Intelligent Calibration Tool – an approach to cover the whole calibration process

Höfer Christoph, Schlager Gerd, Doppelbauer Clemens

Abstract

To handle the whole calibration process and to document the complete workflow a new calibration tool was developed.
Beside the data management, the knowledge gathering from existing information sources and the data acquisition process the analysis and modelling methods are core features, which should be as flexible as possible. To cover all the needs for calibration and function development the tool was designed as a framework with a well-defined workflow. This workflow is independent from the exercise, means independent if the task will be done static or semi (quasi)-dynamic on a test bench or a chassis dyno due to a flexible analysis layer.
The paper describes the necessary infrastructure to realise an automatic calibration process with all necessities to document the process automatically. Furthermore methods for measurement or data based models and optimization types are presented. To optimize some maps over the whole operation range a consistent classification between different local model structures was introduced. Based on the optimized results for the local maps a global map is derived from the global base map. Also some methods to shorten the process are explained. Additionally methods based on intelligent algorithm to shorten the stabilisation phase for the measurement process are established. To analyse the trajectories in the high dimensional space in an effective way a solver was implemented to reduce stabilisation time.

1 Introduction

History shows that engine controlling elements turned from fixed, via speed dependent to map design. Electronic control unit provides a lot more possibilities for dependencies than mechanical magnitudes, like simply speed dependent versus injected mass, or charge pressure versus temperature, even model based ECU design is common. The handicap of a lot of dependencies is that these characteristics have to be defined. State of the art method is using Design of Experiments in order find an acceptable compromise between amount of measurements, which means time, and a good quality of the characteristics. A different approach of reducing the amount of necessary data in a control unit would mean to increase the model based proportion.

Engine control units have to meet transient and steady demands, therefore typical elements are used:

- Steady relevant Maps
- Controls or models, changing steady relevant data into transient signals
- Transient relevant maps

Due to this structure application work follows the evolution of elements: steady, changing from one steady operating point to the next, real transient cycles.
Additionally the aspect of different strategies and continuous intersection of them is a typical duty. In certain cases all strategies have to share single maps, in order to define these common characteristics, compromises have to be made with aspects of fitting each strategy best and a smooth transition.

Normally most of the steady application is done on test bed and transient applications have been done in the vehicle. But as soon as test bed configuration allows transient testing a part of work can be reproducibly done on the bench as well. This gives the possibility to increase the application work without a vehicle and helps to cut down expenses for early and very expensive prototypes. In combination with automated testing this also means a reduction of developing time and costs.

Homologation process forces a continuous ECU map design, which is done by a combination of smooth maps and specific methods of map adaption. The typical procedure would be using steady state operating points and integrating their characteristics into a map. The combination of these single steps with a transient test gives the possibility to change maps by using a shape instead of concentrating on the single interpolation points. Instead a shape is used to provide the change of the map. Timesaving aspects suggest that the parameters of this shape have to be fewer than the amount of interpolation points.

This paper explains the possible domains of using Design of Experiments in order to fulfil the actual ECU design as well as the actual boundary conditions in terms of emissions, consumption and other feasible aspects. In principle methods are shown to get an almost ready and fit for use control unit, in order to test a vehicle in transient as well as in steady state operating points.

1.1 Structure of application duties

Considering all calibration actions, from steady to transient relevant maps, they can be defined by the following steps:

- Define parameter
- Measure parameter and answer
- Modelling answer as function of parameter
- Optimize
- Validate

Measuring combinations and modelling can be assumed to a local loop, please refer to Figure 1: Duty structure. In contrast to local loop, the global loop considers all parameters or actors, which are not included in the modelling process.
Engine speed and torque would be typical global parameters, but the following aspects can be considered as well:

- Open or closed loop control
- Activated or deactivated pilot injection

This interpretation of global parameter leads to a split of the complete operating range into separate sections. In some ECUs is only one map is available for different sections, e.g.: rail pressure, which is treated by an extra optimization before the global validation.

Optimizing and validating are commonly done offline and under human supervision. Including these topics into an automated process means to speed up the complete process. Remaining functions for the application engineer are to review the global validation. In case of not achieving the goal, post processing actions can be defined for changing the target definition or properties for the map generation.

In principle maps are generated, based on the results of the local validation, after all global and local defined operating points are measured. Additionally to this generation the maps are transferred to the ECU and all global operating points are validated. Reason for this extra exercise is the map generation, which is an optimization, for more details please refer to 2.1 Map optimization.

Offline duties, shown in following figure, contain information concerning test bed communication, model definition and additional configurations.

