Model based development: Innovative ways to increase calibration quality within the limits of acceptable development effort

Dr. Michael Kordon, AVL List GmbH, Austria
Dr. Nikolaus Keuth, AVL List GmbH, Austria
Dr. Johann C. Wurzenberger, AVL List GmbH, Austria
DI. Gianluca Vitale, AVL List GmbH, Austria

AVL List GmbH

ABSTRACT

Due to the steadily increasing complexity in the powertrain development the limits of standard development processes are reached. New methods have to be implemented! The transfer of development parts from the real to the virtual test environment is essential. Therefore a new model supported development approach was developed and successfully integrated in the development process. This methodology consists of a semi-physical engine model fulfilling the accuracy requirements, a suitable virtual calibration environment and the adoption of the development process to take into account all available development facilities; Vehicle, chassis dyno, powertrain test bed, engine test bed and the new virtual test bed.
INTRODUCTION

New legislation in the automotive industry such as CO2 limitation, “Real Driving Emissions” (RDE) or “In-Use Tests” have increased the complexity of the development of internal combustion engines and drivetrains. Passenger cars, commercial vehicles and non-road applications have to comply with emissions legislation under diverse operating and environmental conditions. This situation is further exacerbated by the diversity of the vehicle portfolio.

The effort required to achieve an adequate system and calibration validation is enormous. Conventional development processes require the application of large amounts of manpower, test equipment and budget in order to reach the legislative targets while maintaining and keeping the same system reliability, particularly when considering that the majority of effort takes place on the right of the development process, see diagram 1. This is heavily depending on existing engines and vehicles, often located very late in the project timeline. Links to earlier development stages and front-loading is often very difficult due to the lack of models.

![Diagram 1: V development process](image)

The limit of efficiency has been reached with conventional development processes; new approaches are necessary.

MODELING APPROACH

AVL List GmbH has set up a method for model-based development throughout drivetrain development as part of its “Smart Calibration” strategy. This approach is based on a powerful, realtime, semi-physical engine model in combination with a powertrain model and a virtual testbed with established automation and application tools.

As early as in the concept phase, the engine model is coupled with the vehicle model and the performance and emissions behavior under real driving conditions is simulated in a “Model-in-the-Loop” environment. This enables components such as emissions aftertreatment systems to be dimensioned more exactly, or before the first engine start, an emissions and performance pre-calibration to be done. The “Hardware-in-the-Loop” (HiL) test bed is calibrated and validated in the application phase. Modern dataset management systems enable a continuous monitoring of the calibration process, as well as a smooth transfer of datasets from the virtual to the real world, in order to ensure dataset quality. This method is the foundation of a new process and opens up new possibilities in series calibration.
As can be seen in diagram 2, the models are constructed at a very early concept phase using component specifications and development targets. By employing semi-physical modeling approaches, this model, together with knowledge gained from calibration data from earlier development stages, can be used to create first pre-calibrations for the ECU for the first engine start. The models are adapted and improved in steps using measurement data in order for them to be used for virtual component and system development. In a final step, the semi-physical models can be extended with engine specific empirical models using DoE data. In order to be able to use such a workflow, a consistent model, modeling and testing landscape is necessary.

COMBUSTION ENGINE MODEL

An accurate virtual representation of the combustion engine is a pre-requisite for an efficient and meaningful application of a powertrain simulation. The engine model used in Smart Calibration is based on a semi-physical approach. By combining physical and empirical components, the complexity of the model is reduced and the trade-off between computational speed, model accuracy and configuration effort is eliminated.

The zero-dimensional charge cycle is calculated physically by filling and emptying containers connected by throttle elements. The intake is modeled using a special approach that enables simplified configuration. Further, the thermal inertias of the gas transporting components are simulated, as well as the inertia of the turbocharger, in order to be able to simulate realistic behavior during transient engine operation.

The combustion model consists of a network of sub-models that follow the process of combustion chronologically. For computational speed reasons, a crank angle based calculation of combustion and emissions is not considered. However, the most important characteristics of combustion, such as start of combustion, MFB50% and peak pressure are calculated.

Input values to the empirical parts of the combustion model that represent the highly complex combustion events are predominantly calculated physically. This makes it possible to cover a large part of the parameter space, provides the possibility to react to hardware changes and also results in a reduction in the number of input values required for the empirical model.

The engine model is thus able to make quantitative predictions without the availability of measurement data of fuel consumption, temperatures and pressures and NOx Emissions. If measurement values are available, a handful of
parameters are available to adjust the model to reflect the available data. This increases the accuracy so that calibration tasks can be performed. Emissions such as soot, CO and hydrocarbons must currently still be modeled empirically out of the measurement data of the corresponding engine.

