Multiple Tier 3 Engine Applications based on global modelling

Edvige Castagna, Manuele Biondo, John Cottrell, Harald Altenstrasser, Christian Beidl, Hans-Michael Koegeler, Nikolas Schuch

Abstract

Nowadays, the number of electronic engine applications required in ever shorter times-to-market is widely increasing and in particular for the off-highway market there is a requirement for many ratings derived from the same engine hardware, therefore improved development tools for calibration are necessary.

The paper points out to describe a methodology to investigate the whole engine performance envelope in order to define many sub-ratings with different speed and load ranges. Therefore local and global models are used in the AVL-CAMEO calibration platform. It has to be mentioned that this method is very well suited for both steady state and dynamic engine behaviour. Dynamic effects from typical off-road cycles can be optimized.

The method has been tested in a collaboration between FPT, I&M and AVL on a real engine: F4 6 cylinder Common Rail intercooled engine. Particular attention was paid to fuel consumption, NOx, HC and smoke predictions. A "zone" approach was implemented to study in more detail the emissions control speed ranges around rated power and peak torque.

The global model was demonstrated to be a powerful tool used to define multiple ratings from a single DoE plan and which permitted the subsequent optimization based on customer mission data without further testing activity. The correlation to end customer data was remarkably good

Title figure

1. Introduction

Mid-range off-highway engine specifications are, on average, not as sophisticated as their on-road equivalents, but the diversity of the customer product ranges together with the introduction of cost effective internal-EGR technology for Tier 3 emissions limits created a new set of challenges for the product and the calibration engineers. The same base engine is called to power such different machines as excavators, tractors, loaders, dozers, combines, sprayers, windrowers and graders, with a range of specific ratings and working cycles for each application.

Such diversified machines cannot all guarantee the same charge cooling performance and this has to be taken into account during the calibration activity, optimizing fuel consumption, considering European, American and Japanese interpretations of Tier3 legislation. Furthermore, internal-EGR technology, whilst being cost effective, has undesired behaviour in terms of volumetric efficiency during acceleration or load acceptance. This creates a significant amount of work to optimize steady-state and dynamic injection maps that compensate for the lower air flow. In this manner, acceptable response times can be obtained for the customer without excessive smoke or combustion noise. The last challenge is timeframe, as emissions legislation is introduced contemporarily worldwide for all engines for a given power range (1st January 2007 for Tier3), requiring all applications to be defined in parallel.

This paper describes the use of complementary steady-state (local & global modelling) and transient DoE techniques using the AVL CAMEO calibration platform. This approach enables a tailored calibration for performance and fuel consumption taking smoke levels and combustion noise into account. This is based upon data recorded from each machine under real operating conditions.

2. Tasks and Objectives

The strategy defined for the development of FPT's successful 6.7 liter 6 cylinder F4 or NEF engine for Tier 3 is to maintain cost effective technology with simple solutions and easy installation for the customer, in order to maximize the number of potential applications, all without penalizing performance or fuel consumption compared to Tier2.

It is identified that the only way to meet the goals in terms of standardization, fuel consumption, performance, smoke and noise for the many applications involved in the time available is to approach the problem using global modelling with correction for transient operation based on real machine operating cycles. The global model, handling speed and torque can take care of the range of power from 90 to 180kW for such an engine as well as the range of rated speeds from 2000 to 2200 1/min.

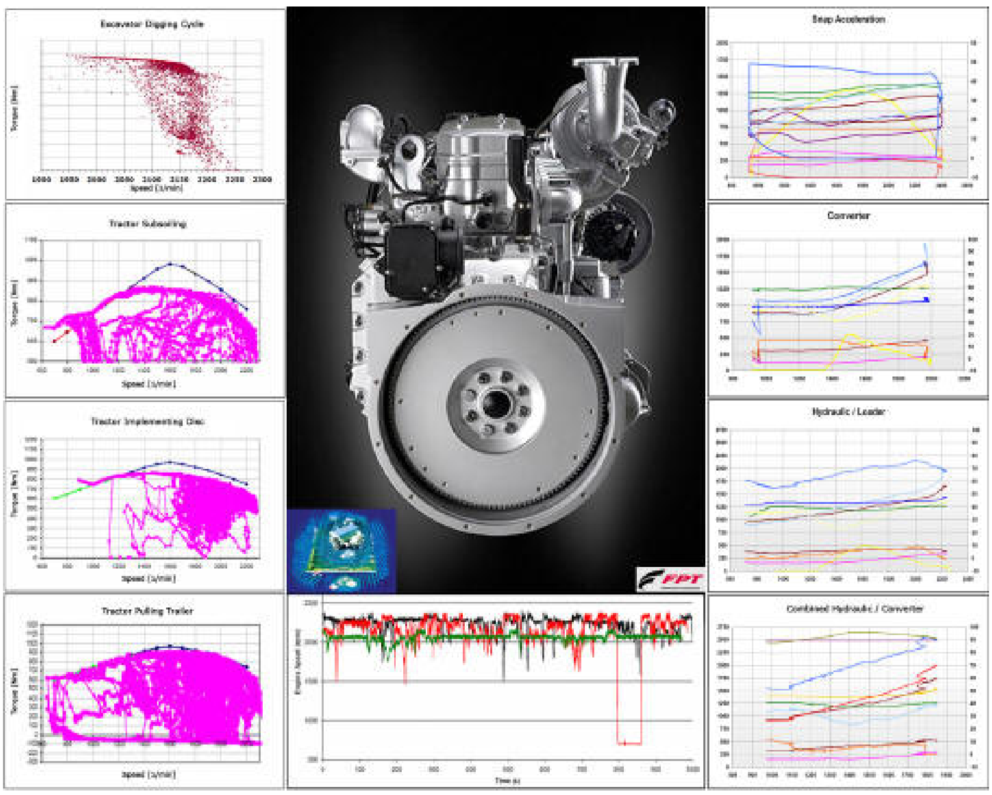

Figure 1: Tier 3 Engine application task by example of IVECOs F4 –off-road engine

