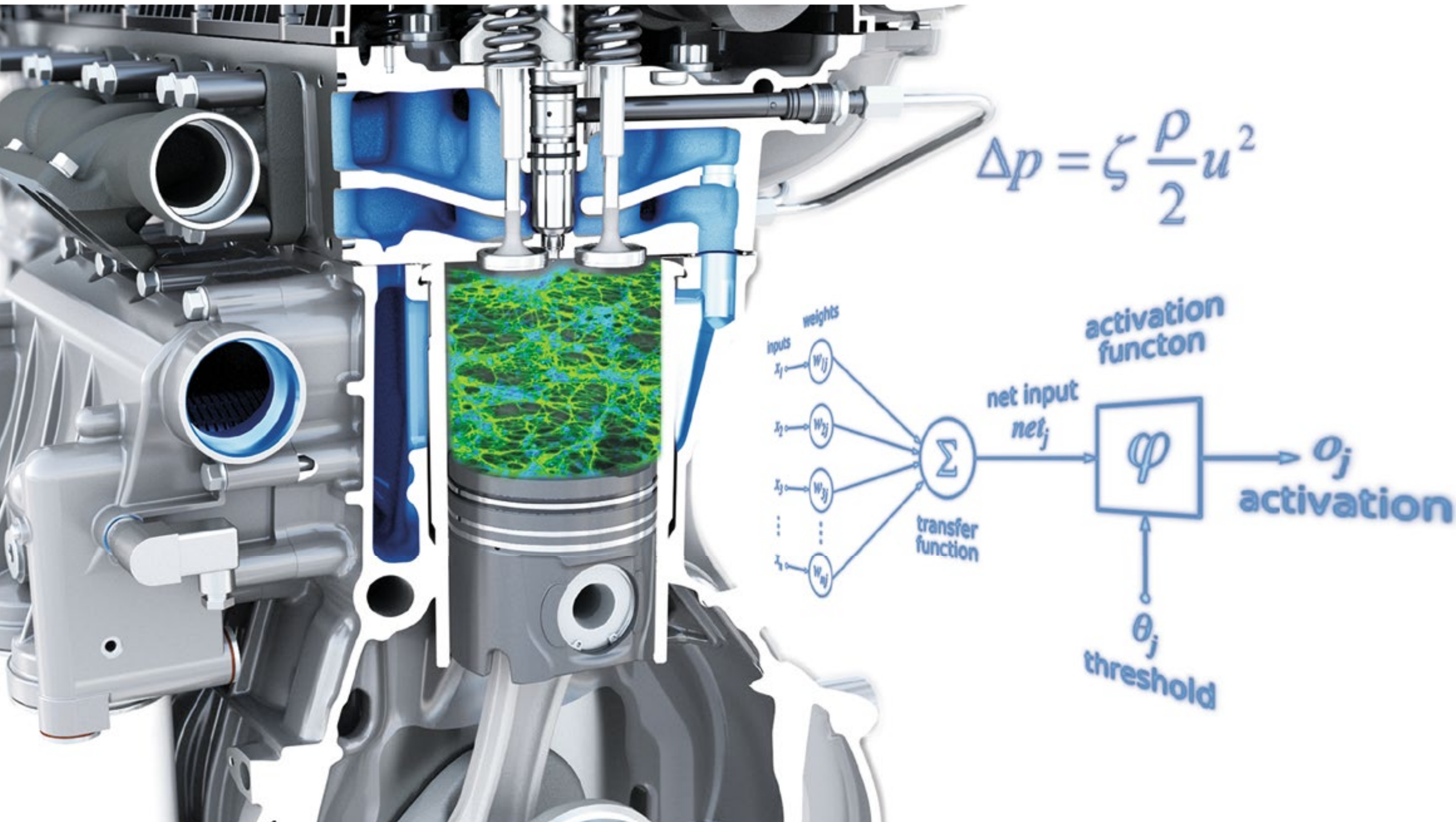


# DoE and Beyond – Evolution of the Model-based Development Approach

With upcoming RDE legislation, ergo cutting real driving emissions, the calibration in the entire performance map range of a combustion engine needs to be robust against a wider operating range at a plurality of driving manoeuvres – and this under most different environmental conditions. Due to this high number of test cases, it is not feasible to proof all variants with the real engine. AVL shows therefore how the model-based development approach on the basis of Design of Experiments (DoE) can be advanced and how legal trends are changing methodology.

