ABSTRACT

For on- and off highway applications in 2012 / 2014 new legislative emissions requirements will be applied for both European (EURO 6 / stage 4) and US (US 2010 / Tier4 final) standards. Specifically the NO\textsubscript{X}-emission limit will be lowered down to 0.46 g/kWh (net power > 56 kW (EU) /130 kW (US) - 560 kW). While for the previous emissions legislation various ways could be used to stay within the emissions limits (engine internal and aftertreatment measures), DeNO\textsubscript{X}-aftertreatment systems will be mandatory to reach future limits.

In these kinds of applications fuel consumption of the engines is a very decisive selling argument for customers. Total cost of ownership needs to be as low as possible. The trade-off between fuel consumption and NO\textsubscript{X}-emissions forces manufacturers to find an optimal solution, especially with regard to increasing fuel prices.

In state of the art calibration processes the aftertreatment system is considered separately from the calibration of the thermodynamics. The thermodynamic engineers find the best fuel consumption in steady state engine operating points and most efficient combustion with regard to engine-out emissions which might be converted by an aftertreatment-system with an assumed conversion rate.

The problem associated with this approach is that the transient and therefore the heat-up behavior of the aftertreatment system are not being considered. The heat-up behavior becomes more and more important in particular for test procedures including a cold started cycle such as WHTC or NRTC. To overcome these problems a second mode for the heating of the exhaust aftertreatment system (EATS) and sometimes a third mode with low NO\textsubscript{X} emissions will be calibrated separately. The optimization of the operation strategy with all modes is mostly done at the test bench. The optimization is always done in a serial way when using this approach. This does not consider all calibration parameters at the same time. Therefore, the overall fuel consumption or the total cost of ownership does not reach the optimum.

A new approach developed by FEV GmbH and the Institute for Combustion Engines RWTH Aachen University (VKA) takes into account the aftertreatment system and all engine calibration parameters from the first calibration step. VKA and FEV have developed a tool (SimEx) which is capable of simulating a freely configurable aftertreatment system. The integrated global engine DoE and an automatic optimizer will calibrate all engine and EATS parameters. The target of the optimization is an optimal solution for fuel consumption / total cost of ownership with regard to the transient tail-pipe emissions. The engineering target for the emissions in the homologation cycle is typically the constraint. Along with the reduction of fuel consumption in the certification cycles the fuel consumption of the specific application can also be taken into account during the calibration process through the use of customer defined cycles. The total cost of ownership can be effectively minimized through this process.

The parameters for optimization can be chosen completely freely e.g. injection and air path parameters for different engine modes, operation strategy, EATS parameters like size and position. Furthermore different models can be included,
such as ECU models for the operation strategy, catalyst aging models, and newly configured ones.

If use of the tool is begun in a state where the exhaust aftertreatment is not fixed, there is the opportunity to design and optimize the aftertreatment system for the lowest total cost of ownership including the prices for precious metal and consumed fuel over life-time.

Overall, this tool allows the integrated optimization of the whole calibration process instead of calibrations based on individually optimized parts.

INTRODUCTION

The next step in the legislated emissions regulations for medium and heavy duty vehicles, as well as for buses, is planned for 2012 with EURO VI\(^1\). Here the nitrogen oxide emissions (NO\(_x\)) are further reduced from 2.0 g/kWh to 0.46 g/kWh. As a result of this, On Board Diagnosis (OBD) limit values are also changed. While in EURO V the malfunction indicator light (MIL) announces an error at 3.5 g/kWh and starting from a value of 7 g/kWh the available output power of the engine is reduced down to 60-75%, in EURO VI a limit value of 1.5 g/kWh is intended.

Furthermore, the certification cycle for commercial vehicles is changed. The previously used European Transient Cycle (ETC) is replaced by the World Harmonized Transient Cycle (WHTC). Therefore, a certain level of development is needed, since the mean temperature of the exhaust system of the WHTC is lower. The most important changes are summarized again in table 1. Also, the emissions limits for industrial engines for the US emissions legislation Tier4i and Tier4f can be found in table 1 for engines higher 160 kW engine power. The emissions limits for Euro V and Tier 4i as well as Euro VI and Tier 4f are quite similar, but use different cycles with different speed, torque and temperature characteristics.