The main steady-state objective is to optimize mission fuel consumption for each application using weighting factors derived from data logged during actual working cycles and taking into account intercooler performance.

Due to the behaviour of internal EGR camshafts which results in not having constant volumetric efficiency during speed and load changes, and in order to meet or improve on Tier2 response times and opacity readings, a suite of new transient test cycles, with several sub-variants in terms of applied torque and speed, is used. By simulating the real-life behaviour of the machines on the test bed, the AVL CAMEO calibration platform can be used to optimize injection parameters, not only for steady state, but also for transient performance, obtaining important improvements in response times and opacity readings. Operation of some construction equipment where load is applied very rapidly by hydraulic pumps is particularly critical but a solution is available for all cases.

3. Calibration workflow used

This big range of engine use-cases requires an effective calibration process. The workflow applied to achieve an efficient variant calibration based on global modelling is shown in figure 2. Steps with online interactions to the test bed are marked in gray and steps, which are done as office work are marked in blue.

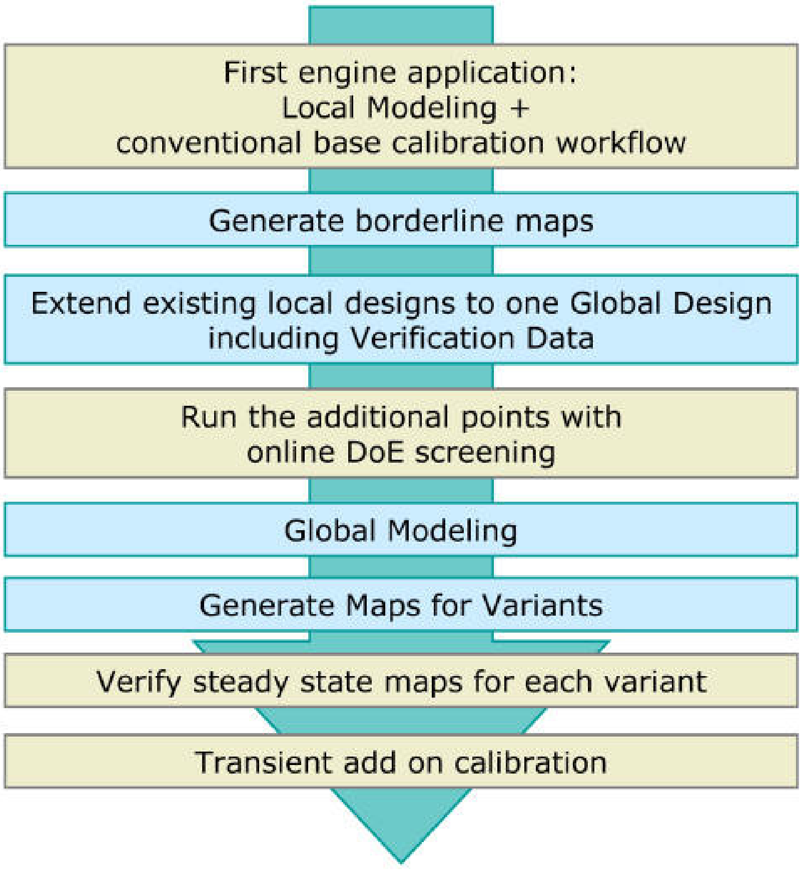

Figure 2: Workflow for developing several engine calibrations using Global Models

The first step is the application of the well-known AVL CAMEO workflow for calibrating the stationary engine behaviour for the 8 operating points required for the first, most important engine calibration variant [1], [2], [3]. In this step, the optimization and map calibration is done according to the actual engine use-case for optimum fuel consumption, and at the same time fulfilling the TIER 3 constraints.

In the next two steps the existing measurement results are used to generate the borderline maps for the varied parameters and to design the additionally needed points all over the speed load range of interest (global DoE).

Next these operating points with the corresponding parameters are measured with the “CAMEO iProcedure online DoE screening”, which ensures a measurement close inside the engine border line should the point requested by the DoE test be positioned beyond the engine´s operating border.

Now the global modelling workflow can be applied resulting in the desired global models for fuel consumption, exhaust gas emissions and noise with the big advantage of being able to also display the dependency of speed and load. The clear challenge in this step is achieving a sufficient quality of the global models [4].

Thus the engine operating points can be selected in a flexible manner and calibrations for several engine use-cases can be derived just by working in the office. The steady state calibration work is finished with the verification of the corresponding maps. Finally, the calibration of the correction functions for dynamic response is carried out [5].

An overview of the important interim results during this workflow is presented using the example of the FPT F4 engine in the following chapters.