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## CHALLENGE DISPLAYING RDE

Upcoming legislation to present practical emission data in brochures, thus to display Real Driving Emissions (RDE), brings new challenges for the automotive world. In order to improve necessary efficiency in calibration of combustion engines, it was focussed on the issue "Model-based Development" more and more in the last 20 years.

Modelling technology was improved essentially, to increase model accuracy with measurement effort as low as possible. These improvements allowed both the fulfilment of the exhaust gas emission legal limits, with minimum fuel consumption and also handling the ascending complexity of an increasing number of data and degrees of freedom in the powertrain. Up to now, emission reduction were optimised within the certification cycle area – while outside, the focus was on fuel consumption minimisation and driveability.

In order to cope with the complexity, the model-based development approach has to be extended to extrapolation capable models. This can only be achieved by a particular defined combination of empirical and physical models and hence can be seen as an extension of the current DoE model-based methodology (Design of Experiments). The new approach developed by AVL is called Mobeo methodology: It enables the calibration of emissions-related corrections, in early development phases, like Hardware in the Loop (HiL) and Software in the Loop (SiL), environments.

Through model improvements during measurement phases, these virtual environments (SiL and HiL) will be able to support from calibration phase to Start of Production (SoP) as an adequate calibration environment. In particular, the extrapolation ability of the models, with respect to hardware changes, dynamic engine behaviour and different climatic conditions, is a key feature for success. The three main requirements of the RDE legislation are, **FIGURE 1**:

– The restriction to a defined driving cycle (the NEDC for Europe for example) will only be valid for determining the $CO_2$ emission – using the world wide harmonised WLTP cycle with slightly higher loads.
– The range which is relevant for the pollutant emissions is more or less the whole engine operating range.
– Under "normal use" conditions the driver is allowed to apply any transient manoeuvre at different environmental conditions and varying any vehicle loading, and in doing so it is not allowed to exceed the RDE values at all times.

By applying different driving styles and vehicle loadings, the change in the RDE emission value in [mg/km] might reach a factor 2, **FIGURE 1** (right). These results were gained from 500,000 emission simulation calculations, using randomised driving style cycles for three dif-

