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ABSTRACT

Modern Internal Combustion Engines - especially Direct Gasoline Injection engines (DGI) - are equipped with an increasing number of actuators, thus enabling the application of new combustion systems for passenger cars.
To fully take advantage of the potential of the combustion system in reducing fuel consumption, it is important to optimize these parameters simultaneously.

The methodology using the CAMEO Optimization Tool supports the basic calibration as well as the optimization in the multidimensional room. Further it is important, to provide the knowledge of the engine behavior through out the whole ECU-calibration process.

INTRODUCTION

Reduction of fuel consumption and emission improvement require increasingly complex engine technologies. Therefore the expenditure for calibration plays an even more important role. On the other side development times have to decrease. New methodologies for development and calibration help to reach this target.

In gasoline engine development there is an abundance of new engine concepts. Figure 1 shows a comparison of different engine types with their potential for fuel saving (CO_2 reduction) and their systems' degrees of freedom.

A low cost but very effective concept is the AVL CBR system, which uses variable charge motion and EGR to reduce CO_2 emission.

Engines with variable valve actuation (EMV, EHVS and mech. VT) use dethrottling techniques and have the highest potential of all concepts with stoichiometric air-fuel ratio.

Downsizing benefits from shifting the operation range to speed and load regions with better specific fuel consumption. Especially turbo charged engines are used for such concepts.

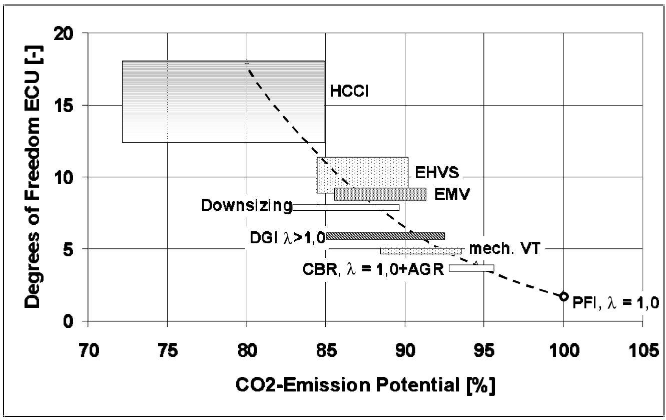


Figure 1: CO_2 emission potential versus system complexity of different engine concepts.

Future combustion systems like homogeneous charge compression ignition (HCCI) have with respect to NOx emission and simple exhaust gas aftertreatment the most promising potential for CO_2 emission reductions. But the system complexity is the highest of all gasoline engine concepts.

Lean burn concepts, specifically with charge stratification (direct gasoline injection - DGI engines) are now in production and have good fuel saving potential in part load. Achieving the CO_2 reduction in the vehicle is a great challenge. Optimization tools and methodologies which can handle the very complex relations between the interacting parameters are essential.

The AVL DGI engine

Direct gasoline injection is one concept promising a relevant potential for fuel consumption reductions in the lower part load region. The improved fuel economy is reached mainly by avoiding the pumping losses of a conventional homogeneous gasoline combustion system.

The method used to realize an average λ of 2 to 3 is charge stratification. This requires at spark timing two different regimes regarding the air to fuel ratio in the combustion chamber; an inner one around the spark plug, where λ is about 1.0 and an outer one with λ much greater than 1. The outer gas is ideally consisting of pure air only. To keep hydrocarbon emissions under control the transition area between the two zones must be very small. This can only be achieved with late injection.
Figure 2 shows a cross section through AVL's 2l DGI engine which is based on a wall guided combustion system with swirl charge motion.