A similar adjustment of the emissions regulations will also be observed with industrial engines. The interest in fuel consumption reduction is getting stronger at the same time. To fulfill the emissions targets with optimized fuel consumption or minimized total cost of ownership, different options can be used:

- Reduced engine out emissions [4]
  - Optimized combustion system
  - Optimized / higher boost pressure
  - Higher injection pressure
  - Increased EGR-Rates / efficient EGR cooling
  - Efficient charge air cooling

- Exhaust aftertreatment
  - DOC size and coating
  - SCR size, type, and coating
  - DPF size, substrate, and coating
  - Exhaust gas aftertreatment system architecture

- Calibration
  - Operation strategy (number of engine modes, and switching strategy)
  - Engine calibration in all engine modes

- ECU structure and sensors
  - EATS control structure

\(^1\)So far the limit values for EURO VI are not finally fixed. It is assumed that the limit values are reduced as described. This comes out from prior publications of the European Union of 22.11.2010.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cycle</th>
<th>NO(_x) / OBD-MIL / TqLim / (g/kWh)</th>
<th>PM / (mg/kW)</th>
<th>NH(_3) / (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EURO V</td>
<td>2008</td>
<td>ETC</td>
<td>2.0 / 3.5 / 7.0</td>
<td>30</td>
</tr>
<tr>
<td>EURO VI</td>
<td>2013</td>
<td>WHTC</td>
<td>0.46 / 1.5 / 1.5</td>
<td>10</td>
</tr>
<tr>
<td>Tier4i</td>
<td>2011</td>
<td>NRTC</td>
<td>2.0 / - / -</td>
<td>20</td>
</tr>
<tr>
<td>Tier4f</td>
<td>2014</td>
<td>NRTC</td>
<td>0.4 / - / -</td>
<td>20</td>
</tr>
</tbody>
</table>
◦ Combustion control structure
◦ Sensor layout

To optimize the overall application all options which can be varied have to be taken into account. The overall optimum can not be found just by the variation of the individual parameters. All parameters have to be optimized in parallel. Due to the high number of parameters this is not possible through engine testing.

To allow this complex optimization, a simulation program was developed by FEV GmbH in co-operation with the Institute for Combustion Engines RWTH Aachen University. This program, SimEx, is able to optimize all previously mentioned and additional parameters as well as simulate the exhaust aftertreatment system, waste heat recovery and hybridization.

CERTIFICATION

The certification is typically the constraint of every optimization. As an example, the certification according to EURO VI has a NOX limitation of 0.46 g/kWh and a PM limitation of 10 mg/kWh. Because of the deviations of the sensors and the actuators with regards to the engine itself and the exhaust aftertreatment system as well as aging of the catalyst a NOX engineering target of 0.33 g/kWh is used for the following considerations. In Figure 1 normalized engine speed and engine torque of the WHTC cycle is shown. Beside the transient test also the emission limits of the steady state test (WHSC) and the Not To Exceed (NTE) area has to be fulfilled.

Figure 1. Normalized engine speed and engine torque in WHTC

COMPLETE SYTEM

The complete system consists of an engine, including its calibration, the exhaust aftertreatment system, as well as the controller concept. To simulate the complete system, the following parts are included in the program SimEx. The engine including the calibration can be simulated through the capability to implement any global Simulink based DoE models from the test bench. This model is capable of predicting the emissions, the temperatures, as well as the brake specific fuel consumption (BSFC). Further parameters can also be included if necessary. The input parameters of the model (named indirect parameter in Figure 2) are calibration values like rail pressure, EGR rate, and injection timings and quantities. These maps can be smoothed by an algorithm. These smoothed input maps are used by the global models to calculate the output values (direct parameters in Figure 2). These output values contain the emissions, exhaust mass flow, temperatures, and also the BSFC. These outputs maps can also be smoothed. Another very important output parameter could also be the costs. The cost models should be set up with specific values to be able to calculate the total cost of ownership. Therefore, the total engine life time has to be defined. Examples for costs are system cost for the engine (life time related), system costs for EATS system (life time related), fuel costs (consumption related), as well as Adblue (urea) costs (consumption related). Some costs also should be set up as a function of other parameters. For example, with catalysts the price is also a function of catalyst size to a large extent. When the cost system is set up completely the total cost of ownership can be optimized instead of fuel consumption.