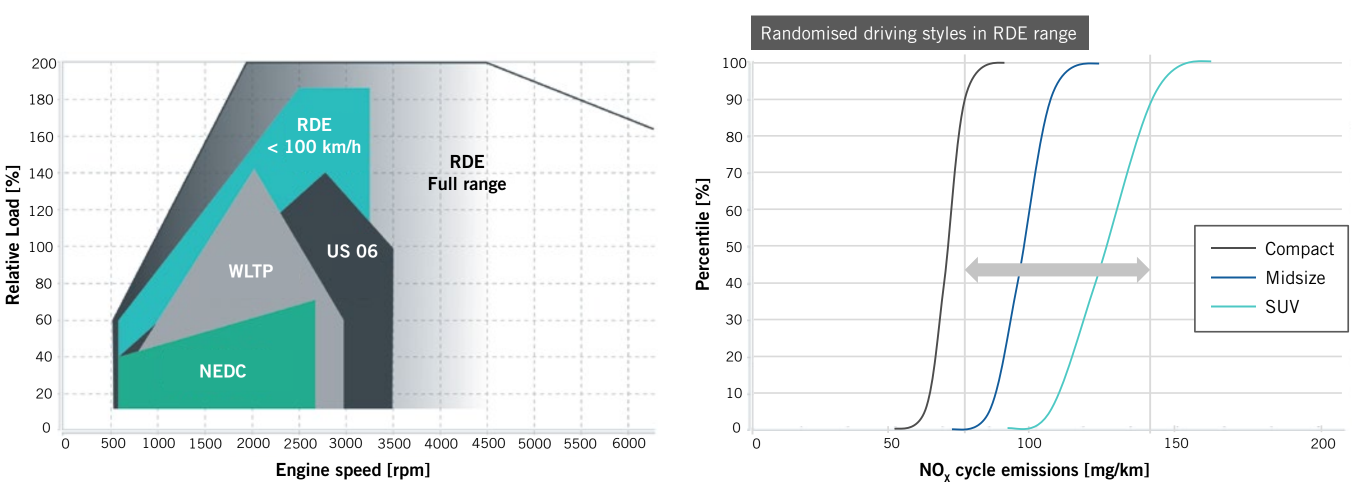


**FIGURE 1** Load/speed areas of old and new driving cycles (left) and consequence of RDE legislation on the $NO_x$ result by example (right)

ferent vehicles, with the same simulated engine and identical calibration.

As already stated in other publications [1, 2, 3] a model-based approach is required which can predict RDE emission values under real driving conditions. But: "What is a model?" **FIGURE 2** shows a schematic of this frequently used and ambiguous term. The Swiss mathematician Werner Furrer defines: "A model is a depiction of reality". For the following, the two types of models are important:

- The physically based, mathematical models are typically applied in the early phases of a development process in simulation tools, for example for designing the gas path including the exhaust gas aftertreatment system. Such models are using well verified and universal relationships and can reach a high degree of detail with high reliability in the prediction quality. The challenge lies often in real-time capability.
- In case of very complex relationships, such as combustion processes, often empirical approaches are used; a system is just observed under defined, different input conditions. The Design of Experiment techniques (DoE) allow correct placement of the varied input parameters, in order to identify empirical, time free, mathematical models, from the observed system responses. This is achieved with low measurement effort. The calculation speed of such models is remarkable very high (multi real-time) but they are typically not capable to predict outside the investigated range.

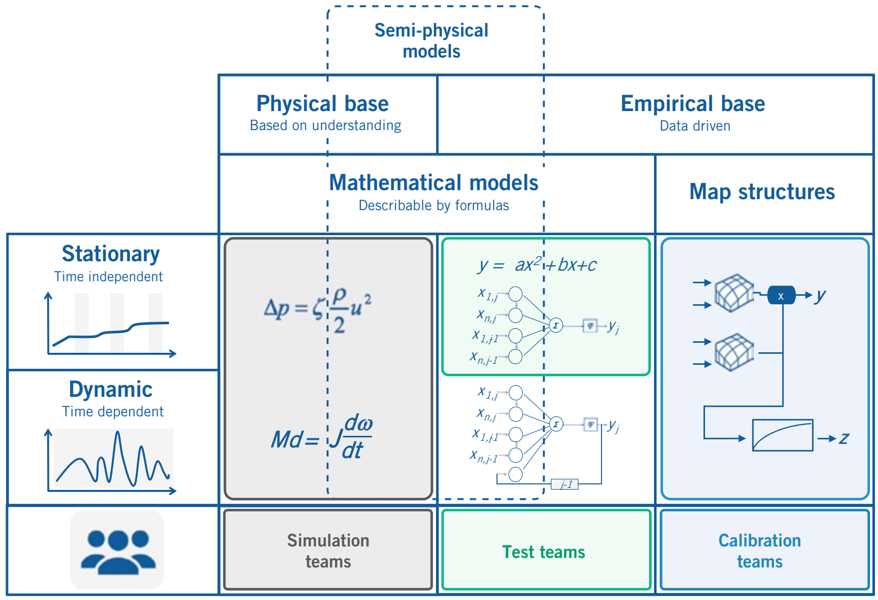


**FIGURE 2** Schematic of the frequently used and ambiguous term "model"

## EVOLUTION IN THE MODEL-BASED DEVELOPMENT

In 1995, an engine was developed for a certain vehicle which applies to Euro-2 regulations. The complexity of the combustion system required was limited (in terms of free parameters to be calibra-