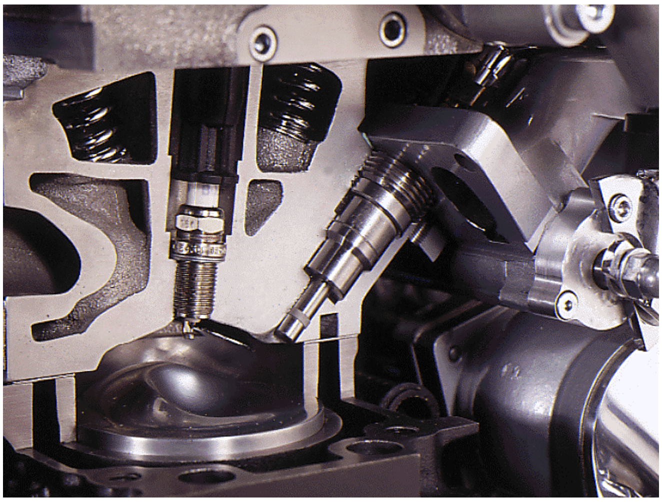


Figure 2: Cross section through the AVL DGI engine

On the right side of figure 2 the high pressure injector is shown which is injecting gasoline with about 100bar directly into the combustion chamber. The interaction of the in cylinder charge motion and the piston bowl shape is very important to obtain a good stratification at ignition and is one of the most complex tasks in DGI development.

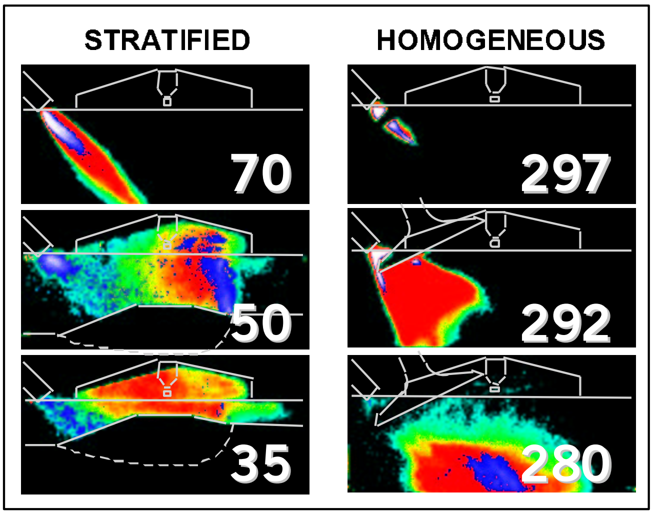


Figure 3: LIF pictures of the two DGI operation modes.

The homogeneous operating mode is still present in the DGI engine to achieve a competitive full load performance. Figure 3 illustrates the two operating modes of a DGI engine by spray pattern pictures made in the transparent engine at 2000 rpm using the technique of laser induced fluorescence (LIF). The numbers in the individual pictures denote the crank angle where the picture was made with respect to (before) firing TDC. The comparison shows a completely different behavior. In the stratified mode start of injection is in the range of 80deg CRA BTDC. The spray is injected into the piston bowl to get a good stratification. The duration between injection and ignition is about 50to 60deg CRA. In the homogeneous mode the fuel is injected at the beginning of the intake stroke. So the time between injection an ignition is about 270 to 280deg CRA which is necessary to get a homogeneous charge. This two mode operation leads to an increased calibration effort, because the standard calibration of the homogeneous operation and the optimization of the stratified combustion has to be done.

Control Parameters of a DGI engine

For a DGI engine test usually stratified and homogeneous combustion modes are investigated. The combustion characteristics of the homogeneous mode is similar to a normal port fuel injection engine as fuel is injected during a suction stroke so that fuel can be mixed well by the intake flow. As injected fuel spray could impinge on the piston crown due to early injection, possible increase of unburned HC emissions and soot has to be measured.
The stratified mode is to realize ultra lean combustion with late injection during the compression stroke. For this mode possible soot generation from impinged fuel spray on the piston bowl, unburned HC and NOx emissions, and combustion stability have to be studied in detail.

The following variation parameters need to be investigated within the calibration and optimization process:

Physical parameters
- in-cylinder air motion
- fuel spray behavior
- piston bowl shape

ECU control parameters
- Spark advance
- EGR-rate
- Start of injection
- Manifold pressure and
- Fuel Rail Pressure

This paper focuses on the online ECU control parameters and discusses the testing techniques available to derive the necessary maps for the ECU when the hardware configuration (piston bowl shape etc.) is given.