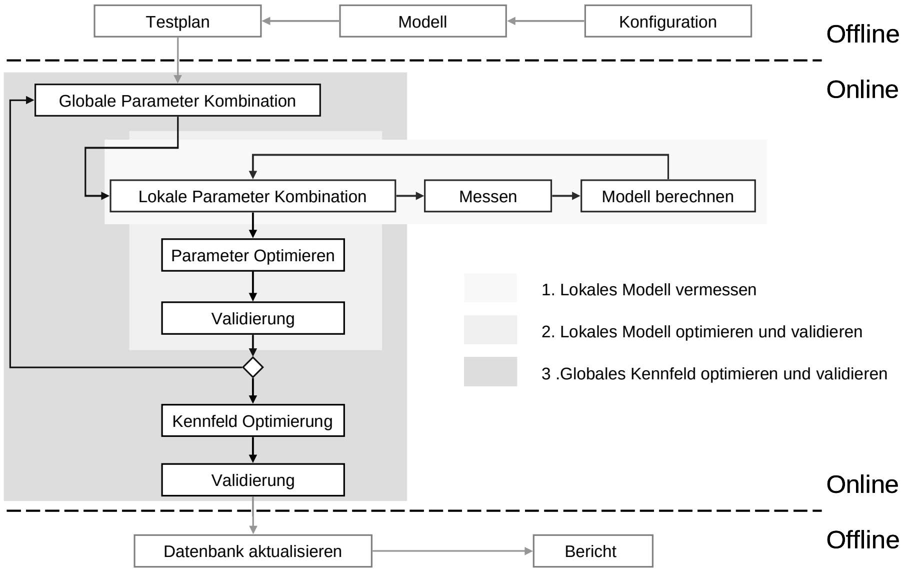


Figure 1: Duty structure

1.2 Test bed communication

Automized application process includes different products at the test bed. Global parameters have to be defined via test bed control, as well as local parameters have to be set at the calibration system. Because different tools for calibration and testing are available at the market, we decided to use standardized interfaces.

Figure 2: Communication shows the design of the interfaces. The special challenge was to keep the time gaps short between sending a command and conversion. Especially changing values at the calibration system is time intensive; in case of limit violations it is necessary to change the parameters fast enough in order to prevent the test object of damage. The type of ECU communication with calibration software is relevant as well, e.g.: a simple CAN is rather slow in comparison to more sophisticated types.

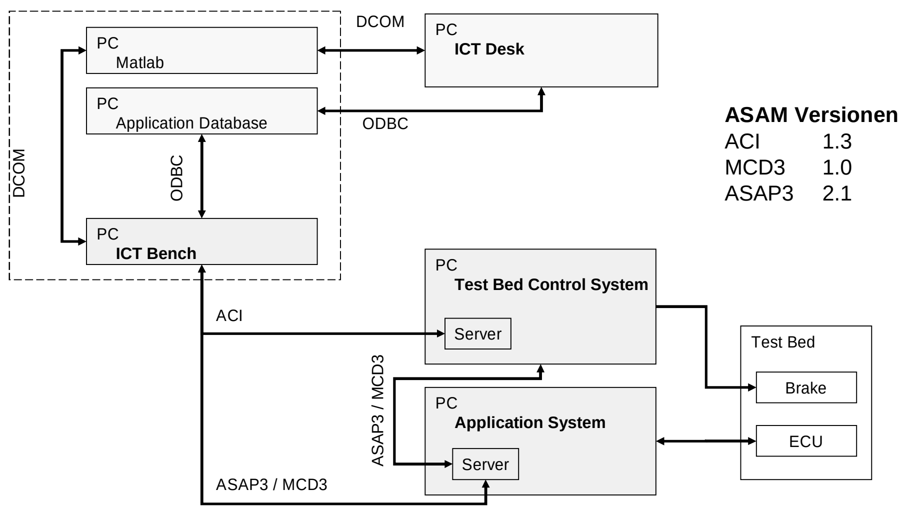


Figure 2: Communication

1.3 Limit Violation

Changing values in the ECU can lead to dangerous situations in terms of component damage; typically the following issues are monitored:

- Peak pressure
- Exhaust gas temperature
- Compressor surge line

Exceeding defined values must not stop the complete optimization process. Therefore strategies were developed, which provide a fast possibility to get back to secure combinations. The following figure shows an example of how to deal with such situations.

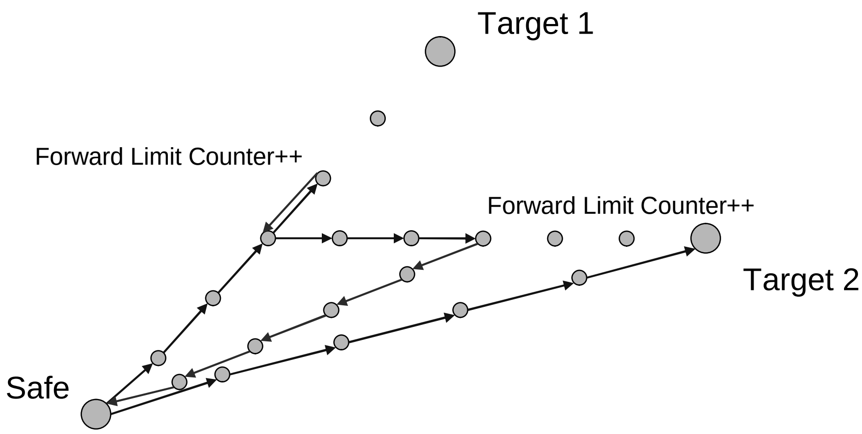


Figure 3: Dealing limit violations

Proceeding to the next local combination is divided into discrete steps, in case of a detected violation the last changes are undone. Due to the time response of the system it is not necessary to get a prompt answer, so the last steps are rewinded until an uncritical status is reached. If rewinding does not succeed, the last non violent combination is reached by setting these safe values at once, mentioned as “Jump to Safe”.

