a} + F_{R,ST} \]

---

**Increasing Model Depth**

**Real Emission**
Engine-in-the-Loop Testing
Simulation of Real Driving Scenarios at the Engine Test Bench

CONTENT

- Challenges
- Virtualization Choices

**FEV Solution for Engine-in-the-Loop Testing**
- Engine-in-the-Loop Use Case
- Engine-in-the-Loop Benefit in Calibration Projects
- Conclusion
FEV Solution for EiL Calibration Environment
Short description of FEV’s Engine-in-the-Loop Test Bench

KEY FACTS

EiL system with real ECU and including virtual vehicle and environment

- Technical specification:
  - Driver, transmission, vehicle model incl. powertrain model
  - Real ECU & residual bus simulation CAN

- Reference Vehicle:
  - EU6 vehicle with DTC transmission

Reference project objectives

- Physical models for complete-powertrain incl. transmission (DCT & AT)
- Implementation of ECU and coupling of residual bus simulation & virtual vehicle
Requirements for Engine-in-the-Loop Test Bench Systems
Modeling Precision Validation – Test Bench System Boundary Conditions

Hardware Modification EiL-Test Bench
- Discreet Real-Time Network
- Dynamic Conditioning of Engine Accessories
- Auxiliary Units Simulation
- Frequency Converter and Test Bench Automation System
- Powerful Reconditioning

Real-Time Co-Simulation Platform
- Powerful HiL-Hardware
- Interface to Test Bench Automation System
- FMU capability
- ECU Residual Bus Simulation
- Modular Model Library for Real-Time Co-Simulation

Holistic Verification of Modified Engine Test Bench System

Engine Heat Up
- Engine Temperature vs. Time

Engine Reconditioning
- Target Temperature CAT reached after < 1 h

Open-Loop Dynamic
- Engine Speed 1/min, Manifold Pressure /bar

Validation of required Dynamic of Engine Test Bench System

© by FEV – all rights reserved. Confidential – no passing on to third parties
Requirements for Engine-in-the-Loop Test Bench Systems
Real-Time Models Validation – Vehicle & Driver Sub-Models

Semi-physic. Tire Model

Chassis Model

Physic. Transmission Model

Functional Validation & Validation of Residual Bus Simulation

ECU: Start & after Start / CAT-Heating / Overrun Fuel Cutoff / CAT Purge / Start Stop / Temperature Dependencies
TCU: Shift Maps / Conduct of Shift Phases / Torque Requests / Communication between ECU & TCU

Virtual Driver & Environment

RDE at dyn. EIL Test Bench

Drivability at dyn. EIL Test Bench

© by FEV – all rights reserved. Confidential – no passing on to third parties
Requirements for Engine-in-the-Loop Test Bench Systems
Full System & Emissions Validation

**Conclusion**

Emissions on EiL identical to vehicle opening wide range of possibilities

→ shift calibration tasks to bench

→ investigate HW diversity (e.g. emissions after treatment layout)

→ impact study on technical definition (e.g. hybridization)

... already in early development phases

New legislative requirements and increased complexity in the powertrain require an efficient calibration approach using XiL systems

→ Prototype vehicles can be reduced or even eliminated
Engine-in-the-Loop Testing
Simulation of Real Driving Scenarios at the Engine Test Bench

- Challenges
- Virtualization Choices
- FEV Solution for Engine-in-the-Loop Testing

- Engine-in-the-Loop Use Case
  - Engine-in-the-Loop Benefit in Calibration Projects
  - Conclusion
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

Comparison of three different virtual vehicle variants to the real reference vehicle:

- **Virtual variant 1:**
  Same vehicle like the real reference vehicle with normal TCU calibration and shift times for upshift and downshift of 800 ms

- **Virtual variant 2:**
  Same vehicle like the real reference vehicle but with fast TCU calibration and shift time for upshift and downshift of 550 ms

- **Virtual Variant 3:**
  Same vehicle like the real reference vehicle with normal TCU calibration but additional with purely virtual 48V BSG

**Reference vehicle with normal TCU calibration and shift times for upshift an downshift of 800 ms without 48V System**

→ RDE Street - normal
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

VEHICLE SPEED IN RDE @ EiL TEST BENCH

- Comparison of three different purely virtual vehicle variants, with normal and fast shift time calibration in virtual TCU and normal shift time calibration with virtual 48V BSG (12kW)

- High reproducibility of Engine-in-the-Loop Approach for the three virtual variants

- Small differences between desired and current virtual vehicle speed are based on functional setup of the virtual driver/Driver model:
  - No prediction of desired vehicle speed
  - Scatter band for desired vehicle speed (+/- 1 kph)
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

- Comparison of three different purely virtual vehicle variants, with normal and fast shift time calibration in virtual TCU and normal shift time calibration with virtual 48V BSG (12kW)