THE CALIBRATION PROCESS ON A DGI-ENGINE

Because of the complexity of a DGI engine it is essential to provide to the application engineer with information regarding the dependence of several ECU control parameters on quantities such as fuel consumption, combustion stability or emissions through out the whole calibration / optimization process. Software tools like the CAMEO Optimization Tool support the complete calibration process - from the basic calibration to the optimization in the multidimensional room. By using test bed data as a basis for modeling the dependency of the ECU parameters on fuel consumption etc. CAMEO enables the application engineer to access the complete information through out the whole calibration process.

I. BASIC CALIBRATION

Fast and efficient calibration of the basic ECU functions of a modern internal combustion engine is one of the main targets in the engine development process. Specialized tools can lead to methodologies that save a lot of time. A typical test bed configuration is shown in Figure 4.

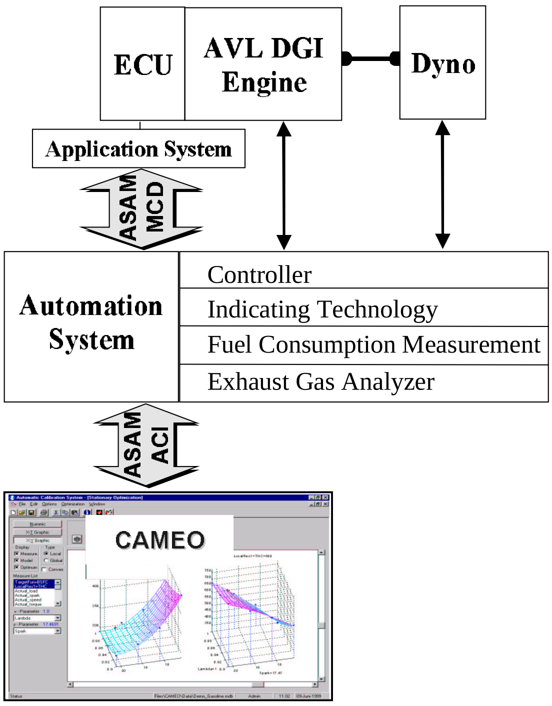


Figure 4: Test bed configuration for ECU calibration.

Part of the basic calibration is the determination of the charge model. To provide the data for the ECU a sequence of special test runs consisting of many measurements have to be done. For efficient data generation automatic test runs are essential. With specially designed tool boxes using the functionality of the software CAMEO a reproducible, well documented test run procedure is guaranteed.

A more sophisticated job is the calibration of the torque structure of modern ECUs like the BOSCH MED7. Automated calibration of the basic maps on the test bed leads to a substantial reduction in time. For that task powerful routines have been developed to enable a save and fast data generation, too. For the torque structure a lot of so-called spark sweeps are necessary to obtain the information of the influence of spark advance on the engine torque /5/.
The developed routine is able to find the spark advance for highest torque for each operation point with respect to the knock borderline and temperature limits. Especially for documentation and repeatability such a toolbox is of great advantage. In Figure 5 a typical spark sweep is shown.

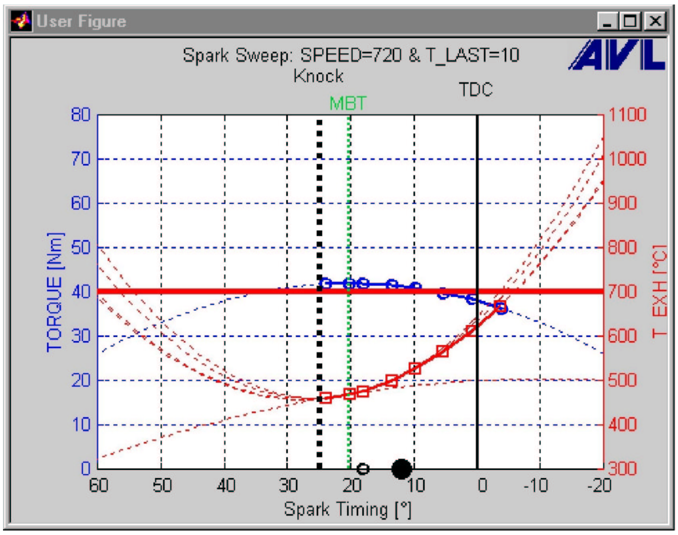


Figure 5: Spark Sweep

Starting at a save spark advance (big black dot) the algorithm is seeking for the maximum break torque (MBT) using a model of third order (blue curve with circle marker) or checking the point of 50% mass fraction burned if available. If knock occurs special limit reactions help finding the knock borderline and guarantee a save engine run. The end of the sweep at late spark advance is set by the exhaust temperature limit (thick red line at 700°C) which is repeatedly recalculated by approximating it with a quadratic model (red curves with square marker).