3.1. Local Modelling for first Engine Application

The engine range considered consists of approximately 30 base ratings. The workflow for the successive phases of the project indicates that it is best to start from the top power rating, in this case 177 kW at 2100 1/min.

As described in the workflow the first step is to measure the 8 steady-state mode points according to the ISO 8178-4 C1 cycle. The measurements themselves are carried out on a test bench using the AVL PUMA automation system and the AVL CAMEO auto-calibration system driving a D-optimal on-line adaptive DoE strategy. 35 measurements for each of the 8 modes are generated. Not only injection control parameters are considered, but also the effects of intercooler dimensions. This allows the impact of customer installation constraints on the performance/emissions trade-offs to be taken into account.

The four variation parameters selected are:

- rail pressure
- start of main inection
- start of pilot injection
- aftercooler intercooler temperature

The responses identified to be optimized are:
- fuel consumption
- combustion noise
- NOx
- HC
- Soot

The first pre-requisite to be able to generate good models is to have good experimental data. Conditioning systems and control parameters for testbed stability have to be optimized to guarantee the necessary precision in temperature control particularly at partial load conditions. The stability of the engine and the repeatability of the measurement values are monitored by repeated acquisitions of daily reference points and by repetition points within each speed load site. The on-line adaptive DoE strategy is chosen due to its ability to adapt the position of points to be measured according to the engine´s operating safety limits.

The raw data analysis is done with AVL CAMEO using the following workflow:
- Comparison of variation demand and actual values to ensure that the maps and parameters in the ECU has been correctly set.
- Analysis of the repetition points regarding noise
- Check of engine conditioning stability regarding temperatures and pressures which have a significant influence on the engine behaviour.
- Basic combustion check e.g.: trade-off analysis for brake-specific fuel consumption (BSFC) versus NOx or BSFC versus smoke.

The next step is the calculation of local regression models for the selected responses. The workflow consists of the following points:
- Construction of models for each desired response channels
- Analysis of the model quality using correlation coefficients such as R^2, R^2adj and R^2pred [6]
- Analysis of the model residuals (difference between measured and modelled value)
- Analysis of the normal probability of the model residuals, which permits the identification of outliers (see figure 3a)
- Analysis of the measured results versus predicted model values

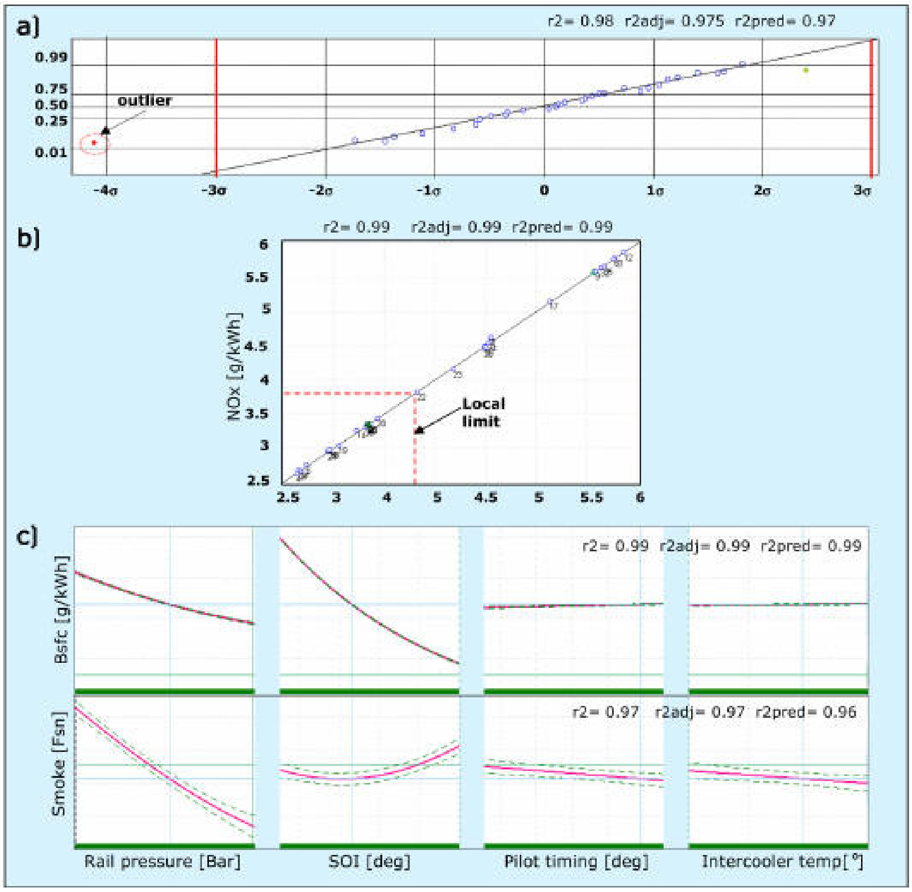

Figure 3: Local modeling and quality evaluation

For the operating points under investigation, second order polynomial regression models are calculated. The automatic significance check of the model terms is used to achieve a high quality level for all responses (r2 and r2pred > 0.96). This is due to the accurate stabilization of the engine operating conditions and the very low noise level of the measurement equipment used.

Figure 3c shows the intersection plot for the models for two main responses (BSFC, smoke) at 805Nm / 2100 1/min. The operating point corresponds to rated power and has a 25% target weight inside the Tier 3 cycle optimization. Further, one can see the 95% confidence intervals for the models.

