Consistent development of hybrid vehicles at the engine-in-the-loop testbed

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Motivation

Development process and tools for hybrid powertrains

Consistent hybrid operating strategy

Testing methodologies for hybrid powertrains

Application examples at the engine-in-the-loop testbed

Summary
Strong Increase of Parameters in Hybrid Powertrains

- Operating strategy
- Vehicle size
- Cost of ownership
- Cost of sales
- Drivability/ fun-to-drive
- Component dimensions
- Powertrain architecture

Hybrid Powertrains

Customer requirements

Vehicle parameters

Usage scenario
Efficient and Coordinated Development of Hybrid Vehicles

Efficiency in Development

Efficient Development

• Few iteration steps
• Few prototypes
• Few test vehicles
• Determination and validation of optimal configurations

Efficient Operating

• Trade-Off:
  • Lowest consumption possible
  • Emission limits
  • Driveability
  • Durability
• Sophisticated tuning in harmonizing strategy and concept (usage rate of installed components)

Consistent Tools, Models and Control Functions
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Development Tools in the Development Process

- Systematic optimization
- Offline
- System integration
- Reverse simulation
- Online
- X-in-the-loop
- Forward simulation
- Component test
- Component dimensioning
- Basic energy management
- Detailed function and component design
- Requirements
- Architecture
- System application
- System tests
Architecture Definition and Component Dimensioning via Reverse Simulation

- **Reverse Simulation:**
  - Targets as inputs (velocity, torque, etc.)
  - Highly comparative results by open loop control
  - Simple models for fast simulation

→ Need for basic operating strategy
Development Tools in the Development Process

 Offline

 Reverse simulation

 Systematic optimization

 Forward simulation

 Online

 X-in-the-loop

 Requirements

 Architecture

 Component dimensioning
 Basic energy management

 Detailed function and component design

 System application

 System integration
 System tests

 Component test
Detailed Forward Simulation
Development Tools in the Development Process

Offline

Requirements
Architecture
Component dimensioning
Basic energy management

Reverse simulation

Systematic optimization

Forward simulation

Online

X-in-the-loop

System application
System integration
System tests
Component test

Detailed function and component design
Detailed Forward Simulation and Engine-in-the-Loop (EiL)

Diagram showing a flowchart of the simulation process, including:
- Driver Model
- Environment
- Operating Strategy
- Vehicle Model
- RT Simulation Platform
- Driver Input
- CAN
- Klemme 15, alpha
- Battery
- ICE
- Clutch
- Speed Control
- Converter
- Dyno
- T_{meas.}
- n_{set}
- v_{act}
Development Tools in the Development Process

Offline
- Reverse simulation
- Systematic optimization
- Forward simulation

Online
- X-in-the-loop
- System application
- System integration
- System tests

Requirements
- Architecture
- Component dimensioning
- Basic energy management

Detailed function and component design

Component test
X-in-the-Loop (XiL)
in-the-Loop-Simulation

Focus of VKM
- Testbed set-up
- Application Methods for Operating Strategies

Vehicle models at VKM:
- Powersplit hybrid
- P1 parallel hybrid
- P2 parallel hybrid
- Boosted Range Extender

Operating Strategy:
- Vehicle-realistic composition
- Depending on signals provided by real components
- Depending on powertrain and vehicle concept
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Summary
Proposed Strategy Structure

Operating Strategy

Driving State
- Driver input
- Driver type
- Road state
- Track information
- Trip information

Operating State
- SOC
- Power in low voltage system
- ICE OP
- $T_{Cat}$
- ...

Energy Management
(OP-Determination, Thermo Management)

Control of Dynamics

Low Voltage System Control

Driver Feedback

BCU
Power Electr.
ECU
TCU
Auxiliaries
Proposed Strategy Structure: State Analysis

Driving State
- Driver input
- Driver type
- Road state
- Track information
- Trip information

Operating State
- SOC
- Power in low voltage system
- ICE OP
- $T_{\text{Cat}}$
- ...

- Driver input interpretation
- Communication with driver assistance systems
- Adaptation and prediction functions

- Interpretation of sensor signals
- Communication with Control Units
- Virtual sensors

High potential for reuse of functions in different strategies
Proposed Strategy Structure: Operating Point Assignment

- Quasi-stationary
- Basic operating point determination
- Conditioning functions

- Coordination in dynamic manoeuvres:
  - Engine start
  - Mode switch
  - Gear shifting

Operating Strategy

- Energy Management
  (OP-Determination, Thermo Management)

Control of Dynamics

- Coordinate power peaks
- Coordinate heat provision with heat usage

Facilitation of continuous evolution and parallel development
Separation of test procedures
Proposed Strategy Structure:
Driver Feedback

- Advise for efficient driving
- Range and Risk information

High potential for reuse of functions in different strategies
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Summary
Test Scenarios in the Development of Hybrid Vehicles

Maneuvers

Durability
Drivability
Emissions
Functionality

NEDC

Cycle Consumpt.
Emissions

Real World

Real World Cons.
Durability
Drivability

Driver and Road Adaptation

Road Profile
Traffic
Driver

Trade-Off
Strategy Development and Application in Corresponding Test Scenarios

- **Driving State**
  - Driver input
  - Driver type
  - Road state
  - Track information
  - Trip information

- **Operating State**
  - SOC
  - Power in low voltage system
  - ICE OP
  - T_Cat
  - ...