Once the parameterization of the test runs for the basic calibration are done, a rerun of the automatic procedure is readily available. This enables fast verification of optimized maps and also in case of slight hardware changes a very efficient and systematic optimization is possible.

The optimization software CAMEO in combination with specialized tool boxes is a sophisticated, powerful tool not only for optimization but for basic calibration as well.

II. OPTIMIZATION TARGETS

Improving fuel consumption with special respect to combustion stability and low emissions in order to comply with legislative standards is one of the main targets when optimizing an ECU calibration.

In this paper the optimization target is minimizing the overall fuel consumption and bringing NOx emissions below the engineering target for EURO 4 while guaranteeing good combustion stability in each operating point.

The focus of the investigations in this paper will be only on the stratified mode of the AVL DGI engine. The baseline engine maps were already pre-optimized. The optimization thus should take into account operating conditions that are relevant for the when implemented in the car. It is necessary to choose relevant operating points within the stratified regime. Additionally their weights within the test cycle have to be determined. In Figure 6 a typical load distribution of the NEDC driving cycle is shown for a 2l engine in a middle class vehicle.

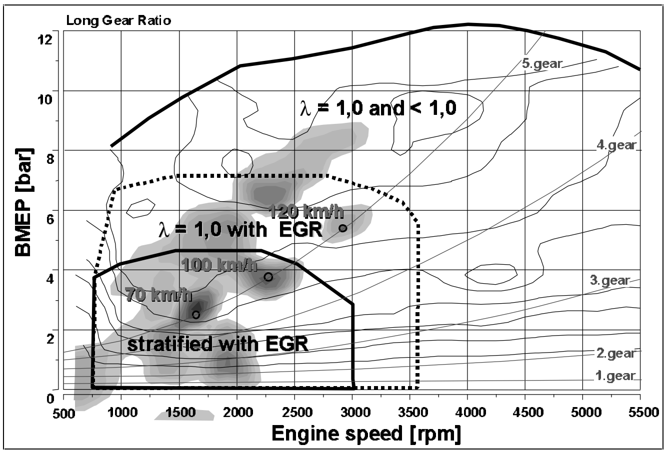


Figure 6: DGI Load distribution in NEDC driving cycle.

Out of this distribution 7 operating points and their weights in the load map were statistically determined to approximate the load distribution in the area of stratified mode in the NEDC driving cycle. The engineering target for allowable NOx emissions was estimated for the time of operating the engine in the stratified mode. It turned out, that NOx emissions resulting from the pre-optimized engine maps for tis load distribution needed to be lowered by about 15% to reach the Euro 4 target in the car.

Driveability demands must be taken into consideration as well. In this study the variation of the IMEP (V.o.IMEP) was used as a measure for driveability. Based on experience VARIATION was restricted to two different extents in all operating points.

Thus three cases of optimization targets were investigated in this study: Beside the parameterization of

- the existing engine maps (case 1)
- one with high level Variation of IMEP < 0.10 bar (case2) and
- a more secure one with Variation of IMEP < 0.07 bar (case3)

For case 2 and 3 emissions should comply with the engineering target while in all cases fuel consumption is kept as low as possible.

III. OPTIMIZATION ON THE TEST BED

The outlined approach consisted of the following 3 steps:

1. Run a test with a proper variation strategy in the 7 operating points
2. Modeling and visualization as basis for optimization
3. Map calculation and verification

By means of a practical example it is shown, how the calibration of the pre-optimized maps (case 1) could be improved for the AVL-DGI engine which is supposed to be used in the middle class car (figure 6).

1. Run a test with a proper variation strategy in the 7 operating points:

The ECU-parameters were varied while controlling engine and dyno demand values in steady state condition - e.g. constant speed and torque. CAMEO offers three “ready to use” variation strategies namely

- Full Factorial
- Online Model Based
- DoE Screening

The Full Factorial strategy creates automatically a test run with all possible combinations of ECU parameters according to the specification of the range and resolution of the selected variation parameters. Only those parameter combinations where no limit violation such as knocking, too high exhaust gas temperatures or misfiring occurs are actually set at the test bed and measurements are taken. The Full Factorial strategy is typically used in the basic calibration or tests with not more than 3 variation parameters.