The figure above shows limit-counters, separated into forward and backward. On the state of these counters it is decided what to do next, e.g.: a backward counter with values higher than 2 will initiate a jump to safe. Having a dangerous situation handled, leads in proceeding to the next combination, independent of the actual state, is it a safe point or an intermediate. As one of the original combinations is lost due to limits, an alternative measurement is targeted. This measurement can only be done in case of a handled violation, which means that the actual point is an intermediate operating point. Reason for keeping amount of measurements constant can be found in model definition, as a minimum of data sets have to be executed in order to ensure enough input for the evaluation.

1.4 Limit Estimation

In addition to the monitored physical magnitudes, estimation can be calculated on these values as well. Two different forecast types of algorithms are available:

- Holt Winters
- ARMAX

The basic difference between these types of calculators is considering only the monitored value in comparison to considering input and output values.

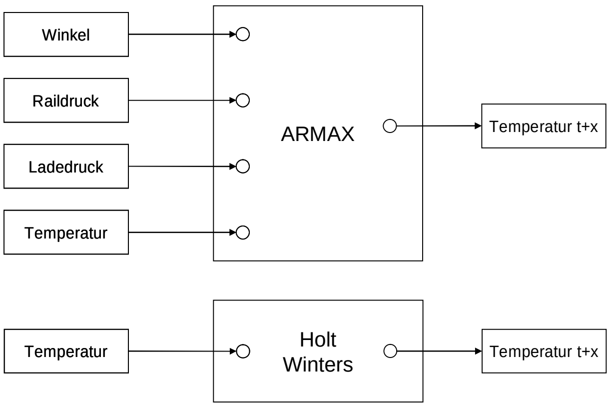


Figure 4: Estimator types

Due to the differing principles Holt Winters forecasts best, when the actors of the system did not change, the stabilization phase of a measurement for instance. Its results can also be used during continuous stepping to a target value as well, facing the disadvantage that at the beginning of travelling to the next operating point the quality of the forecasts is rather poor. But the properties of this algorithm assure a fast congruence between measured signal and forecast.
In contrast ARMAX is using the inputs of the system, the calibrated magnitudes, in addition to the monitored signal. This property helps in terms of faster response time, as well as the quality is higher compared to the more simple Holt Winters. Concerning CPU capacity there is a disadvantage using ARMAX, because this type of system identification is more complex.

Typical examples for usage could be defined due to the properties of these algorithms, slow magnitudes could be handled with Holt Winters:

- Temperatures
- Boost pressure
- Slow magnitudes

Whereas faster magnitudes should be applied by ARMAX:

- Peak pressure
- Turbocharger speed or pumping

The following graph shows the behaviour of the simple algorithm, tested on the exhaust gas temperature before turbine during an online test at the bench. The upper part shows the real magnitude and a 10 [s] forecast. At time of 1180 [s] the differences are becoming higher, which is caused by the change of an actor. As Holt Winters is only using the temperature signal itself, the information of change has to be transported via the magnitude, which leads to this lack of quality. After a short overshoot the signal is quite fast in feasible range, even though the actor is still changing.
At approximately 1190 [s] the actor has reached its target values and is no longer changed, which results in an additional deviation. Once again the difference is calming within the next few seconds. For this behaviour Holt Winters can be proposed to be used for slow magnitudes.