Based on these models, the driving cycle optimization workflow step is applied. In this kind of optimization task, the optimizer acts on all 8 operating points simultaneously according to two sets of individual weighting factors for each point - one for the customer requirements of smoke and noise limitations and one for the legal emission limits according to the Tier3 regulations. In addition, maximum map gradients are used as constraints during the optimization process in order to achieve smooth ECU maps.

3.2. Expand to Global Modelling for several Engine Applications

In order to create a global model, speed and load must be included in the test design as variation parameters.

The advantages in using global models are:

- The possibility to predict each response over the whole measured engine range and also between measured operating points
- The global model can be used for different optimizations of the engine according to the intended application

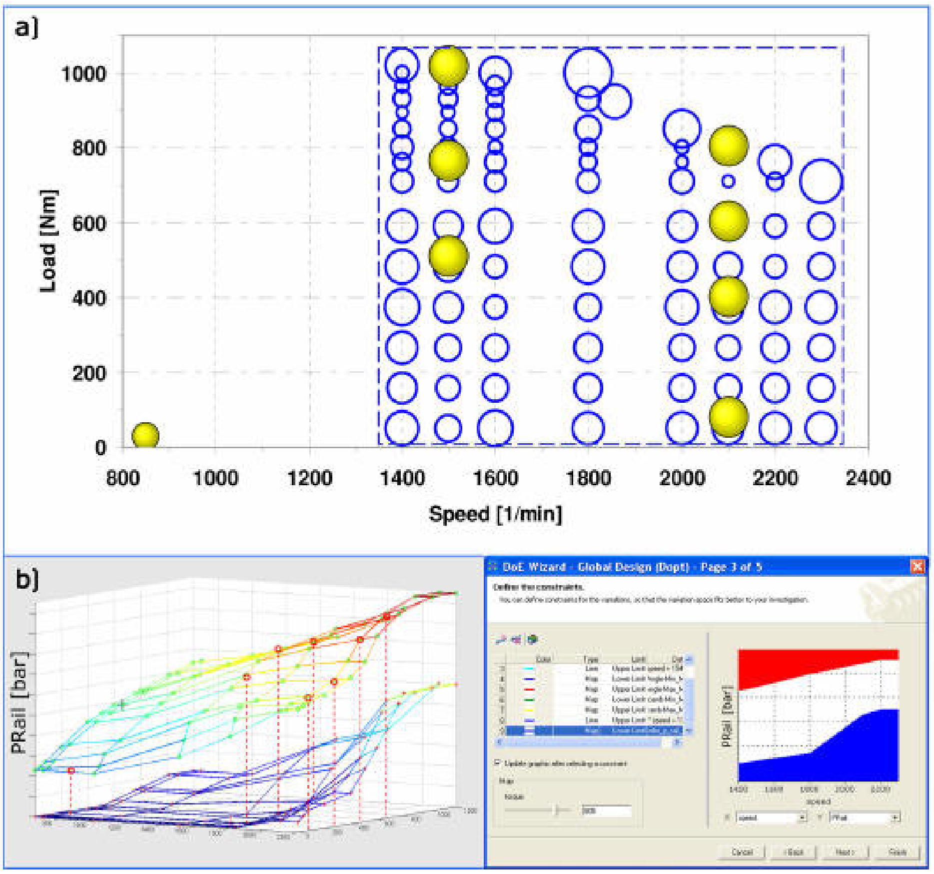

Figure 4: Expanding local measurement results to a global DoE

To expand the existing local engine models over the engine operating range of interest, an adequate number and distribution of operating point candidates have to be defined. This selection must cover the physical region under analysis regarding peak torque speed to rated power speed of all the engine applications (see Figure 4a).

The new CAMEO Global DoE test designer provides a combined design for operating point candidates and variation parameters, which typically depend on speed and load. Out of the measurements done so far, borderline maps for the combustion relevant parameters such as start of injection, rail pressure, pilot injection separation time or boost air temperature are calculated as a function of speed and load. The Global DoE test designer uses these maps as inputs to ensure that the designed points will be, with a high probability, within the driveable area of engine operation. In any case, the first parameter combination for each operating point is taken from the start value maps and thus will be a driveable starting point.

Figure 4b shows the calculation of the rail pressure borderline maps and the usage of the Global DoE test designer. This wizard in CAMEO allows the user to incorporate pre-knowledge and experience in terms of maximum model order or specific model terms. Further, the user can demand additional points, which can be used for modelling in order to gain confidence in the new approach and as verification data. In this investigation for both aspects, additional points are required resulting in a design with 1600 points. Using the "CAMEO iProcedure Online DoE screening" these points can be measured in a total of 133 hours within 7 working days on the test bed.

The workflow of raw data plausibility and modelling is principally the same as for local modelling. The main difference is the higher model order of the regression models due to the larger range of variation parameters and measured values.

Figure 5a shows the comparison between local (red) and global (green) models for BSFC [g/kWh] at rated power (805 Nm at 2100 1/min). Regression models of maximum 2nd order were applied for the local modeling approach and 5th order or an INN [4] for the global models. When analyzing these curves it is important to note the design space, which is shown as a bar on the bottom of each diagram.