The Online Model Based strategy is tailored for a situation where the area of interest is not yet known very well. This strategy is very efficient even with a large number of variation parameters. The Online Model Based strategy allows finding the optimum parameter combination quickly by modeling the dependency of a specified target function (e.g. fuel consumption) with respect to all variation parameters during the test procedure. Based on the online calculation a new combination of ECU parameters is determined. This iterative procedure is repeated until the optimum is found. During the whole process user defined limit monitoring ensures engine protection.

The DoE screening strategy is based on a Central Composite Design (CCD). The algorithm automatically searches first for limits (screening) and then measures. By screening the multidimensional parameter space first the approach overcomes the problem of a traditional CCD where typically some parameterized ECU parameter combination are not save for running the engine (limit violation) and therefore cannot be set. Together with the relatively few number of variations this strategy is well suited for complex optimization tasks with many variation parameters /3/.

In this specific study the DoE screening strategy was used to vary the following 5 ECU parameters:

- Spark advance
- EGR-rate
- Start of injection
- Manifold pressure and
- Fuel Rail Pressure

Figure 7 shows a 3D cross section of the five dimensional space of varied parameters. The figure is a snap shot taken at the test bed in one of the operating points while running the DoE screening:

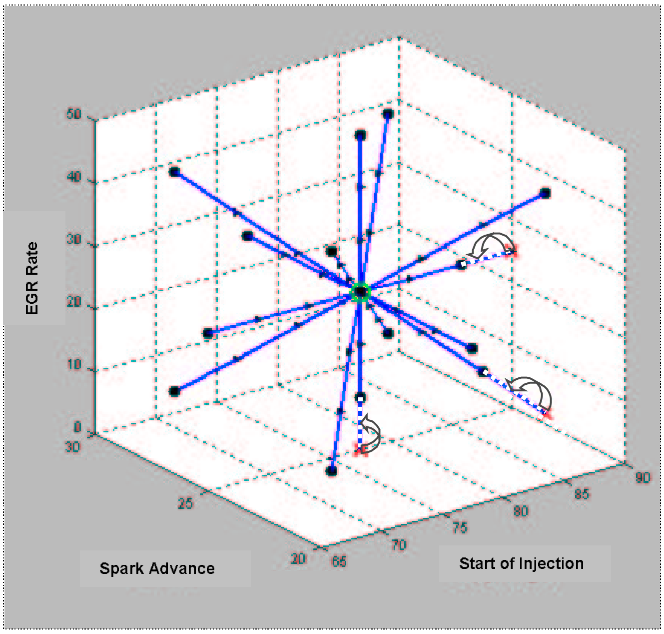


Figure 7. Online DoE Screening. The procedure tries to reach the points of a Central Composite Face-Centered Design. The points for taking measurements are denoted by black markers (●). A red marker indicates a limit violation (✕).

Measurements of several quantities such as fuel consumption, emissions (NOx, HC, smoke, etc.), indicating results (VARIATION of IMEP, MFB50%, etc.) or ECU onboard data were taken after a stabilization phase. These data were then used for optimization in the next step.

2. Modeling and visualization as basis for optimization:

Our optimization target was, to minimize fuel consumption while bringing NOx emissions below the target for Euro 4 standard.
The optimization is based on modeling each measured quantity such as fuel consumption. It is important to note, that all models are functions of all varied ECU-parameters. Therefore for the optimization all 5 ECU parameters are varied simultaneously.

Figure 8 shows for example fuel consumption as function of Manifold pressure (MP) and Start of injection (SOI).