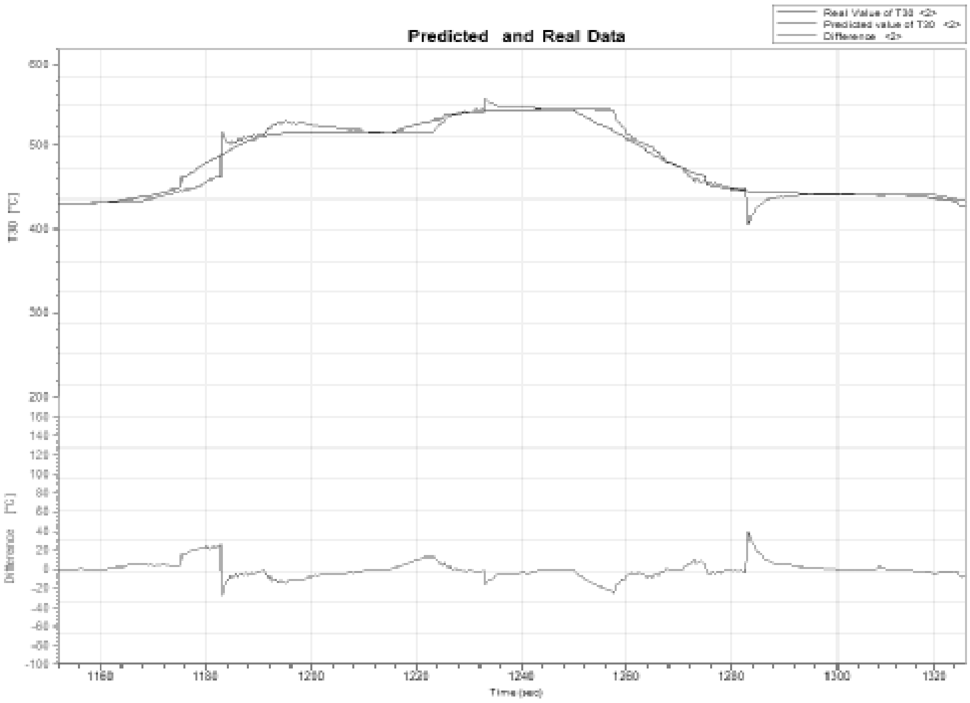


Figure 5: Example, Holt Winters

As flexibility was kept high during this development the calculation rule of an estimator can be exchanged. Even more sophisticated system identification methods may be imported in order to improve forecast quality.

1.5 Target Definition

Optimization can be reduced to a zero point problem. Therefore a virtual magnitude has to be defined in order to fit the mathematical demand. Typical values are included in an optimization:

- NOx
- HC
- CO
- Soot
- Consumption
- Sound pressure level

A typical approach for defining a target value is to use weighted sums in order to reduce a lot of measurement values to 1 virtual magnitude, which can be optimized with available algorithms. The following graph compares different calculation rules; additional target values of emissions are added. Target formulations lead to 4 different optima, whereas 2 of them are outboard the limits.
Target formulation 4 is based on the shortest length within the points, origin, actual and target. A shift was applied, so that the minimum has to be zero. This type of weighted assumption seems the most stable concerning multidimensional duties.
Formulations 2 meets only NOx target value at 1.6 [g/kWh], whereas the soot limit is 12[%] off. Method 3 is far within the limits of soot, but the specific NOx emission is 1[%] out of range.

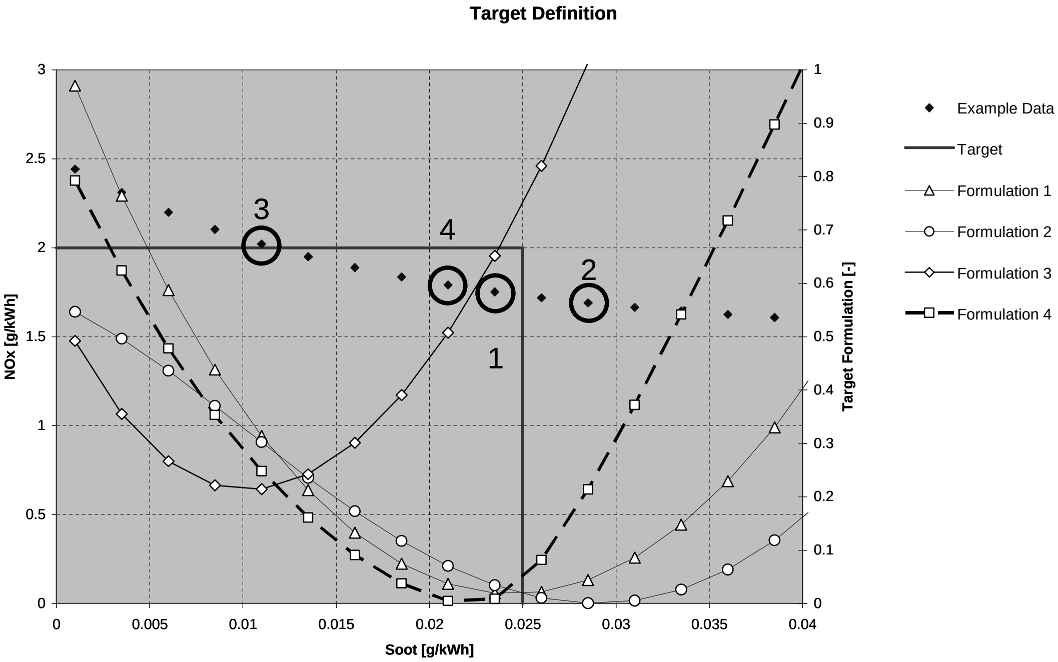


Figure 6: Target Definition for EU Stage III B Category L

Target definition 1:

$$\sum_{i=1}^{n}\left(\frac{x_i}{x_i^{target}}-1\right)^2 \qquad (1)$$

Target definition 2:

$$\left(\sum_{i=1}^{n}\left(\frac{x_i}{x_i^{target}}\right)-n\right)^2 \qquad (2)$$

Target definition 3:

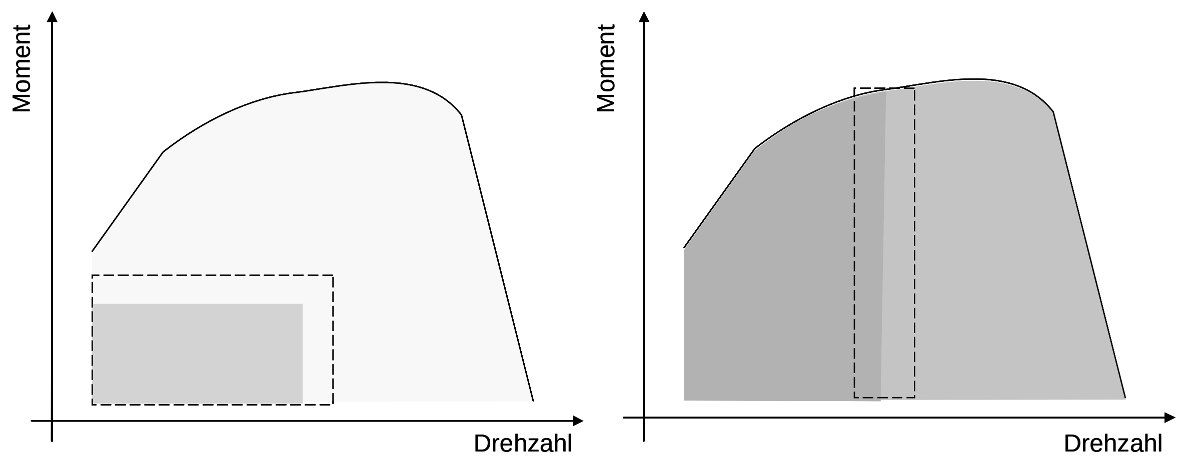
$$\sum_{i=1}^{n}\left(\frac{x_i}{x_i^{target}}\right)^2 \qquad (3)$$

Target definition 4:

$$\sqrt{\sum_{i=1}^{n}\left(\frac{x_i}{x_{Target}}-1\right)^2}+\sqrt{\sum_{i=1}^{n}\left(\frac{x_i}{x_{Target}}\right)^2}-\sqrt{\sum_{i=1}^{n} i} \qquad (4)$$

1.6 Strategy handling

In many applications different strategies are necessary, e.g.: closed loop versus open loop control of a charging system or a pilot injection. In order to handle these differences within one online operation constants are interpreted as global parameters to switch between these different calibration types.



Open & closed loop charging **Pilot injection on & off**

Figure 7: Strategy

Maps are separated into sections and these sections can depend on different actors, as well as different amounts. But they can consist of the same actors as well. An example for a section comprehensive actor could be rail pressure. In some ECU there is only one map for all strategies available. At the end of the completed testing a map optimization has to be treated separately, the best combinations of all operating points have to be fitted to one common map.

2 Steady state optimization

The typical automized task for model based DoE is for steady state operating points. A time based chart of a single operating point is shown below.