- High reproducibility of Engine-in-the-Loop Approach between normal and fast virtual variants

- Virtual 48V BSG reduces the load on real combustion engine
  - Lower acc. pedal position

- Conceptional differences between real accelerator pedal actuation and actuation by the virtual driver/Driver model:
  - Driver model reactions are based on vehicle speed differences
  - No prediction of desired vehicle speed
  - Scatter band for desired vehicle speed (+/- 1 kph)
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

- Comparison of three different purely virtual vehicle variants, with normal and fast shift time calibration in virtual TCU and normal shift time calibration with virtual 48V BSG (12kW)

- High reproducibility of Engine-in-the-Loop Approach for the three virtual variants

- Quite good matching between real longitudinal vehicle acceleration (reference cycle on real street) and long. acceleration of the three virtual vehicle variants.
  - Overall high accuracy of simulation models incl. virtual environment and street

**VEHICLE ACCELERATION IN RDE @ EiL TEST BENCH**

![Graph showing vehicle acceleration comparison](image)
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

- Comparison of three different purely virtual vehicle variants, with normal and fast shift time calibration in virtual TCU and normal shift time calibration with virtual 48V BSG (12kW)

- High reproducibility of Engine-in-the-Loop Approach between normal and fast virtual variants

- Virtual 48V BSG reduces the load on real combustion engine → Lower acc. pedal position
  - During acceleration phases of the virtual vehicle the virtual TCU requests upshifts earlier
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

Comparison of three different purely virtual vehicle variants, with normal and fast shift time calibration in virtual TCU and normal shift time calibration with virtual 48V BSG (12kW)

High reproducibility of Engine-in-the-Loop Approach for the three virtual variants
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

CO₂ EMISSIONS IN RDE @ EIL TEST BENCH

- Comparison of three different purely virtual vehicle variants, with normal and fast shift time calibration in virtual TCU and normal shift time calibration with virtual 48V BSG (12kW)
- High reproducibility of Engine-in-the-Loop Approach for the three virtual variants
- No impact of shifting time variation on real CO₂ emission
- Reduction of real CO₂ emission by the use of purely virtual 48V BSG
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

PN EMISSIONS IN RDE @ EiL TEST BENCH

- Comparison of three different virtual vehicle variants against the real reference vehicle:
  - **Virtual variant 1:**
    Same vehicle like the real reference vehicle with normal TCU calibration and shift times for upshift and downshift of 800 ms
  - **Virtual variant 2:**
    Same vehicle like the real reference vehicle but with fast TCU calibration and shift time for upshift and downshift of 550 ms
  - **Virtual Variant 3:**
    Same vehicle like the real reference vehicle with normal TCU calibration but additional with purely virtual 48V BSG

Reference vehicle with normal TCU calibration and shift times for upshift an downshift of 800 ms without 48V System

→ RDE Street - normal
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

Comparison of three different virtual vehicle variants against the real reference vehicle:

- **Virtual variant 1:**
  Same vehicle like the real reference vehicle with normal TCU calibration and shift times for upshift and downshift of 800 ms

- **Virtual variant 2:**
  Same vehicle like the real reference vehicle but with fast TCU calibration and shift time for upshift and downshift of 550 ms

- **Virtual Variant 3:**
  Same vehicle like the real reference vehicle with normal TCU calibration but additional with purely virtual 48V BSG

Reference vehicle with normal TCU calibration and shift times for upshift an downshift of 800 ms without 48V System

→ RDE Street - normal
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

- Comparison of three different virtual vehicle variants against the real reference vehicle:
  - **Virtual variant 1:**
    - average in take-off
    - high PN in strong acceleration
  - **Virtual variant 2:**
    - worse in take-off
    - similar in strong acceleration
  - **Virtual Variant 3:**
    - big improvement for take-off and strong acceleration
    - PN benefit by engine load decrease through hybridization

PN EMISSIONS IN RDE @ EiL TEST BENCH
EiL Use Case: Impact Study on Technical Definition
Results from RDE @ EiL Test Bench for Three Different Setups

- Comparison of three different purely virtual vehicle variants, with normal and fast shift time calibration in virtual TCU and normal shift time calibration with virtual 48V BSG (12kW)
- High reproducibility of Engine-in-the-Loop Approach for the three virtual variants
- High impact on PN emission by shift time variation
  + 70% Particulates
- Reduction potential of PN emission by the use of virtual 48V BSG
  - 50% Particulates
Engine-in-the-Loop Testing
Simulation of Real Driving Scenarios at the Engine Test Bench

CONTENT

- Challenges
- Virtualization Choices
- FEV Solution for Engine-in-the-Loop Testing
- Engine-in-the-Loop Use Case