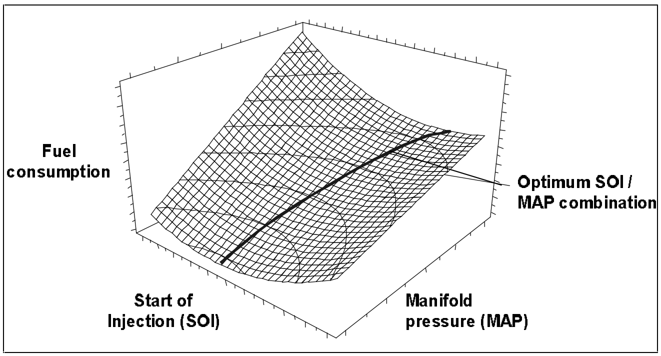


Figure 8: Fuel consumption as function of SoI and MP in the second operating point.

One can see clearly, that a change - e.g. in manifold pressure - maybe needed for increasing combustion stability - will lead to an other optimal start of injection. To find the optimum combination for the other ECU parameters it is of advantage, to have a visual presentation of fuel consumption as a function of all variation parameters in one plot. This graphical tool is offered by CAMEO with the so-called intersection plot (see figure 9).
As an example the models for fuel consumption (FC, top panel), NOx emissions (NOx, middle panel) and the variation of IMEP (V.o.IMEP, bottom panel) for each variation parameter are shown for one operating point in Figure 9. On the x-axis of each of the panels in Figure 9 the range for the ECU control parameters is displayed. KFIGAGRS is the ECU parameter for the EGR rate, KFPRSOLS for the rail pressure, KFPSSCH for the manifold pressure, KFWESBS for the start of injections, and KFZWSCHU for the spark advance, respectively.

The y-axis in figure 9 is defined by the actual range of measured values, that are fuel consumption, NOx emissions, or V.o.IMEP in that specific case, respectively. For each ECU parameter the dependency on the quantity shown on the y-axis is plotted in blue. Models with slopes close to zero (e.g. rail pressure - KFPROLS) indicate that changes of the parameter within the given range do not correlate with the quantity displayed on the y-axis (e.g. fuel consumption). The calculated optima are plotted in green, restrictions in red. When doing the optimization local constraints (in red) such as variation < 0.10 bar, and smoke number < 0.8 were applied. The dotted lines parallel to the models (blue) indicate the 95% confidence intervals of each model.

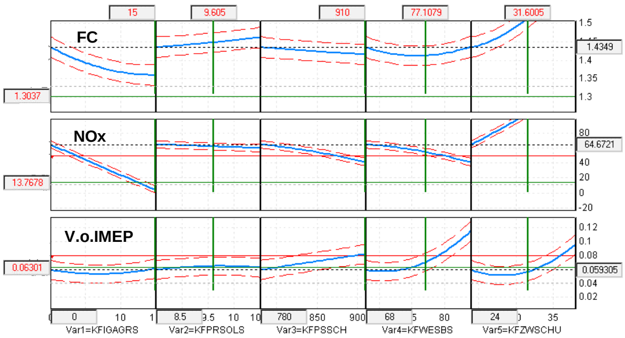


Figure 9: Intersection plot for fuel consumption (top), NOx emissions (middle), and variation of IMEP (bottom). Details see text.

This interactive graphic, allows the user to get a one dimensional cut for each independent parameter (5 ECU-parameters), while keeping the other four parameters fixed in the position of their cursors.

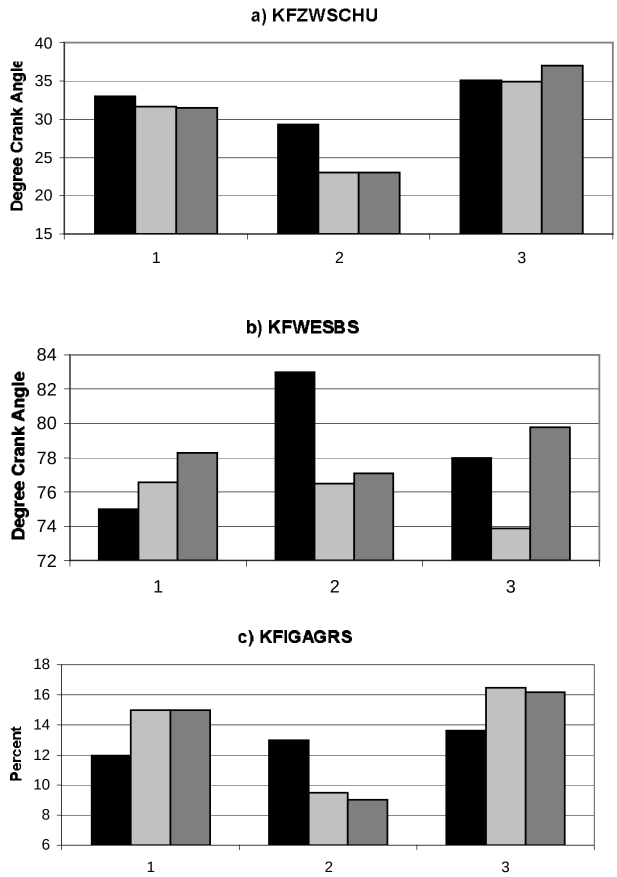
With this graphic the application engineer can study and understand the interaction between the ECU-parameters on fuel consumption, NOx and variation of IMEP, respectively.