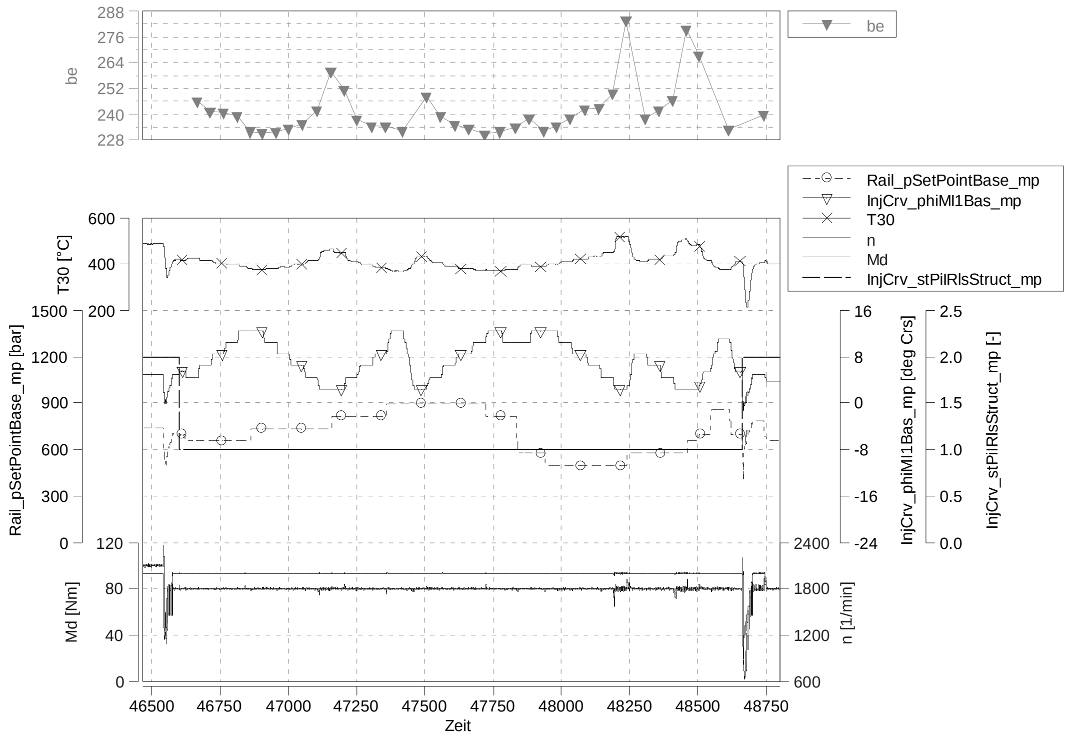


Figure 8: Steady Operating

Two features create possible time saving potential. The easier option is to order all necessary combinations most efficient, a typical travelling sales man problem. A challenge for this ordering is calculation capacity. As the original operating point of the ECU is unknown, it is mandatory to measure the original combination, as they vary depending on the global combination. These values are called centre values and on them the dimensionless test plan will be updated and ordered. An advantage of this procedure is that absolute number of the combinations need not be used as input of the system. The variation can be designed by deviation of the original values in percentages, or unit affected differences as well as absolute ranges. Additional to the sales man optimization a stabilization detection was implemented, which is based on gradients and quantiles.

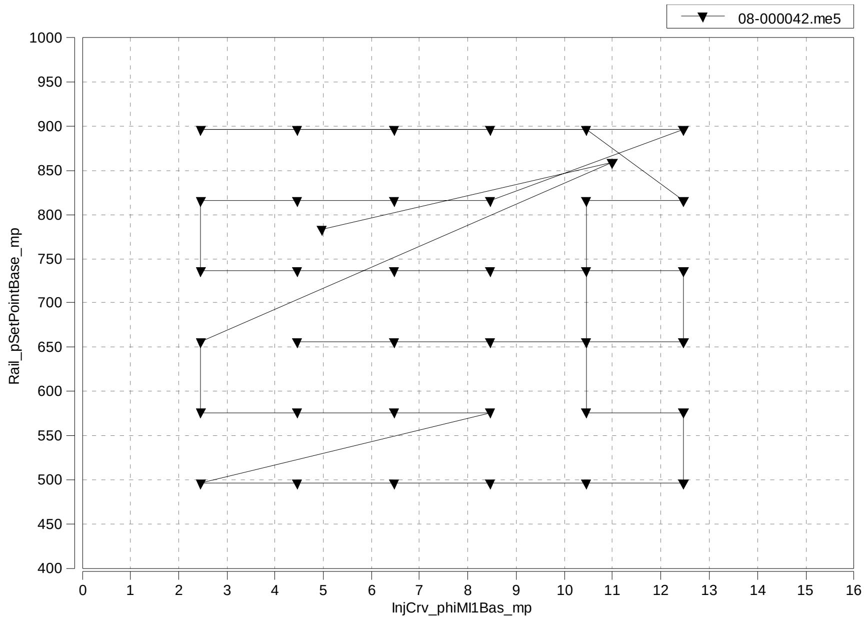


Figure 9: Travelling Salesman Problem

2.1 Map optimization

The sums of local optima per steady operating points mark the vertices of the map. As homologation forces smooth characteristics, as well as controlling aspects, a differentiable approach was chosen for this optimization. The figure below shows a simple example of the structure. Based on an original map, not containing the local optima, a radial basis function is added to the original map. The position, width in each direction and the height is optimized in order to get the best fit. This procedure is repeated for several times until no better solution is computed. In order to speed up this calculation the centre position of the added curve is replaced in this inner loop by a shift of the centre. For this exchange the outer loop has to define the centre, which is found by the highest deviation between the sum of local optima and the actual computation.

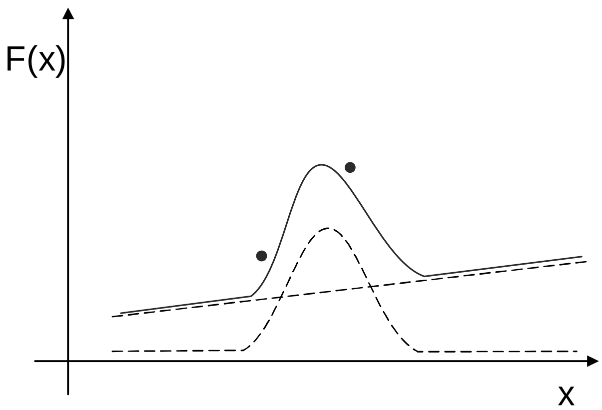


Figure 10: Strategy

Formula (5) shows the principle of this strategy. The additional benefit of this semi analytic map description is a very easy remapping of the variables to the original map design. As long as the engine behaviour, within the chosen operating points, can be represented by a sum of numerous basis functions, the amount of measured operating points may be reduced to a minimum. This once more leads to a reduction in calibration time.

$$F(x) = Orig(x) + RBF(x, x_0, w, h)$$
$$\sum_{i=1}^{n} (F_i - F(x_i))^2 \rightarrow Min(\Delta x, w, h)$$

$$\begin{array}{ll} Orig... & Original\,Curve \\ RBF... & additive\,Basis\,Function \\ x_0... & Center\,of\;Basis \\ x_i... & Available\,measured\;points \\ \Delta x... & Deviation\,to\,Center \\ w... & Width\,of\;Basis \\ h... & Height\,of\;Basis \end{array} \qquad (5)$$

The example below shows the main injection advance of a marine engine. This map is active for 2 strategies, activated and deactivated pilot injection. The switching engine revolution is at 2250 [1/min], which causes a rather deep canyon in the characteristic. Basis for the local optimization was a combination of consumption and all necessary emissions.