EXHAUST AFTERTREATMENT MODEL

The models for the exhaust system consist not only of the catalytic components and particle filter, but also the injection lines, injectors and sensors. The exact measurement of the thermal conditions in the exhaust system forms the basis of the calculation of emissions at the tailpipe. The application of models for the simulation of dynamic drive cycles brings with it the necessity of second-by-second calculation of emissions after each exhaust system component.

Apart from the catalytic conversion, storage phenomena of emissions species are also considered. These are soot in the particle filter, NOx in the storage catalytic converter, or ammonia in the SCR catalyst and also, for example, fluid urea-water solution or adsorbed hydrocarbons.

In order to guarantee an efficient workflow despite the large number of model parameters, it is necessary to have available a coordinated methodology, from the selection of the necessary model characteristics, via the characteristic measurements, to parameter identification.

In the concept phase, the model parameters for the various components are accessed from a database and are continuously fine-tuned during the development project, in order to increase accuracy.

PHYSICAL BASED PLANT MODELING ON SYSTEM LEVEL

The engine model used within this methodology is part of a broader system level simulation framework. Diagram 3 gives an overview of this framework with the distinction into the main physical domains of drivetrain, engine including combustion pollutant formation and exhaust aftertreatment, cooling and lubrication. The individual domains on their own and also their interactions are controlled by various types of control functionality that interact with the plant model through a layer of actuators and sensors. The xCUs are typically controlled by a driver model that follows given driving profiles.

Diagram 3: Schematic of a system engineering plant model comprising the domains vehicle, engine and cooling

It turned out that the following list of requirements was essential for the Model-in-the-Loop (MiL) and Hardware-in-the-Loop (HiL) environments in order to efficiently support engine development and calibration. These requirements have been driving the development of the applied tool ever since. These are:
Multi-physical simulation tools are capable of comprising the different physical effects taking place in the different domains of drivetrain engine cooling etc. by dedicated models and numerical methods. Especially the application of individually tailored integration rates together with conservative coupling techniques allows the running of numerically highly efficient models with real-time capability, as this is a key requirement to support HiL based calibration activities.

Consistent plant modeling is essential to support the development process from the early concept phase to the late function development and calibration phase. Model consistency enables the handshake between different development teams, each adding a focused value to a common model that accompanies the hardware development as virtual twin brother. Consistent handling of models and model parameters additionally allows a thorough tracking of model changes during its lifetime in the development process.

Scalable plant modeling in a consistent overall framework is the answer to requirements that also scale throughout the development process. On the one hand, highly predictive plant models are needed in the early concept phase and on the other hand highly accurate models are a must to support calibration. Both goals are addressed by a tailored combination of first order principles, physical, semi-physical and fully empirical approaches. Here it turned out that models featuring both a maximum of physical depth and running real-time are the best choice.

Customizable plant models are the key to efficiently support the dynamic advancing requirements in modern engine development programs. System simulation tools offer libraries of fundamental components that can be used to assemble entire vehicle, engine or cooling topologies. These components are typically parameterized only on the high level of the user-interface. Access to specific parts of the component source code on a fundamental programming level additionally allows modifying existing components or designing new ones. A comprehensive numerical solver basis together with a smart equation manager taking care of all fundamental balancing rules enables the calibration engineer to focus on the modeling of physical correlations.

Open and integrative simulation platforms target, amongst others, the fulfillment of the requirement of maintaining existing models built in different tools by typically enabling co-simulations. A second way of combining models is model-import where the equation of the “sub model” is integrated in time using the numerical solver of “main-model”. Here, the Functional Mockup Unit (FMU) standard is used to define interfaces. This approach is chosen to embed customized cylinder and exhaust aftertreatment models into an air path network built out of library components. Besides openness in an office application, it is essential to port plant models to various hardware platforms for HiL and also test-bed applications.

Engineering driven plant model development can be seen as a generic requirement covering all previously mentioned functionalities. The application of tools (software and hardware) in daily engineering work allows the simple tailoring of them to the right engineering needs.

MODEL VERIFICATION

An example of the achievable model quality for an off-road engine is demonstrated in diagram 4 and table 1. The model shown in this diagram is only adopted on one steady state operating map and one transient Non Road Transient Cycle (NRTC). Displayed is engine speed, engine torque, intake air mass flow, NOx emissions, opacity and the temperature upstream the turbine. It can be seen that the time resolved results show good correlation between measurement and simulation. Also the calculated NRTC cycle results displayed in table 1 are matching very well.
Table 1: Deviation of NRTC cycle results between measurement and simulation

<table>
<thead>
<tr>
<th></th>
<th>NRTC NOx emission</th>
<th>NRTC Soot emission</th>
<th>NRTC Fuel consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deviation</td>
<td>3 %</td>
<td>7 %</td>
<td>1 %</td>
</tr>
</tbody>
</table>

APPLICATION

The virtual testbeds, whether HiL or MiL environment, are used for concept investigations, calibration and validation under various ambient conditions as required by legislation. In particular, the robustness of the system can be ideally tested, related to component tolerance, ageing and different environmental conditions.
The broad and consequent use of powertrain models in development means a breakthrough in model-based calibration. What has been considered impossible for many years is now possible.