- **Energy Management** (OP-Determination, Thermo Management)

- **Driver Feedback**

- **Control of Dynamics**

- **Low Voltage System Control**

- **Operating Strategy**

- **Simulation**
  - Real World
  - Functionality Driver and Road Adaptation
  - Maneuvers

- **XiL**
  - Functionality

- **EiL, XiL**
  - Durability Drivability Emissions Functionality

- **Simulation, EiL**
  - Cyc. Consumpt.
  - Emissions

- **Simulation, XiL**
  - RW Cons.
  - Durability Drivability

**Maneuvers**

**Real World**

**XiL**

**EiL**
Example for Energy Management Application

- **Driving Cycles**
- **Vehicle Parameters**
- **Simulation+Test**
- **Optimization**
- **Targets (out of modelling)**
- **Validation**
- **DoE**

**Vehicle Kinetics**
- **HCU**

**Environment Information (Friction, Inclination, …)**

**Mech. System**
- **Wheels**

**Consumption/CO₂-Em.**
- **Emissions**
- **Durability**
- **Driveability**

**Model**

**Parameters**

**DoE**

**Simulation+Test**

**Optimization**

**Vehicle Parameters**

**Driving Cycles**
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Application examples

Summary
Example for Energy Management Application

Testrun:
- Forward simulation
- Powersplit hybrid
- TUD urban cycle (Real World)

Variation of 6 Parameters
- 2D-map for battery charging power (3 Parameters)
- ICE state parameters (3 Parameters)

Targets
- Efficiency – fuel consumption with SOC equivalent
- Durability – battery stress index (depending on SOC and current)
Example for Advanced Energy Management Application

Scenario and its parameters

- Initial Speed
- Ego-Vehicle
- Parameters
- Energy Management
- Traffic Speed
- Road Gradient

Control functions and parameters

- ACC parameters
  - Time gap
- Control constants
- HCU parameters
  - SOC swing
  - Max. el. Power

Simulation results

- Cum. Battery Stress [Wh]
- Energy Consumption [Wh]

Road Gradient [m/m] vs. Traffic Speed [m/s]
Example for Control of Dynamics Application

Driveability issues for clutch actuated ICE start in P2 hybrid

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Speed [rpm]</th>
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<tbody>
<tr>
<td>17.7</td>
<td>-500</td>
</tr>
<tr>
<td>18.0</td>
<td>0</td>
</tr>
<tr>
<td>18.3</td>
<td>500</td>
</tr>
<tr>
<td>18.6</td>
<td>1000</td>
</tr>
<tr>
<td>18.9</td>
<td>1500</td>
</tr>
<tr>
<td>19.2</td>
<td>2000</td>
</tr>
<tr>
<td>19.5</td>
<td>2500</td>
</tr>
<tr>
<td>19.8</td>
<td>3000</td>
</tr>
</tbody>
</table>

- **Combined Torque [Nm]**
  - -240
  - -160
  - -80
  - 0
  - 80
  - 160

- **ICE Speed**

- **EM Speed**

Operating Strategy

- **Driving State**
  - Driver input
  - Driver type
  - Road state
  - Track information
  - Trip information

- **Operating State**
  - SOC
  - Power in low voltage system
  - ICE OP
  - $T_{ca}$
  - ...

- **Energy Management**
  - (OP-Determination, Thermo Management)

- **Driver Feedback**

Control of Dynamics

- **Low Voltage System Control**

Diagram showing the relationship between driving state, operating state, energy management, and control of dynamics.
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- Consistent simulation-based development methodologies help to manage high complexity and number of variants in the development of hybrid powertrains.

- In-the-loop simulation is key development methodology for a reliable determination of relevant targets like fuel consumption or exhaust emissions in early development phases.

- Necessary consistent use of hybrid operating strategy demands a consequential structure of the hierarchy of the functions.

- Testing methodologies like emission cycles, maneuvers or real-world cycles have to be adopted to development targets.

- Systematic optimization methodologies enable an efficient and reliable determination of optimal parameter configurations for energy management functions.
Thank you for your attention.