Figure 2. Overview SimEx optimizer

These map based models are combined with a turbo charger model which is used for transient cycles. Also transient corrections are possible with regard to the emissions. As a second input, catalyst data from a synthetic gas test bench or engine test bench is used. These models predict the conversion efficiency of the different catalyst/EATS types like DOC, SCR, LNT and DPF. The third part is the software structure of the ECU with the strategy for the exhaust aftertreatment system (EATS) and the engine operation modes. For example the SCR dosing strategy (e.g. with or without drift correction and NH3 storage model) is quite important for the real EATS efficiency.
The complete system including all parts is shown in Figure 3.

The optimization itself is completely flexible. The engine calibration with all varied input values can be optimized, as well as catalyst sizes, positions, and coatings. Different ECU strategies can also be taken into account.

As an example, the Tier4 final emissions limit can be reached by a particulate oxidation catalyst (POC) in combination with a high efficiency SCR system, or also a combustion system with low PM emissions in combination with such an SCR system (Figure 4). Tier4f emission limits can also be fulfilled by low NOX combustion system in combination with a DPF only. Last but not least a state of the art combustion system with DPF and SCR can also be used to fulfill the Tier4f requirements. To be able to find the best way, all possibilities have to be taken into account, with optimized engine calibrations and also an adopted operation strategy. The simulation software SimEx has the ability to take into account the different combustion systems as well as different EATS concepts and define the best calibration and operation strategy for each concept.

If the “Model Evaluation” is verified a conditioning WHTC will be simulated. This has to be done, because the conversion efficiency during the cold cycle is strongly dependent on the NH3 start loading. This NH3 storage depends on the cycle temperature, especially at the end, and also the dosing strategy and ECU functionality. With regard to EU6 emissions legislation, two transient cycles have to be conducted with an intermediate soak time of 10 minutes for cool down. The weighting of the emissions results of these cycles is 14% for the cold cycle and 86% for the warm cycle. The weighted cold and warm WHTC are used as a constraint for NOX and PM emissions during the optimization. For example the NOX emission has to be lower than the engineering target of 0.33 g/kWh and the PM emission has to be lower than the engineering target of e.g. 20 mg/kWh upstream DPF. If the constraint is fulfilled two customer cycles, which represent the real operation condition, will be simulated. They can be weighted e.g. by 50% with respect to the fuel consumption. This fuel consumption is the overall optimization target during the optimization. Due to the fact, that the OBD limits also have to be fulfilled during the customer cycles this will be checked as a constraint during the optimization run.

OPTIMIZED VALUES

During the optimization the combustion system, the engine calibration, the EATS system as well as the ECU functionality can be optimized.

In Figure 6 shows different strategies to reduce the raw NOX emissions. With regard to the combustion system, the EGR can be increased (1) to lower the NOX emissions and the rail pressure can be increased (2) to lower the engine out PM emissions. Therefore the capability of peak cylinder pressure has to be increased. If the EGR is increased further (3) the relative air to fuel ratio has to be reduced to lower the peak...
cylinder pressure. By reduction of the compression ratio ($\varepsilon$) the peak cylinder pressure can be reduced further. \[1\]

Figure 6. Optimization combustion system in C100 operation point \[1\]

Also highly efficient boosting \[7\] and cooling systems, in combination with higher EGR rates, can be applied to get a better NO\textsubscript{$X$} / PM ratio.