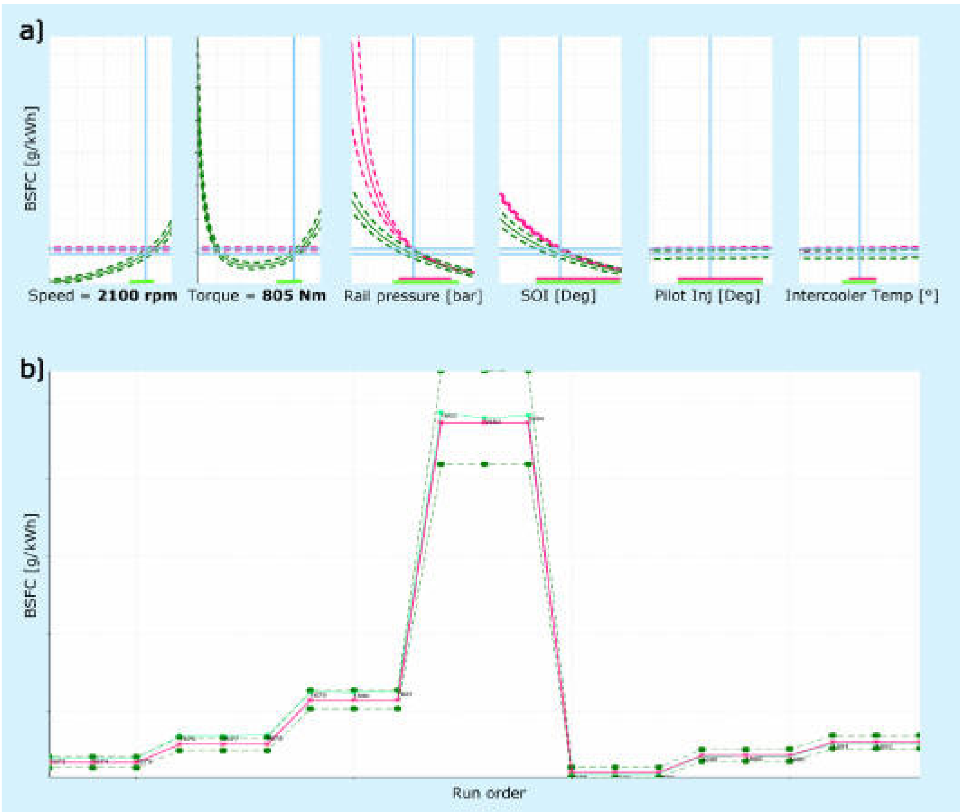

Figure 5: Comparison of local and global models

Figure 5b shows the verification of the global model using the verification points gained from the first local modelling approach. The verification data (light green) for BSFC are inside the expected prediction interval (green) of the model (red).

3.3. Comparison of local and global modelling

To run a cycle optimization an idle point is added to the global design. This solution is chosen to avoid a complex model of the whole operating area from 800 to 2300 1/min.

For the cycle optimization 7 operating points from the global model and the idle point from the local model are used. Each point has the same weight as in the optimization using local models to be able to compare the results. For the optimization a genetic algorithm is used.

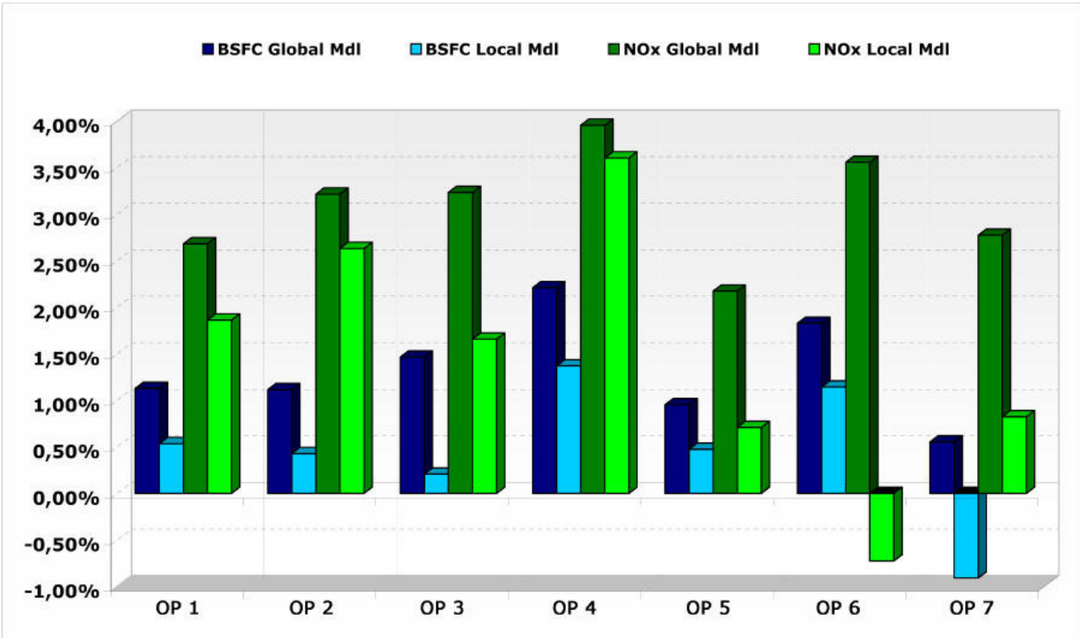

Figure 6: Comparison of BSFC and NOx using local and global model

Figure 6 shows the comparison of the local models with the global model for the operating points of the Tier3 test cycle. The difference between model values and verification measurements after optimization is displayed. As a matter of principle, the quality of the local models is better than the global ones with smaller deviations at full load. Nevertheless the model prediction is acceptable for the task of a driving cycle optimization.