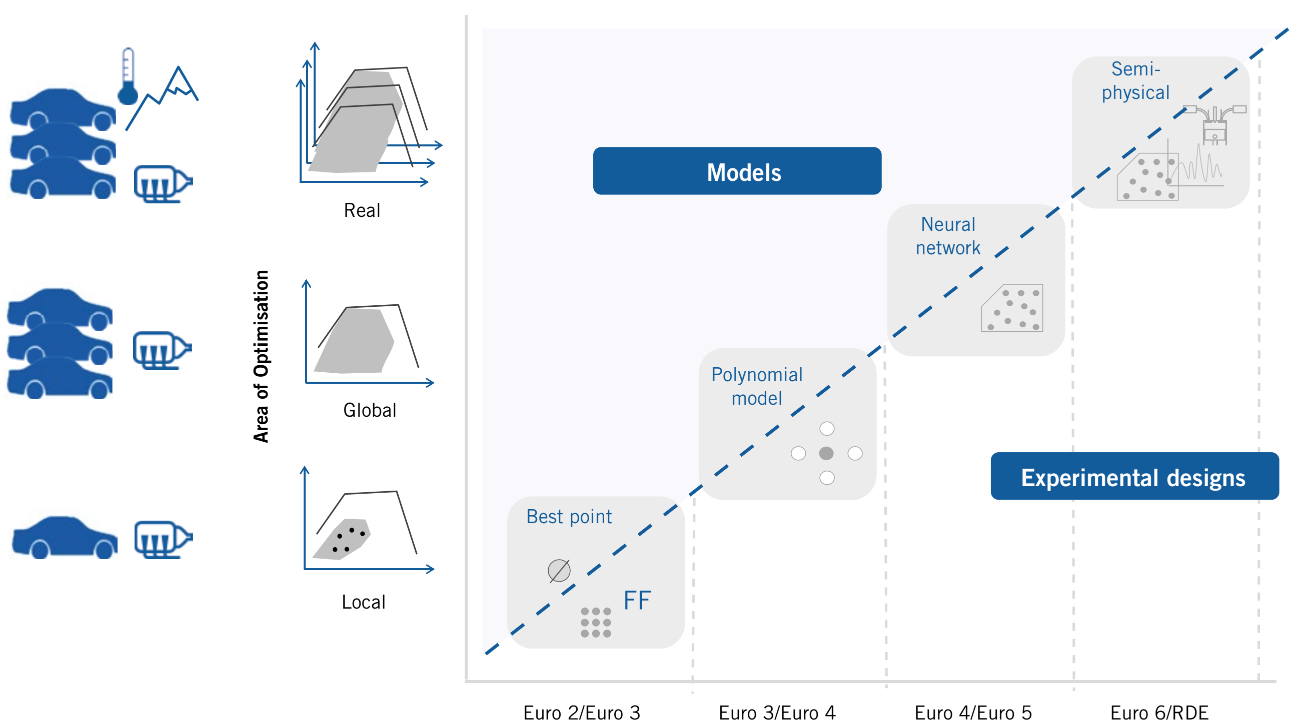


**FIGURE 3** Evolution in modelling methodology from Euro 2 in 1995 to Euro 6 today (2014)

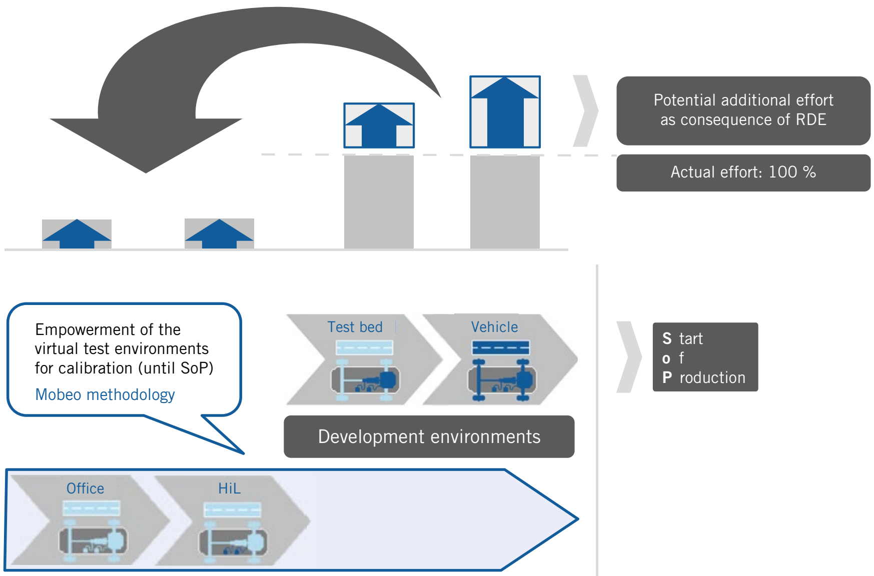


**FIGURE 4** More agility in the calibration process requires an extension to the virtual test environments

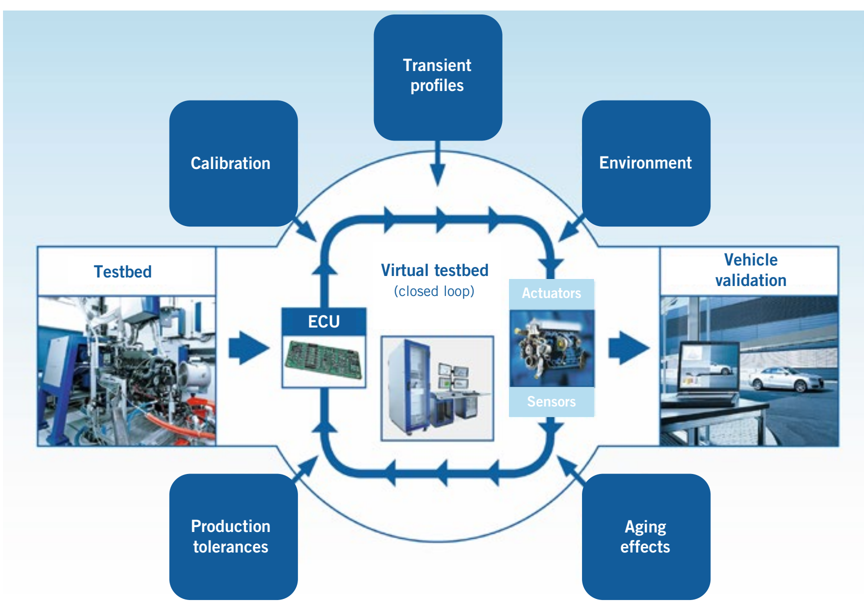


**FIGURE 5** Calibration tasks performed in advanced HiL/SiL environments

ted); for example: there were only two combustion relevant control unit parameters mapping (start of injection and rail pressure). It was common practice in industry, to measure on engine testbed, a full factorial mapping of these parameters. The optimisation practice was to select the "best measurements", **FIGURE 3** (bottom).

In the following years the complexity of the engines increases with further lowering of the emission targets (Euro 3 to Euro 5). "All possible combinations" of parameters (for example for six combustion relevant ECU parameters) could not be measured at multiple operating points on the testbed in a reasonable time. Alternatively, empirical models are used for fuel consumption, $NO_x$, in-cylinder peak pressure, or knocking as function of the varied ECU parameters. This is supported by the DoE – first based on operating point specific (local) engine models [4], later on for global engine models [5, 6].

