Increased Efficiency with Model Based Calibration

Robert Diewald
robert.diewald@avl.com

Thomas Cartus, Martin Schüßler, Hanno Bachler
Content

- Introduction
- Model based development process
- Application example
- Conclusion
Introduction
Development Challenges in the Off-Road Segment

One single engine type requires different power ratings for a wide range of applications, each with low annual production volumes ( < 1000 ).

Extremely wide range of different duty cycles requiring different aftertreatment hardware and operation strategies

Each application has to be optimized for fuel consumption and emissions.
Introduction

De Not-To-Exceed Standards

1.25 * Limit (1.5 * Limit if NOx < 2.5 g/kWh or PM < 0.07 g/kWh)

With Tier 4, the emission limits for non-road machinery (NRM) are similar to the most stringent on-highway legislation.

-> Increased complexity of engines and aftertreatment systems

Engine Speed

Characterized by high load and speed regimes
Introduction
Development Challenges in the Off-Road Segment

What is the optimum regarding fuel efficiency and costs?

Aftertreatment Technology
Content

- Introduction
- Model based development process
- Application example
- Conclusion
Model Based Development Process
Our solution for the challenges

Concept / Layout
Component and system development
Endurance testing
Calibration
Validation

Engine & EAS Simulation

Inexpensive Simulation
Model Concept for Simulation

Model ECU

Sensors

Actuators

Engine and EAS Hardware Model

IN

torque_{dem} engine speed

OUT

torque NOx, soot, (HC, CO), temperatures, heat to coolant, BSFC

p,T, m, λ, NOx, ...
AVL Model based Development Process

Boundary conditions & requirements (e.g. duty cycle, packaging)

Concept (clustering, definition lead variant, definition emission concept)

Variant cluster n
Variant cluster 2
Variant cluster 1

Layout
HW & ECU algorithm design
Component development
System development

SOP

Office work
Development work (Test Bed & Vehicle)
Phenomena Analysis with AVL FIRE during the Development Process

**CFD Analysis of DPF Regeneration**
- **DPF Temperatures**
- Mapping of Temperatures on FEA model
- FEA Calculation of Total Stresses on DPF Substrate

**CFD Analysis of Urea Water Injection**
- Wall temperature [K]
  - 470
  - 420
- Wall film thickness [m]
  - 1e-04
  - 1e-06
- Wall film formation on mixer
AVL Model based Development Process

Boundary conditions & requirements (e.g. duty cycle, packaging)

Concept (clustering, definition lead variant, definition emission concept)

Layout adaptation

HW design adaptation

Component Verification

System Verification

Calibration Adaptation

Calibration Verification

Validation

SOP

Office work

Development work (Test Bed & Vehicle)
Content

- Introduction
- Model based development process
- Application example
- Conclusion
Engine and EAS Specification

**Lead variant**

**Engine Inline 6**
- Displacement: 5 l
- Rated Power: 115kW @ 2200 rpm
- Rated BMEP: 12.5 bar
- Max Torque: 625 Nm @ 1400 rpm
- Max BMEP: 15.7 bar
- NOx Limit: 3.4 g/kWh
- PM Limit: 0.02 g/kWh

**EAS**
- DOC
  - Dimensions: Ø 9" x 5"
  - Volume: 5.2 l
  - Material: Cordierite
  - Cell Density: 400 cpsi
  - Wall Thickness: 7 mil
  - PGM Loading: 50 g/ft³
  - PGM Ratio: Pt:Pd 10:1
- DPF
  - Dimensions: Ø 9" x 10"
  - Volume: 10.4 l
  - Material: Cordierite
  - Cell Density: 200 cpsi
  - Wall Thickness: 12 mil
  - PGM Loading: 10 g/ft³
  - PGM Ratio: Pt:Pd 10:1

**Derivative**

1.5 m
Comparison of Measurement and Simulation Results (modified TIER 3 engine, C1 Test)

Excellent correlation measurement ↔ simulation
Exhaust temp. downstream of DOC is mostly above 250°C over the NRTC.
Regeneration performance of the lead variant (baseline) during NRTC

Average $T=301$ °C, NO$_2$/Soot ratio = 19.3

Passive regeneration works well for lead variant over NRTC
Regeneration Performance of the Derivative Over NRTC

Average T = 250°C, NO₂/Soot ratio = 19.3

Cumulative soot engine out [g]

Specific soot load DPF [g/l]

Mean temp. DPF [°C]

Time [h]

Passive regeneration insufficient!

→ What would it take to keep the system strictly passive?
Initial Recalibration: Temperature Management

Increase of exhaust gas temperature

- Reduction of intake air mass (keeping diluent content similar)
- Reduction of EGR mass
- Boundary condition: constant NOx level, higher soot accepted (timing adaptation)
TIER4i Exhaust Gas Temperature downstream DOC after Recalibration

Exhaust Gas Temperature downstream DOC significantly increased
Regeneration Performance of the Derivative Over NRTC After Initial Recalibration

Average T=274 °C, NO2/Soot ratio = 22.4

Cumulative soot engine out [g]

Specific soot load DPF [g/l]

Mean temp. DPF [°C]

Mean DPF temp.

Despite exhaust temperature increase passive regeneration insufficient due to increase in engine-out emission
Final Recalibration: Soot Reduction

Reduction of engine-out soot

- Increasing injection rail pressure $\rightarrow$ higher mixing rates
- Boundary condition: no increase of NOx level and no decrease of exhaust gas temperature (timing adaptation)
Recalibration resulted in acceptable passive regeneration for the derivative application but would come with a 4.6% fuel economy penalty. -> active regeneration preferable
Content

- Introduction
- Model based development process
- Application example
- Conclusion
Conclusion

- Meeting future TIER 4 emission limits requires the integration of many new technology elements in the powertrain of non-road machinery.

- AVL’s approach to handle this challenge is its new model-based development and calibration process.

- The integration of zero-dimensional semi-empirical models allows a robust system layout, avoids additional development loops, and enables concept transfer during the development phase from a lead variant to derivatives as well as efficient recalibration of derivatives.

- Consequently, a significant part of the costly facility-related development and calibration work can be shifted to low cost virtual engine testing increasing efficiency, product quality and robustness.