To take different combustion systems into account, models from all relevant systems can be implemented and used during the optimization process.

In addition to the combustion system, the engine calibration itself can also be optimized during the overall optimization process. The basis to set up the DoE models is typically a global DoE (Design of Experiment), which also contains the engine speed and the torque as variation parameters in the modeling. The program is capable of handling nine engine operation modes, which can be switched between, depending on the ECU capabilities. Therefore, the operation strategy of the ECU can be implemented in the simulation tool. An example for the operation strategy could be the following (Figure 7):

- A heating mode (mode 1), whereby the exhaust gas temperature is maximized, in order to bring the exhaust system up to operating temperature, where the NH\textsubscript{3}-storage level of the SCR is filled sufficiently, and no urea dosage is still permitted due to low temperature.
- A NO\textsubscript{$X$} optimized mode (mode 2) in order to avoid high NO\textsubscript{$X$} emissions when the SCR NH\textsubscript{3}-storage is almost empty, and
- A fuel consumption optimized operating mode (mode 3) for the part of the cycle, in which the urea dosage is active and conversion rates of the SCR are high enough. This mode is also of high importance with regard to customer use, because typical customer cycles have very often longer duration w/o cold start and therefore sufficient EATS temperatures which are needed for a high conversion efficiency.

Figure 7. Calibration based on three different modes of operation

To compare different ECU structures and capabilities, the structure which should be compared can be implemented and the optimizer can decide which one has the best capability with regard to the overall optimization target.

In addition to the combustion system and engine calibration the EATS system also has to be optimized. With a suitable exhaust aftertreatment system setup consisting of DOC, DPF and SCR with suitable SCR technology with appropriate base calibration (NH\textsubscript{3}- governor calibration, dosing temperature threshold), the operation strategy as well as the catalyst size and coating technology has to be defined (Figure 8).

Figure 8. Exhaust aftertreatment system setup

In addition to the catalyst size and the coating, the ECU software capability is of major importance. Therefore this can also be included in the simulation program SimEx (e.g. aging models, NH\textsubscript{3} governors…). Also for these models the
comparison of different structures is also possible with SimEx.

Figure 9 shows examples of different possibilities for the engine operation strategies. In the first example, the switch from the heating mode into the NO\textsubscript{X} optimized mode is done at an SCR temperature of 150 °C and into the fuel consumption optimized mode at 250 °C. Also, a direct switch from NO\textsubscript{X} optimized mode to BSFC optimized mode as well as a direct switch from heating to BSFC optimized mode is shown.

Figure 9. Variation of the points of operating mode switching on the basis of the SCR temperature

While the test procedure described in Figure 5 takes about 100 minutes in real time (without engine shut-off of approx. 8 h to cool down for the cold start cycle), the simulation needs only 4 seconds. Thus the variations suggested in Figure 9 take about 3 minutes simulation time.

OPTIMIZATION EXAMPLES

In the following figures some examples of the SimEx capabilities are shown, to show the principle possibilities of the program. The graphs are examples with only 2-dimensional variations. The overall optimization is capable of handling any higher dimension. The number of variables should of course be minimized to the needed values to minimize the optimization time and reduce the risk of a system which has several local maxima or minima which make the identification of the global maximum and minimum difficult.

The first example is a single mode strategy with a DoE engine model and one engine maps set. The variation parameters are rail pressure, EGR rate and injection timing. The target is a Tier4f calibration with Cu-zeolite SCR and DPF. Therefore the optimization cycle is the following:

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Weighting for Objective</th>
<th>Weighting for Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Evaluation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NRTC (Conditioning)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold NRTC</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Soak Time 20 min.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm NRTC</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td>C1 Test</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Optimizer:</td>
<td>(\Sigma)</td>
<td>(\Sigma)</td>
</tr>
</tbody>
</table>

Figure 10. Optimization cycle Tier4f application

Overall, the fuel consumption for the customer cycle is reduced significantly during the optimization process (Figure 11). The optimization is done in three generation steps which include up to 6200 simulation cycles. The results of the plotted generations include only calibrations which fulfill the “Model Evaluation” and are within the emissions limits. Also the final engine maps for NO\textsubscript{X}, BSFC and Temperature upstream turbine are shown in (Figure 11).