Global engine modelling allows adaptation of an engine to diverse load spectra as they occur for different vehicle applications. For building the models themselves, advanced polynomial modelling techniques and neuronal networks [7] are used to cover the high nonlinearity. Additionally, a COR DoE approach [8] allows an adaptive, interactive online process which concentrates the measurement points in the area of high nonlinearity, thus saving measurement effort in total and modelling the most extreme nonlinearities, as they arise for example for the soot dimension, **FIGURE 3** (centre).

When considering the RDE requirements nowadays, one must be able to extrapolate the models to environmental conditions, which are not available on a conventional engine testbed, as the RDE values have to be fulfilled under altitude, hot and cold conditions, **FIGURE 3** (top).

The answer to that challenge is a semi-physical model approach for engine operation and after-treatment (Mobeo approach), which combines physical models (for example for gas dynamics) with semi-physical combustion models. The empirical parts are based on the wide project experience of AVL: The results of many engine development projects are used in comparable way, to represent generic empirical combustion part-models. In combination, this approach is the key enabler to provide HiL and SiL environments to be ready for calibration.

## ENLARGEMENT OF THE DEVELOPMENT ENVIRONMENTS

The simulation of RDE emissions on a HiL/SiL environment is suggested as cost effective and quality increasing paradigm change [9] for two main reasons because

- the validation of all test cases needed for the RDE-legislation would not be possible in the real vehicle for an OEM (expensive test trips in high number, availability of prototype vehicles)
- the number of climatic engine testbeds and climatic chassis dynos would be not affordable which would be needed to develop the altitude calibration with real engine hardware.

Further the agility and quality of the calibration process are increased, as the environmental influences can be simulated and considered at any time, **FIGURE 4**.