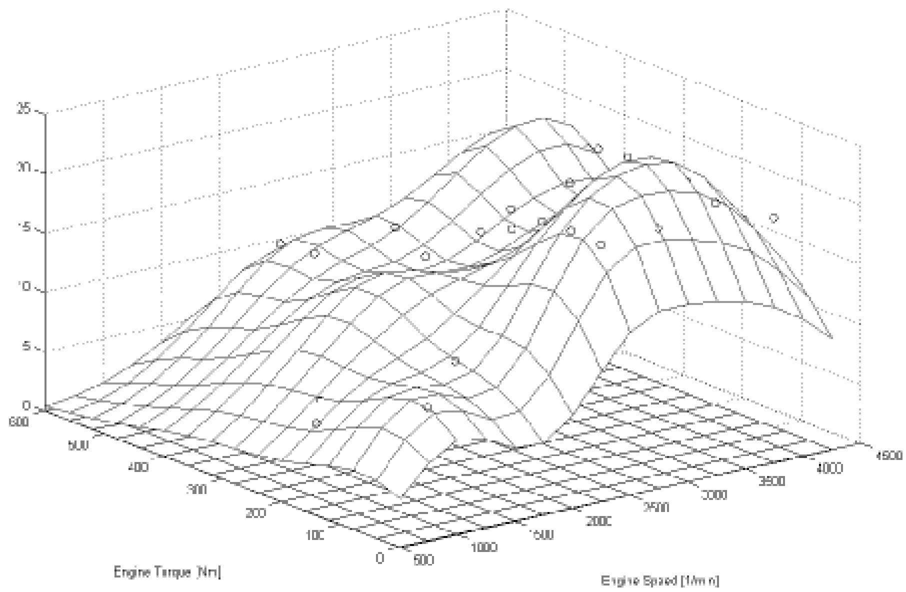


Figure 11: Map optimizing, main injection advance

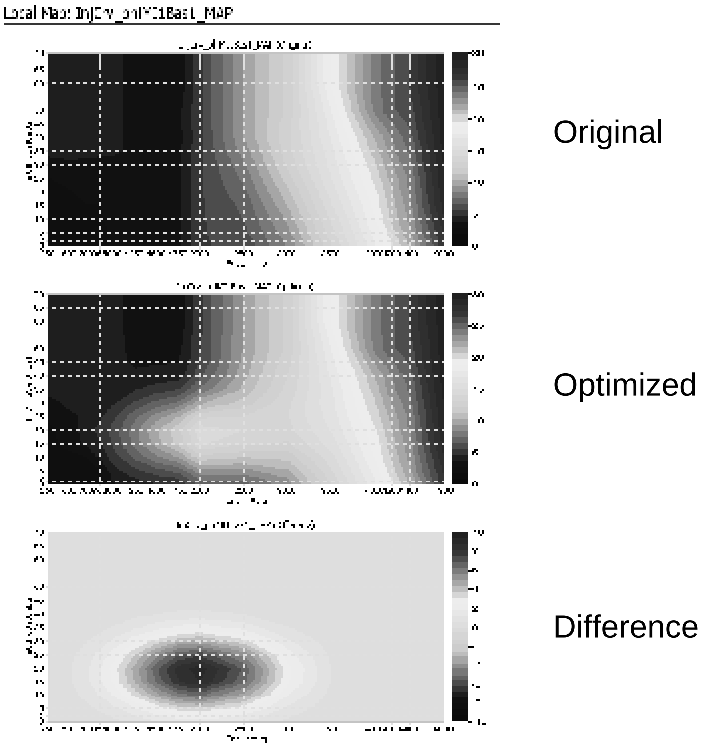


Figure 12: Map optimizing, main injection advance for single operating point

Figure 11 shows an example of a single operating point, optimized by RBF. Target formulation in this case was a sum of consumption, noise and soot. In addition with other optimized parameters the advance was shifted in direction early for an acceptable optimum.

3 Controller Optimization

Transient homologation and customer requirements of heavy-duty engines are very intensive in manual calibration. The definition of short significant cycles is a key feature for automated transient testing.

In comparison to the steady state optimization there are some little differences. Using a set of parameters, testing, reducing the measured values to one scalar are the main features. A simple controller consists of single values, which are interpreted as local actors. The test changes from steady to a simple cycle, which is defined in the test bench controller and launched by the calibration tool. Reducing the time curves into a single value can either be done at the bench or within the tool.

The figure below shows in principle a load step. The boost pressure control is integrated in the optimization and the response of the charge pressure is monitored. The reduction of the time signal is done in terms of failure integration between a target curve and the system response. This value is combined with the actual parameter set of the controller and used as input for the local optimization.