The Optimization itself is based on models. Exactly one target function has to be defined (e.g.: fuel consumption). Additionally an unrestricted number of constraints (e.g.: NOx, HC, Smoke, variation of IMEP to be below or above a certain value), which must not be violated by the optimization result can be defined. Keeping the constraints, the optimizer suggests the combination of varied parameters, which gives the lowest possible value for the model of the target function. If this optimization is done seperated for each operating point of the engine (speed/load set), we talk about a local optimization.

In our example, we used the feature of CAMEO, to do a so-called global optimization: That means, that the target function (fuel consumption) is calculated as the weighted sum over all seven operating points. Also for the global constraint (NOx emissions) the weighted sum over all seven operating points is calculated.

As the models for fuel consumption or NOx are different in the seven operating points, the optimizer suggests a new combination of ECU-parameters in each operating point. The new settings lead to a global decrease in fuel consumption and NOx emissions but not necessarily to a decrease in each individual operating point.

As defined in section II, three cases for the optimization target were compared in this study: case 1 relates to the original pre-optimized calibration, case 2 to the newly optimized calibration and case 3 to an optimized calibration with special respect to improved driveability. In case 2 the variation of IMEP was restricted to values < 0.10 bar locally. In this paper we approximate driveability with high combustion stability. Therefore enhanced driveability was simulated by tightening the constraint on the variation of IMEP. In case 3 a value for the variation of IMEP < 0.07 bar should allow us to estimate the influence on fuel consumption and NOx emissions that can be expected to result from tests in the vehicle, which will follow in future. Corresponding to this three cases the result of the global optimization for the first three operating points with the highest weight, is shown in Figure 10.



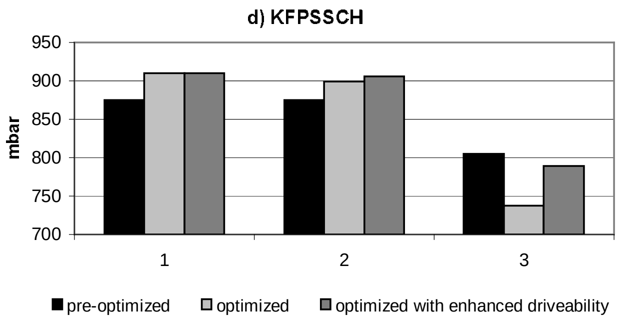


Figure 10 a) to d) shows the changes of al the ECU-Parameter except, fuel rail pressure, which altered very much due to the optimization.
It is not enough room, to discuss all the effects here in detail, but the important message is, that all ECU-parameters have to be changed simultaneously, to reach the optimization target defined above.

3. Mapcalculation and Verification:

Out of the obtained optimization results for each of the seven operating points, five maps could be calculated for the five ECU parameters. As an example Figure 11 shows the resulting engine map of spark advance for “case 3” including the data of the optimization results for the 7 operating points that were investigated in that paper.