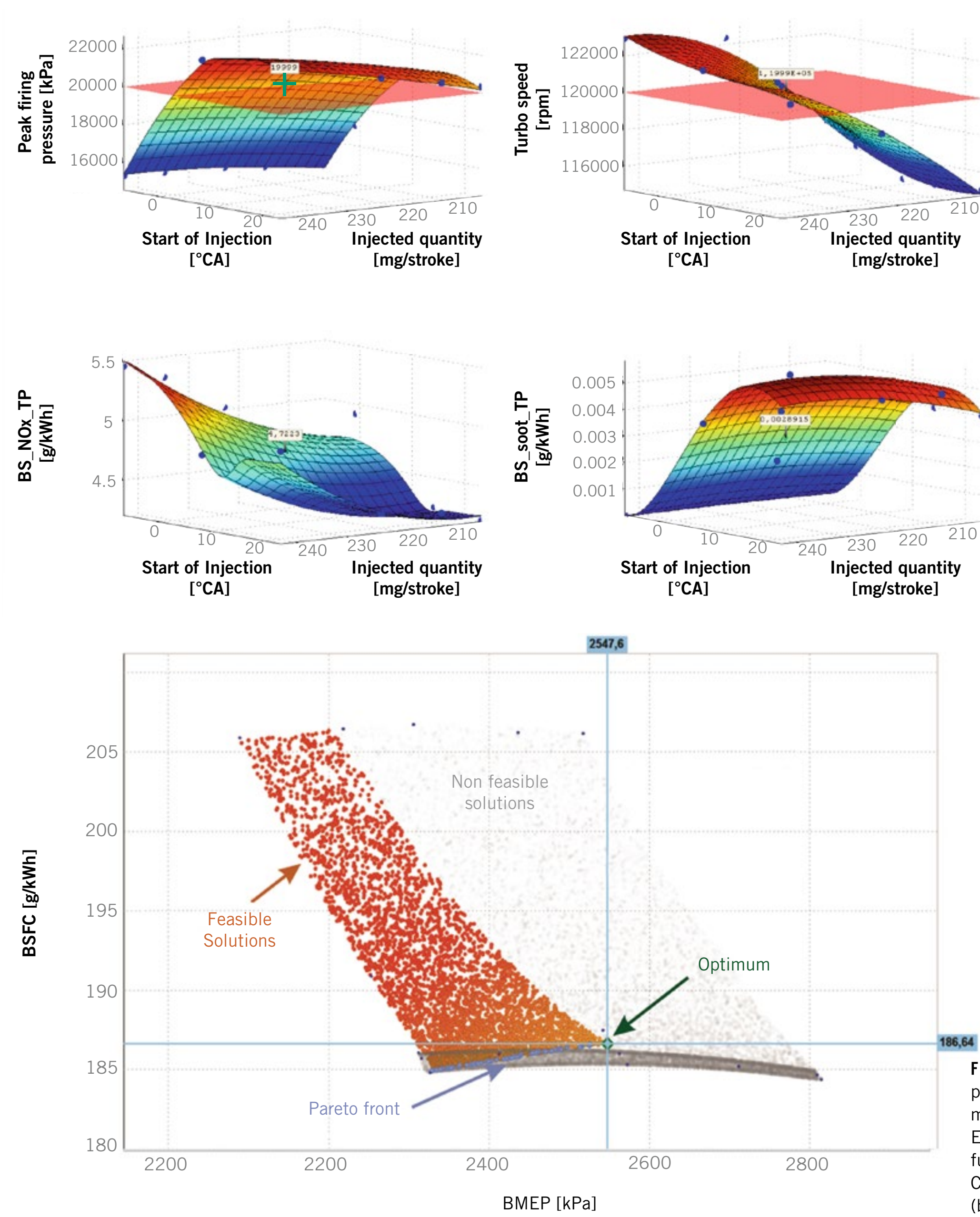


**FIGURE 6** Functions of the calibration parameters (top) and optimisation of maximum engine torque (Brake Mean Effective Pressure, BMEP) at minimised fuel consumption (Brake Specific Fuel Consumption, BSFC) at the same time (bottom)

## REALISATION WITH EXTENDED HIL/SIL ENVIRONMENTS

**FIGURE 5** shows use cases, which can be supported by HiL/SiL using the Mobeo approach. A high number of transient sequences as well as any environment situations can be investigated. Exhaust gas emissions at tail pipe can be predicted with accuracies of approximately 10 % error [9]. Furthermore data status can be calibrated and validated, also under consideration of ageing effects as well as production tolerances.

A further key success factor is the user interface for the calibration engineers: the front end tools remain the same as on the engine testbed and also the proven, model-based optimisation approach can be applied here.

DoE investigations on a HiL system are used to calibrate the altitude power reduction. It is essential to ensure that peak firing pressure, turbocharger speed and exhaust gas temperature keep within their durability engineering targets. Here runs the semi-physical engine model which was calibrated for a certain engine in real-time interaction with the real control unit. The whole system is operated like an engine testbed and allows measurements at reduced ambient pressure as it occurs on an altitude of 2200 m. As a first result one can see the empirical meta models from these measurements for

- peak firing pressure
- turbocharger speed
- power specific tailpipe emissions for $NO_x$ and soot

as function of the two calibration parameters injection quantity and start of injection, **FIGURE 6** (top). The optimal calibration should not exceed the maximum allowed target values for long-term durability of the parts and should result a maximum engine torque (BMEP) at minimised fuel consumption (BSFC) at the same time, **FIGURE 6** (bottom). As a result, the calibration engineer can judge on the pareto front of the trade-off graphic which calibration priority he wants to reach most – keeping in view the emissions for a consequent calibration decision and choosing the right optimum.

## SUMMARY AND OUTLOOK

The RDE legislation is generating a further demand to the model-based development. The extrapolation capability of the models is key to ensure the prediction of the RDE values at transient and different environmental conditions. Using the Mobeo by AVL approach to empower HiL and SiL environments for calibration work, is a realistic possibility to cope with RDE developments effectively. There is seen the potential, to even increase system robustness by transferring calibration work from real to virtual testing.

Especially development tasks under non-standard conditions, as they are needed for RDE investigations, can now be processed in HiL/SiL environments. The front end to the calibration engineer remains familiar and allows applying the proven DoE methodology and the model-based optimisation methods – as established already on the engine testbed.

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