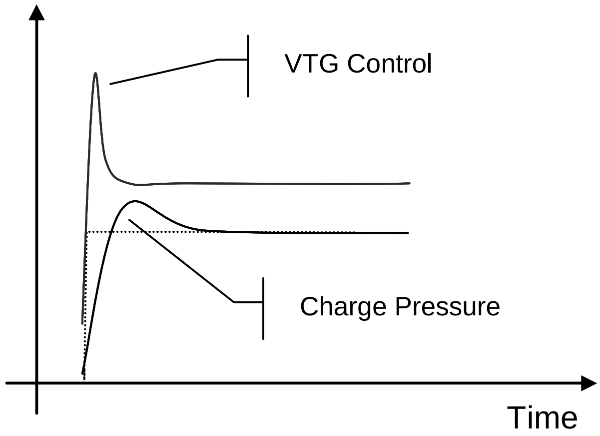


Figure 13: Strategy

As this type of optimization could not be validated at the moment of establishing this paper, there are no test bed results available.

4 Transient relevant map optimization

The last type of ECU maps are transient relevant compensations. At first they testing procedure has to be adapted to the principles of the described method. Core promise for the optimization is to generate sets of scalar values for modelling. In case of these characteristics a shape has to be defined or changed based on an input combination. This transformation is considered to be done with radial basis functions, with the coefficients width (variable in each direction), height, rotation and centre.
Following chart shows an example of the possible scenario. The upper part of the figure defines the relevant ECU characteristic in addition of one RBF. The test procedure is defined by full load acceleration, followed by a short load disruption and full load again. After a gear shift an operating point change at full throttle leads to a steady operating point at moderate engine speeds.
Opacity is monitored during the cycle and the numeric reduction can be defined by a simple integral of values or a sum of failure squares. The definition of the RBF and the result of the measurement are used for the local optimization.

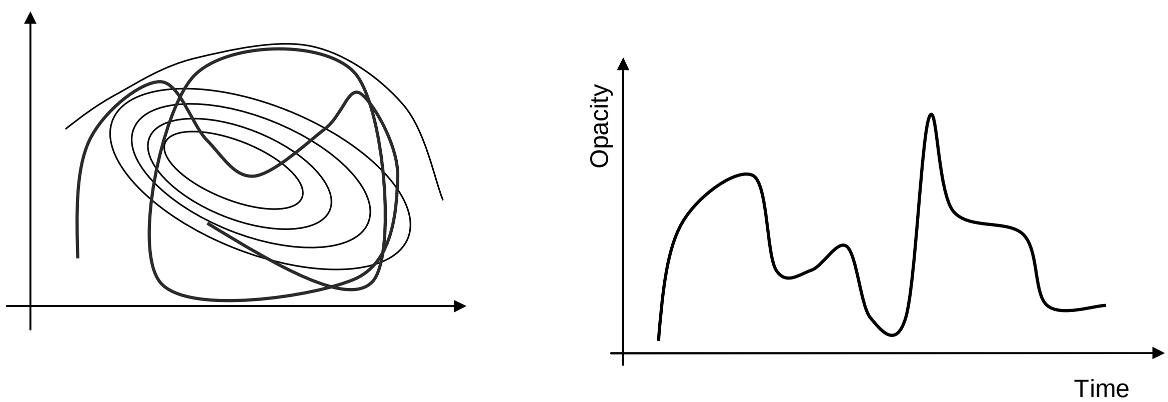


Figure 14: Transient map correction

5 Conclusion

It has been shown that the typical modelling process can be applied on all different types of ECU maps and parameterized controllers. This key feature allows a tool covering all steps in application. In addition to the steady state optimization only post and pre processing actions have to be introduced.
The automated workflow gives the possibility to for a completely usage of an automatic test bench. The gain in time efficiency safes resources for further duties, or researches that are more intensive.

6 Literature

[1] Bernd Klein: Versuchplanung – DoE Einführung in die Taguchi Shainin Methodik, Oldenbourg, 2007, ISBN 978-3-486-58352-6

[2] Pischinger, Klell, Sams: Thermodynamik der Verbrennungskraftmaschine, Springer Verlag, 2002, ISBN 13 978-3211836798

[3] Merker, Schwarz, Stiesch, Otto: Verbrennungsmotoren Simulation der Verbrennung und SChadstoffbildung, Teubner Verlag, 2001, ISBN 3-519-16382-9

[4] Karsten Röpke and 84 co-authors: Design of experiments (DoE) in Engine Development II , Expert Verlag, 2005, ISBN 3-8169-2498-0

[5] Karsten Röpke and 96 co-authors: Design of experiments (DoE) in Engine Development III , Expert Verlag, 2007, ISBN 978-3-8169-2720-4

[6] Colannino: Modeling of Combustion Systems , CRC Press Taylor & Francis Group,2006, ISBN 13 9780849333651

[7] …

7 Authors

Höfer Christoph, DI (DW 758)
Schlager Gerd, DrDI
Doppelbauer Clemens, DI

Engineer Center Steyr GmbH & Co KG
Steyrer Straße 32
4300 St. Valentin
Austria

Tel: +43 7435 501 – 0
Web: http://www.ecs.steyr.com