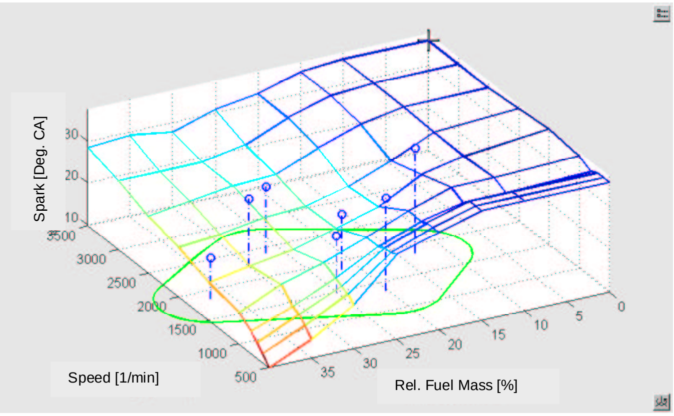


Figure 11: Resulting spark advance engine map based on the results from a global optimization.

The area at the bottom of the map (speed – rel. fuel mass – plane) marks the values corresponding to the grid points of the map where the map was recalculated. The circles represent the optima. The application engineer has also the possibility, to edit manually the map values, while comparing them to the optimization results.

Verification runs using the two sets of engine maps obtained by the global optimization are shown in Figure 12 and 13. The results are the sum of the global optimization for fuel consumption and NOx emissions. They are compared to the corresponding run based on the pre-optimized maps.

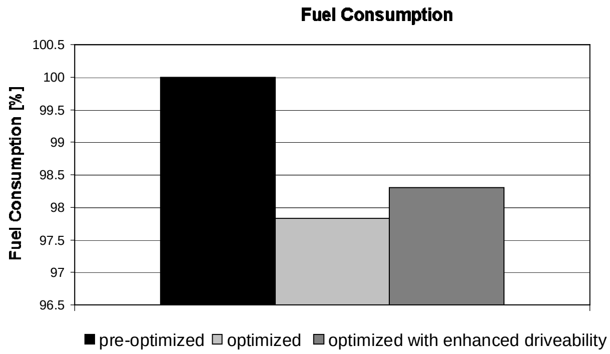


Figure 12: Fuel consumption in percent for the 3 cases: case 1 (black bar) original calibration, case 2 (light grey bar) with CAMEO optimized calibration, case 3 (dark grey bar) with CAMEO optimized calibration with enhanced driveability.

The global optimization approach results in a significant reduction in NOx emission for case 2 and case 3, so that the estimated target for Euro 4 can be reached clearly. The local constraint for the variation of IMEP below a value of 0.07 bar in all operating points is a restriction, which should also ensure desired stability of combustion in the car.

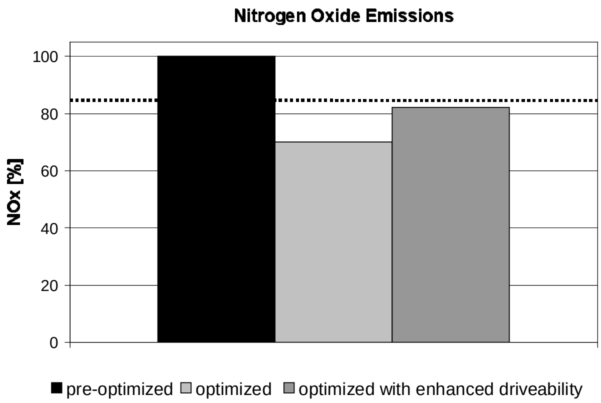


Figure 13: NOx emissions in percent for the 3 cases: case 1 (black bar) original calibration, case 2 (light grey bar) with CAMEO optimized calibration, case 3 (dark grey bar) with CAMEO optimized calibration with enhanced driveability. The dotted line marks the engineering target for the Euro 4 standard.

CONCLUSION

One could see, that the increasing complexity of modern combustion systems like DGI engines raises the demand, to use new methods of variation, modeling and optimization of ECU-parameters.

It was shown, that such methods are supported by the software tool CAMEO for the basic-calibration and for the optimization of combustion relevant ECU-maps as well. Even a pre-optimized set of engine maps for the stratified operation mode of the DGI engine could be improved, by checking changes of all possible ECU parameters at the same time. Out of one data set from the test bed, two new sets of engine maps could be calculated. The new optimized engine maps allow to reach the Euro 4 target for NOx and to lower fuel consumption while ensuring combustion stability.

The applied method changes generally the whole set of engine maps. This requires consequent modeling of the information gained from the test bed even during adaptation and refinement phase in the car.

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