CONCEPT PHASE

Simulation tools have been successfully applied to the development of new powertrain concepts for a long time. However, up until now mainly steady state operating points under standard environmental conditions have been used for the evaluation of future concepts. Due to the increasingly complex interrelationship between engine and exhaust aftertreatment system and the necessity to comply with legislative emissions limits under real world driving conditions, concepts must be evaluated within a broader scope. This is exactly the point where fast, dynamic powertrain models are necessary and represent a useful extension to existing simulation tools. It is possible, in very early stages of development, to test the behavior of the combustion engine in the future vehicle under real driving conditions with various boundary conditions and also to estimate the effect of component ageing.

By observing all interactions between engine, exhaust aftertreatment, control unit, software and calibration, sensors and actuators and the environmental conditions, concepts can be evaluated and optimized in all their entire complexity.

The exact observation of the future application of a combustion engine in various vehicles makes it possible to cluster the application into individual groups as early as in the concept phase. By evaluating whether sections of a dataset from other applications can be reused, it is possible to calculate exactly what the calibration effort will be, thus creating a tight and optimal calibration phase without duplicated effort. By clustering the work well, the effect that the calibration effort increases directly proportionally to the number of vehicle variants can be avoided.

EMISSION AND FUEL CONSUMPTION UNDER REAL DRIVING CONDITIONS

Emissions legislation for passenger cars in the European market is still based on the certification of emissions and fuel consumption in the standard test cycle (NEDC). This cycle is, apart from a few transitional phases, basically steady state and does not represent all real driving conditions of a vehicle. Conventional combustion engines are optimized such that they comply with emissions and fuel consumption limits during the legislative test cycle. Outside of the cycle, CO2 and driveability are optimized. Even the engine's hardware is designed so that the emissions limits in the test cycle are complied with; large reserves for emissions reduction outside of the operating areas relevant to the cycle have not yet been built in.

In recent years, various institutes have measured the emissions and fuel consumption of passenger cars under real driving conditions, with sometimes shocking results. The European Commission is working on a draft that will end in an “In-Use Compliance” or “Random Certification Cycle” concept, in order to guarantee that the emissions are kept low throughout the entire engine map. Although the draft for the legislation has not been finalized, most manufacturers are optimizing their vehicle’s emissions over a large area of the engine map and under different environmental conditions.

The requirement of “Real Driving Emissions” in combination with the CO2 legislation and the broad OEM vehicle portfolio are the drivers of even bigger challenges in the development process. This has experienced continually increasingly complexity over the last ten years, but is now, in some cases, on the limit of what is possible. The use of virtual testbeds can defuse this situation, since tests are independent of the currently prevailing environmental conditions and can be run on virtual test systems, thus allowing parts of the development to be relocated upstream to earlier stages. The use of virtual testbeds is thus a necessary extension to currently used test environments.

Up until now, emissions optimization was mainly limited to a steady state approach with a focus on the few transient conditions in the NEDC cycle. The optimization of the combustion engine for all driving and environmental conditions can no longer be achieved using this approach. In order to be able to keep quality and development costs at the same level under such legislative requirements, a paradigm shift is mandatory concerning the application and introduction of new test and simulation possibilities.

What is to be introduced for passenger cars in the future is already in force for commercial vehicles. Emission limits must be complied with in the vehicle under real driving conditions, with different altitudes and temperatures – and this not just with new, but also with aged components.

To cope with this new challenge with high quality, parts of the calibration at AVL List are performed on a virtual test bed. To do this, a virtual representation of the vehicle is created during the development phase: The vehicle specific engine installation and the drivetrain are taken into account and with them, the test bed development under standard conditions is supported as well as the calibration of correction and protection functions outside the standard environment conditions.
Virtual “In-use” tests are run, so that the cycle emissions can be calculated for the vehicle in real situations. The environmental conditions and the state of the components are varied, in order to simulate real operation with aged components. The complex evaluation of these simulated tests is done on the virtual test bed in the same manner as for a real vehicle using “AVL PEMS Post Processing”.

By pre-calibrating on a virtual testbed, the efficiency on real testbeds and in the vehicle can be increased considerably. The work begins with datasets with a high degree of maturity and the in-vehicle tests are practically pure validation exercises. The following table shows a comparison between measurements and simulation on a commercial vehicle engine in the 10l class. The measurements were taken during a winter test at 2,200m.