- Engine-in-the-Loop Benefit in Calibration Projects
  - Conclusion
### EiL Implementation in Standard Calibration Workflow

**Required Technology Packages in Engine Bench Setup**

<table>
<thead>
<tr>
<th>Base Package</th>
<th>Technology Package 1</th>
<th>Technology Package 2</th>
<th>Technology Package 3</th>
<th>Technology Package 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original Set-up</strong></td>
<td><strong>Extended Simulation</strong></td>
<td><strong>Extended Temperature</strong></td>
<td><strong>Altitude Simulation</strong></td>
<td><strong>Powertrain Dynamics</strong></td>
</tr>
<tr>
<td>- original set up (air path, exhaust line, coolant &amp; EGR charge air cooler)</td>
<td>- complex transmission simulation (converter behavior / warm-up)</td>
<td>- deep temperature test cell (-30°C … +40°C ambient temperature)</td>
<td>- pressure conditioning of air path &amp; exhaust path</td>
<td>- original powertrain set-up incl. shafts/axle drives</td>
</tr>
<tr>
<td>- (simple) vehicle simulation for longitudinal dynamics and gear shifting</td>
<td>- vehicle &amp; driver simulation, predictive and variable driver behavior</td>
<td>- coolant / oil conditioning (-30 … 120 °C)</td>
<td>- altitude / climate chamber</td>
<td>- gear shifting robotic &amp; control of hybrid components</td>
</tr>
<tr>
<td>- fuel variants</td>
<td>- switchable accessories</td>
<td>- air stream blower</td>
<td>- cornering, wheel slip, independant dyno control</td>
<td>- 48V supply</td>
</tr>
<tr>
<td>- Battery emulator</td>
<td>- 48V supply</td>
<td>- underfloor air flow (especially for EATS/diesel)</td>
<td>- Realtime networked test benches (virtual shaft)</td>
<td>- accessible load unit simulation</td>
</tr>
<tr>
<td>- accessory load unit simulation</td>
<td>- fuel tank ventilation (gasoline specific)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Engine controllers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**MiL**  
**HiL**  
**Engine test bed**  
**Powertrain test bed**  
**Chassis dyno**  
**Road trial**
### EiL Implementation in Standard Calibration Workflow

#### Benefits in Development Time (Generic Project)

<table>
<thead>
<tr>
<th>Test bench technology packages</th>
<th>Resource optimizations</th>
</tr>
</thead>
</table>

Up to 30% time saving at highest complexity!
EiL Implementation in Standard Calibration Workflow
Achievable Project Duration Benefit by Using EiL (2 Scenarios)

TIME SAVING POTENTIAL

- Calibration with EiL implementation:
  - Road to Rig to Desktop (R2R2D)
- Extensive time saving achieved in many calibration tasks
- 2 scenarios for an concrete project example with 10 variants. Achievable calibration time savings
  1. 6 months with extensive complexity level
  2. 3.5 months with moderate complexity level
- Further: Over-all number of prototype vehicles reduced in early stage of project
EiL Implementation in Standard Calibration Workflow

Achievable Project Duration Benefit by Using EiL (2 Scenarios)

COST SAVINGS POTENTIAL (CALIBRATION SUB-PROJECT VIEW)

- Calibration with extended implementation of EiL (scenario 1 from previous page)
- This example shows:
  - For some tasks, direct cost for calibration is reduced
  - For other tasks, direct cost for calibration can be higher due to expensive resource
- But: Tasks with higher cost in calibration budget show benefit in global development project through
  - reduced number of prototypes
  - shorter development: earlier start of sales
  - risk frontloading

Individual calibration Tasks

Cost Savings Potential / %

Exhaust Temp., Torque structure, Variable Valvetrain, Fuel Path, Cold start, Cat Heating, Emissions warm, Emissions cold

Start/Stop
Comp. Protection
Drivability
Engine-in-the-Loop Testing
Simulation of Real Driving Scenarios at the Engine Test Bench

- Challenges
- Virtualization Choices
- FEV Solution for Engine-in-the-Loop Testing
- Engine-in-the-Loop Use Case
- Engine-in-the-Loop Benefit in Calibration Projects

- Conclusion
CONCLUSION

- EiL – a key technology for future calibration challenges
- FEV EiL solutions – full transparency compared to vehicle testing
- Achieved results: Very good comparison for NEDC, WLTC and RDE at EiL test bench for emissions incl. particulates
- EiL use cases expand beyond the substitution of vehicle calibration tasks on test bench
- Early project stage hardware decisions possible even before first prototype built
- Significant benefits in project schedule and budget
- Project duration reduction potential up to 30%
- Major time savings in nearly all calibration tasks
- Over-all number of prototype vehicles reduced in early stage of project
- Important potential for cost reduction in calibration and in global development project