In this particular customer use-case, a fuel economy improvement of 6% was achieved. The engine of this excavator application is mainly used in the area of the rated speed (1900 to 2250 1/min). Figure 7 shows the customer specific calibration adaptation for this application, improving fuel consumption in the main operating range, whilst maintaining Tier3 compliancy.

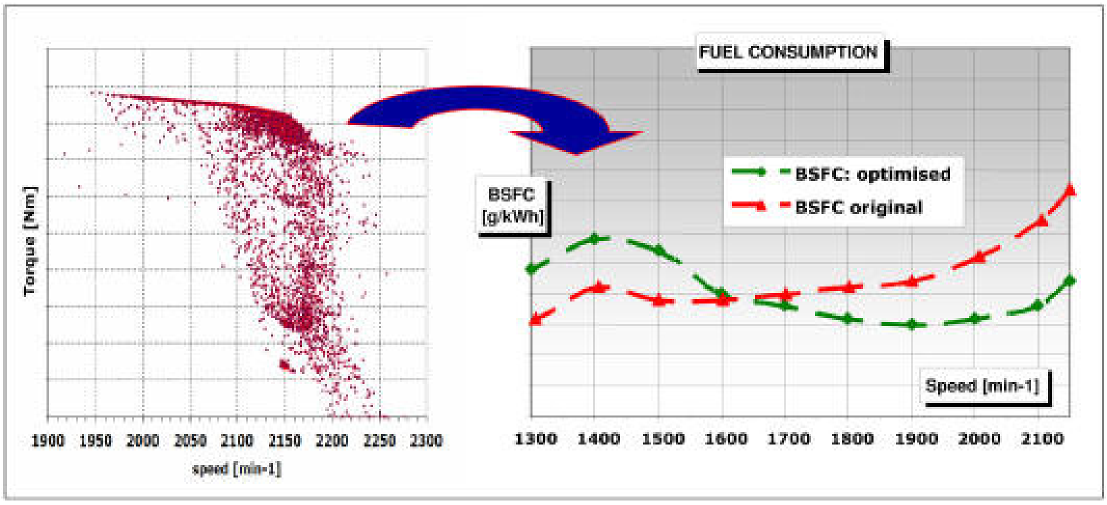

Figure 7: BSFC improvement for the important digging use case of the excavator

4. Transient add-on Calibration

In order to fulfill customer needs regarding this kind of off-road engines it is very important to have a close look on the dynamic behavior of the engine. Particularly load steps with fast torque increase at a low level of smoke are important criteria for medium duty engine customers. Finding an optimal calibration of the ECU regarding these constraints is a very hard task to do manually either in the field or on the test bed. Therefore, an automated method of running the test and evaluation is very beneficial.

To optimize this behaviour, the first step is the definition of transient test bed cycles which cover the main working conditions of an off-road engine. The next step is the implementation of these cycles into a test run, which is able to be run on a dynamic test bed. The evaluation and calculation of important parameters are performed immediately after each test cycle fully automatically.

An example of such a dynamic step together with its evaluation results is shown in figure 8. The most important evaluation parameters are acceleration time and peak opacity.

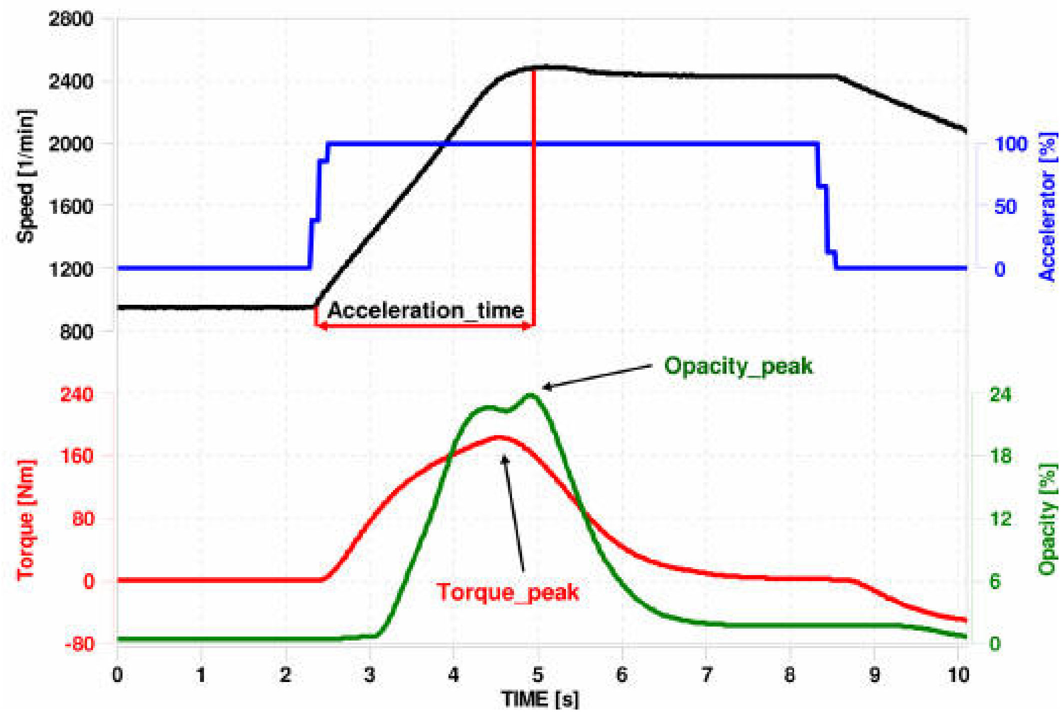

Figure 8: Snap acceleration of a backhoe use-case

This kind of automatic evaluation of the dynamic engine behaviour enables the use of a standard AVL-CAMEO calibration approach. To optimize dynamic behaviour it is not desired to change steady state maps because steady state calibration has already been completed.