**Table 2: Comparison between measurement and simulation**

<table>
<thead>
<tr>
<th>Turbocharger speed low pressure stage [Rpm]</th>
<th>Turbocharger speed high pressure stage [Rpm]</th>
<th>Compressor exhaust temperature low pressure stage [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>84981</td>
<td>88002</td>
</tr>
<tr>
<td>Measurement</td>
<td>86000</td>
<td>131</td>
</tr>
<tr>
<td>Deviation abs.</td>
<td>-1019</td>
<td>7202</td>
</tr>
<tr>
<td>Deviation [%]</td>
<td>-1.2%</td>
<td>8.2%</td>
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**Table 3: Comparison between measurement and simulation**

<table>
<thead>
<tr>
<th>Compressor exhaust temp. High pressure stage [°C]</th>
<th>Exhaust temp. at high pressure turbine bank 1 [°C]</th>
<th>Exhaust temp. at high pressure turbine bank 2 [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>157</td>
<td>561</td>
</tr>
<tr>
<td>Measurement</td>
<td>156</td>
<td>541</td>
</tr>
<tr>
<td>Deviation abs.</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Deviation [%]</td>
<td>0.4%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

**DATASET VALIDATION**

One of the critical points in development is the validation of all vehicle variants under all of the different driving conditions, in order to guarantee that the development, in terms of quality and cost, is carried out under the same conditions as in the past. Compared to calibration, the role of validation is ever increasing.

Test equipment is expensive and the question arises as to whether simulation can replace or at least support real validation, in order to reduce test effort. This question requires an exact analysis of all current activities to be able to define where new methods could be inserted.

So far, the validation at the end of the calibration phase was a secondary activity with, compared to calibration, low effort. The new legislative requirements, however, make validation one of the most important points in the calibration process, since the quality of complex products can be ensured.

In order to better understand AVL’s approach, the following three main sources of errors in calibration can be noted:

- **Process**: errors that are implemented, although the technical solution is correct.
- **Complexity**: errors that are caused by high system complexity. This means that each component is intrinsically correct, but is calibrated without considering the interaction of all the individual components together.
- **Time and resources**: errors that are caused through insufficient time and resources.

AVL has developed a validation approach to address and hence avoid these three error possibilities, as described here:
1. Dataset management (Dataset merging, clustering, tracing).
2. Automated HiL dataset validation taking different component tolerance into account before releasing the dataset.
3. A wide-ranging, simulation-supported fleet validation with active search for critical events. Known error sources are continually monitored, not just when limits are violated.

IMPLEMENTATION

The methods of model-based development are being implemented on AVL List GmbH's development platform. Great emphasis is being placed on consistency, model interchangeability, efficient model development and simplicity of model use. Diagram 5 shows the tool chain used, consisting of calibration data management (AVL CRETA), semi-physical modeling (AVL CRUISE™), automated test execution (AVL CAMEO and AVL PUMA), measurement data evaluation (AVL CONCERTO) and calibration and simulation (AVL fOX).

![Diagram 5: The AVL Calibration Process](image)

A solution has been developed specially for HiL that permits the calibration engineer to work in the same environment as for a conventional test bed, see diagram 6. The Hardware in the Loop test bed is controlled by the same test bed and automation systems as the real test bed. The data is stored on the same servers with same units and norm names. This enables the calibration engineers to use their well know post-processing tools.

![Diagram 6: The AVL HIL System Setup](image)
The SiL/MiL environment consists of a combination of the simulation environment (AVL CRUISE™) and the workflow-based calibration tool chain (AVL fOX™) in order to standardize calibration tasks.

CONCLUSION

As shown in this article, there is already a broad spectrum of applications that can be run on the basis of a powerful and consistent model-based tool chain. By applying model-based calibration methodology, considerable cost savings can be made and a number of calibration tasks can be carried out that are not possible in conventional development environments for reasons of time and cost, such as IUPMR, RDE or component tolerance investigations, with many different variants, vehicles and cycles.

The AVL HiL environment (AVL XiL Station) not only permits the simple software validation of individual ECUs, but also complex calibration tasks with several networked control units, such as hybrid strategy calibrations. The MiL/SiL environment offers the advantage of being able to run many simulations and tests in a short space of time, thanks to the possibility to simulate faster than realtime. The ability of the models to simulate different environmental conditions, such as altitude, cold, humidity etc. means that calibration work can be efficiently carried out and analyzed, and later, in the vehicle, only needs to be validated.

All in all, 30-50% of all calibration tasks can be run on a model-based development environment, which demonstrates the high potential of such a tool chain using Smart Calibration methodology, and which is an important step towards the frontloading of calibration tasks.

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