Figure 11. Reduced BSFC by optimization; final engine calibration
The effects of catalyst size Figure 12 and NH$_3$ loading and operation strategy Figure 13 are shown as sensitivity study instead of an optimization to visualize the optimization background. During the optimization the best combination will be found automatically as for the example in Figure 11.

The second example demonstrates the effect of the DOC size on the overall fuel consumption. A larger DOC size results in a higher NO$_2$/NO$_X$ ratio and therefore in higher SCR efficiency [8]. The SCR efficiency depends on the NO$_2$/NO$_X$ ratio, especially in the lower temperature range. The simulation was done with two fixed engine map sets. One operation mode is for heating, and the other for optimized fuel consumption. Depending on the DOC size, the switching temperature between heating mode and BSFC optimized operation mode can be changed in order to achieve a constant NO$_X$ tailpipe emission (in this example NO$_X$ target = 0.3 g/kWh). At higher DOC volume the BSFC optimized mode can be released earlier and therefore the overall fuel consumption is reduced. (Figure 12). With further increased DOC size the heat mode is needed for a longer duration due to increased temperature losses and higher heat capacity.

The effect of the initial NH$_3$ loading on the SCR catalyst is simulated as a third factor (Figure 13). The greater the initial NH$_3$ load the earlier the BSFC optimized engine mode can be used. Therefore, the overall fuel consumption during the NRTC cycle can be lowered with an increased NH$_3$ starting load. The start loading of a cycle is depending on the conditioning cycle, and in particular on the dosing strategy of the ECU. With higher NH$_3$ load the risk of NH$_3$ slip due to high temperature gradients over the cycle increases. Therefore, the overall dosing algorithm has to be quite complex in order to ensure high NH$_3$ loading at a low NH$_3$ slip level [3], [5], [9].

The ECU strategy could also help to reduce the fuel consumption over a lifetime through use of a catalyst aging model. The aging of a DOC reduces the NO$_2$/NO$_X$ ratio at lower temperatures. Due to that effect, a longer engine heating phase is necessary (Figure 14). Without an aging model the operation strategy has to be optimized for the worst case (aged DOC). With an aging model the heat mode can be activated for shorter times for a fresh catalyst and longer for aged ones based on the results from the simulation process. This helps to reduce fuel consumption over lifetime.

**SUMMARY/CONCLUSIONS**

In state of the art calibration processes the aftertreatment system is considered separately from the calibration of the thermodynamics. The thermodynamic engineers define the best fuel consumption in steady state engine operating points and most efficient combustion with regard of engine out emissions which might be converted by an aftertreatment-system with an assumed conversion rate. This could lead to problems because the real EATS efficiency could be much lower due to low exhaust gas temperatures at the EATS system in transient or cold start conditions.

A new approach based on the combined optimization of different parameters of the combustion system, engine
calibration, exhaust aftertreatment, as well as ECU functions shows potential to further optimize the fuel consumption while fulfilling the legislative emission demands. In addition to the optimization of fuel consumption this program further provides the possibility for optimization of the total costs of ownership, which are typically the most important value for the end customer.

The potential of this new approach has been demonstrated by several examples. It was e.g. pointed out that fuel consumption might be reduced in the legislative test cycles as well customer relevant cycles taking higher hardware costs (e.g. for the oxidation catalyst) into account. Furthermore the importance of initial ammonia loading on the SCR catalyst and thereby also the SCR control strategy (here especially the ammonia storage control) as well as the potential of an adapted calibration over catalyst ageing with regard to fuel consumption was shown.

To reduce the development time the program is able to optimize all of the mentioned parameters in a simple way with very short simulation times. For example one NRTC cycle can be calculated within one second using a standard PC.

REFERENCES


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