Therefore, in modern ECU's a lot of correction functions for dynamic behaviour, such as the correction of the injection timing, are available. This function enables a temporary change of the SOI based on the injection mass change and the engine speed. In figure 9a this ECU function is displayed.

Finally, 5 ECU parameters are selected to calculate a CAMEO D-optimal test design. This design is measured on the test bed. Polynomial models for the transient behaviour of the engine are calculated out of the evaluated results.

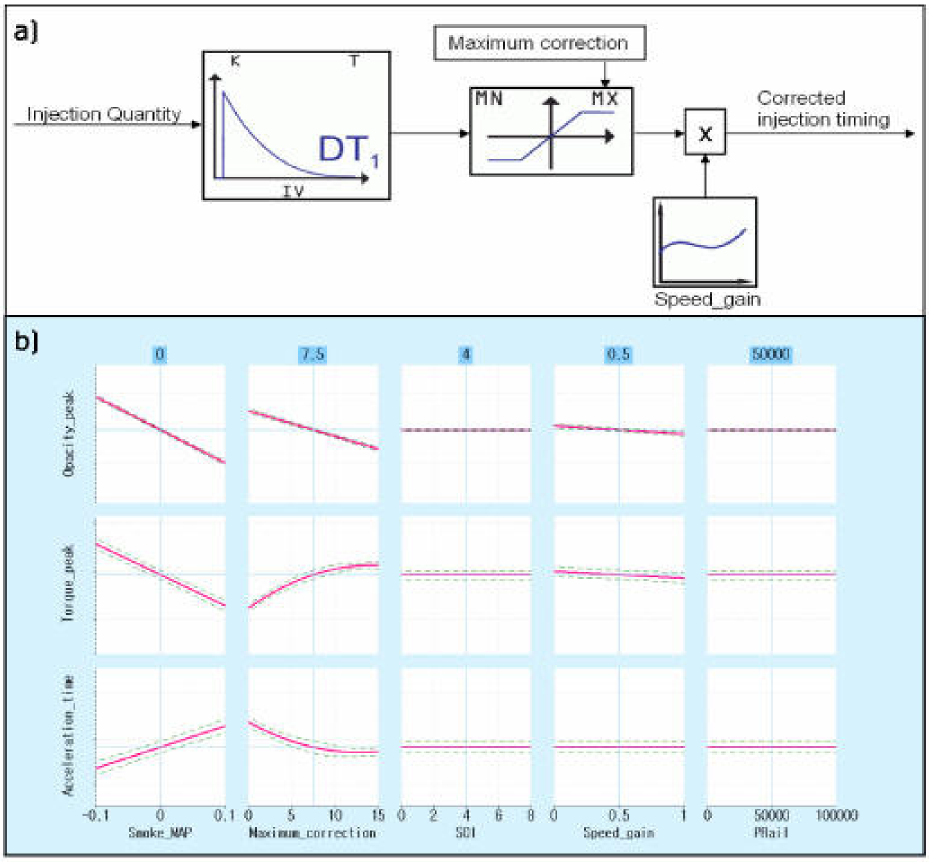

Figure 9: Correction function and model for dynamic behaviour

The intersection plot in figure 9b shows that the steady state maps have practically no influence on the transient behaviour. A change in the minimal lambda value in the smoke map can decrease the generated opacity but reduces the performance of the engine (column 1). The smoke limitation map, the rail pressure map and the SOI map are changed as an offset to the base calibration (e.g.: +/- 0.1 lambda). The speed gain curve (column 4) for the transient correction is changed only in the first part of the map while the second part is set to 1.

The correction function is not only able to decrease the acceleration time, but also helps to reduce the smoke during this kind of step. In this particular cycle an advance of the SOI is used in order to increase torque, especially at the beginning of a load step.

Together with other transient cycles, it is possible to cover the main machine working cycles. For some operating areas it is necessary to find a compromise between different optimization targets. This must be mainly based on a classification of the most important driving situations for the particular operating area.

Figure 10a shows the faster speed increase at a significant lower smoke level after optimization. Figure 10b displays an 8% reduction in time for tractor trailer pulling performance.

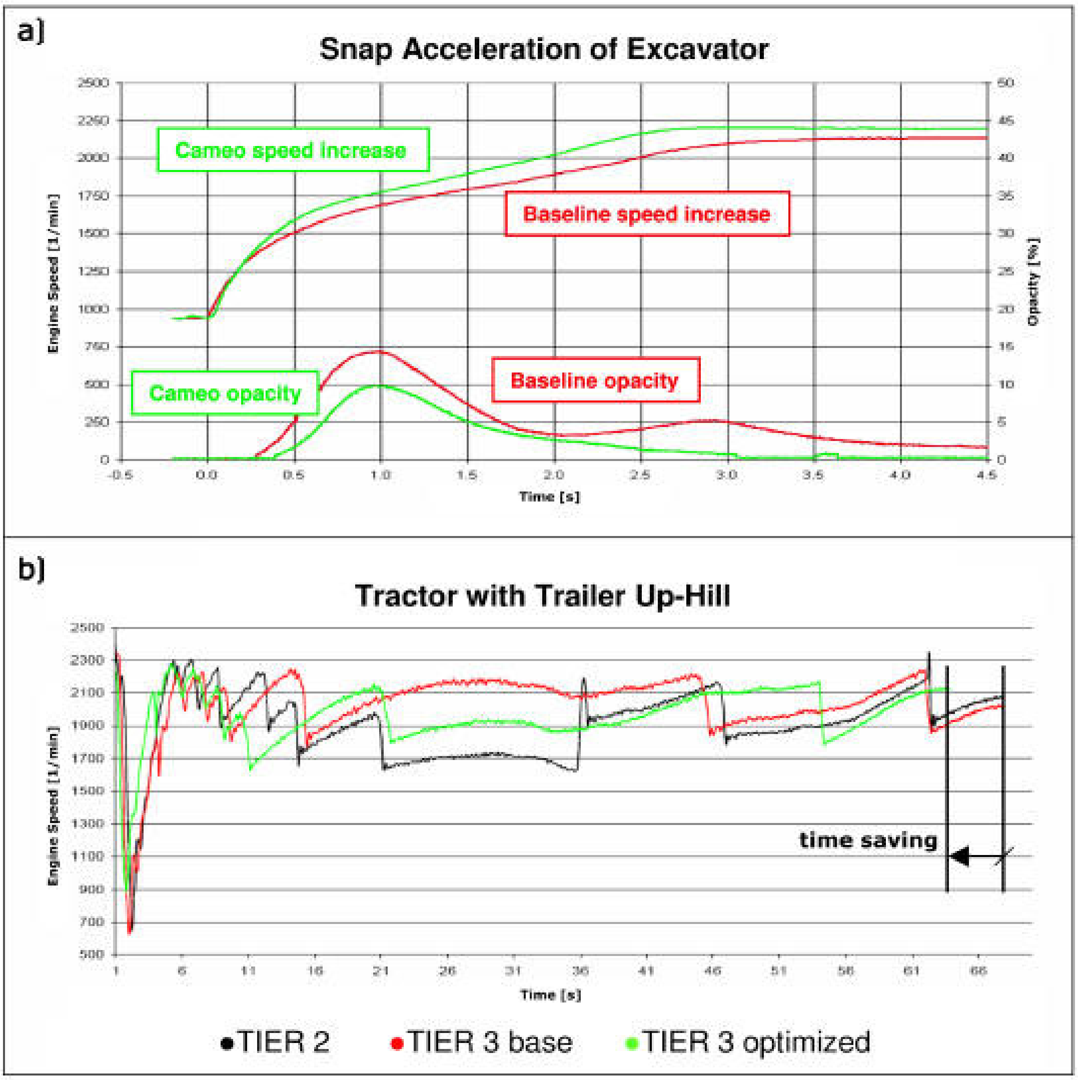

Figure 10: Improved transient performance

5. Summary

The article describes a new approach to the complex task of calibration development for Fiat Powertrain Technology's off-highway diesel engines for multiple applications using DoE techniques handled by AVL CAMEO. The approach of considering all known ratings and the whole possible engine operating range from the beginning permits the definition of an integrated test plan maximizing the test bed utilization. Care must be taken to ensure stable operating conditions as well as accurate calibration of the instruments to obtain the necessary precision in the results.

Full advantage can be gained from such a method only if the real operating conditions of the engine in the customer's application are well known. A fundamental part of this program was preliminary data logging on the machines to understand their working cycles and requirements in terms of performance, fuel consumption and smoke. These real working cycles were then transformed into dynamic test bed simulations or test cycles. CAMEO, working with the test cell automation, can then run optimization programmes 24 hours a day.

The potential of this three step DoE approach (local / global / transient) using the CAMEO platform could be exploited. Significant improvements in fuel consumption for an excavator application, smoke reduction for a backhoe loader and trailer pulling performance for a tractor were achieved. The global approach also allows for the simultaneous release of many datasets when new emissions legislation comes into force.
This technique is currently being further developed, integrating AVL DRIVE and AVL SOUND to create a fully objective calibration process.

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Authors:

Edvige Castagna
FPT Industrial&Marine (Turin) – Italy, Methods and Calibrations.
Responsible for the introduction of new engine development methodologies

Manuele Biondo
FPT Industrial&Marine (Turin) – Italy, Member of Methods and Calibrations Team

John Cottrell
FPT Industrial&Marine (Turin) – Italy,
Testing Manager Fiat Powertrain Technologies. Responsible for testing and application of the whole range of FPT Industrial and Marine engines from 40kW to 1200kW

Harald Altenstrasser
Development Engineer in the Optimisation Technologies Division of AVL List GmbH, Graz

Christian Beidl
Director Powertrain Calibration, AVL List GmbH, Graz

Hans-Michael Koegeler
Specialist Team Leader in the Optimisation Technologies Division of AVL List GmbH, Graz

Nikolas Schuch
Application Engineer in the Optimisation Technologies Division of AVL List GmbH, Graz