ABSTRACT

Modern powertrains have a growing number of variabilities. The new generation of turbo direct injection engines require a control unit parameter calibration with advanced methods and tools. The paper shows ways to cope with the increasing amount of measurement data. In order to reduce development time and find a balanced optimum, a mixed approach is proposed using full mathematical test planning and regression modeling in areas, where the system behavior function is known, but the parameterization of the system function is done. In other areas a practical analysis method uses the system behavior out of experimental data and avoids full simulation approaches. Additionally the methodology integrates the developing engineer’s experience especially in areas of non linear complex system behavior.

INTRODUCTION

Brazilian automotive industry has seen an impressively strong increase of the demand of new vehicles in commercial and in the passenger car segment. New legislation requirements came along as anti break systems or airbags as well as fuel consumption fleet regulation and emission as well as OBD legislation constraints. Along with this the Brazilian customer demands are increasing towards higher amount of performance, comfort and drive ability as well as safety level. Powertrain technical approaches have to include new advanced features in order to give the appropriate answers. The share of automatic transmission will rise in the future. The new turbo direct injection technology is introduced and in general the powertrains show a higher degree of variabilities. Driving factor for the trend towards more variabilities is the need for fuel consumption and CO2 reduction to reduce the greenhouse emissions.

The vehicle mass and installed propulsion power has been increasing in the last years and will do so in the future. Therefore the engine operation moved to a lower load point distribution on an average. In order to reach the tighter fuel consumption targets powertrain engineers rated the part load efficiency as decisive. The technologies developed to production tried to reduce losses of the engine driven in part load. Consequently the solutions in the spark ignition engine area were lean burn or high residual gas or early intake closing to avoid pumping losses and enhance the lower load combustion efficiency.

The latest development trend in combustion engine design is still driven by the part load efficiency requirements. But modern transmissions and more accurate NVH vehicle layout allow lower engine speeds and can to a certain extent rise the statistical engine load up again. The downsizing of the engine moving to a lower number of cylinders and reduced displacement is the current overall trend not only in gasoline but also to a lesser extent in Diesel engine design. The downsizing approach is also moving up the operation points to higher loads. The way to realize this is an enhanced full load performance by a new turbo engine technology with relatively high compression ratios feasible due to new direct injection techniques which avoids knocking. Low end torque performance is increased by several means. One very effective measure is the scavenging of the combustion chamber with air. A variable camshaft on intake and exhaust is required to realize large overlapping control and opening periods of intake and exhaust valves.

Due to the fact that the powertrain layout is now done in a way that the engine is operated closer to its optimum efficiency area, the actual development activities try to include the optimum engine efficiency load and speed area for improvement strategies. In the optimum load and speed range the losses of the engine are minimal and the combustion phasing and combustion speed also close to the desired optimum thermodynamic process with heat release in top dead centre. The major influencing factor is therefore the compression ratio allowing an efficiency increase following the equation:

\[ \text{eta} = \frac{1}{1 - \varepsilon^{k-1}} \]
The variable compression ratio is a technology to work on the main influencing parameter. Fig 1 shows a solution with a variable conrod that is controlled via oil pressure. The conrod is extended or compressed and allows a switching between a lower and a higher compression ratio value. A fuel consumption reduction of approx. 5% was demonstrated in the emission cycle.

- CO2 reduction potential
  - NEDC approx. 5-6%
  - WLTP approx. 4-5%
- Low sensitivity of CO2 against choice of C.R. high/low combination
- System optimization in different projects
- Cost efficient VCR solution (approx. 20€/%CO2)
- Demonstrator vehicle available at FEV
- Can be combined with Gasoline Controlled Auto Ignition (GCAI)

Figure 1: variable compression ratio as example of increased variability

As in everyday life nothing is for free and all these technological approaches lead to a higher complexity of the powertrain. The resulting effect is not only an increase in cost but also a higher pressure to keep the timeline in the development process. The development periods for new engines or engine updates with these technologies are not only more difficult to keep, they are even facing time schedule reductions in the more dynamic modern market situation.

The challenge for the control unit development and the parameter finding in the engine control maps is high. Every new variability in the engine control leads to an exponential increase in required measurement and ECU calibration data: A classical port fuel injection naturally aspirated engine with fixed camshaft timing required a base mapping operation point number of e.g. 12 x 10 = 120 points, assuming 12 speed breakpoints and 10 load break points. Assuming you vary your only free parameter the ignition advance in 5 steps you result in 600 measurement points, easily to be done in an engine test bench trial of maybe some days.

In case of not only ignition advance as adjustable parameter the effort increases: E.g. an engine with turbo DI and variable camshafts has as additional adjustable parameters:

- Injection number (often up to 3)
- Injection timing of every single one of these injections
- Waste gate actuation (e.g. for drive ability purposes)
- Intake cam timing
- Exhaust cam timing
- Intake system variability

In a full factorial measurement plan with 5 levels this results in \(120 \times 5^7 = 9 \text{ millions and 375.000 points!} \)
The Brazilian flex fuel capability (assuming also 5 levels, i.e. 5 ethanol quantities) will give it one degree more and result in 46 millions and 875,000 points.

The same applies to the variabilities in vehicle calibration. In order to cope with the new challenges a ECU calibration development work is not feasible without intelligent and more efficient methods.

MAIN SECTION

On engine test bench automatic mapping of the engine requires more sophisticated control and survey methods. Different systems are on the market and serve as overall test cell manager. They are in communication with combustion surveillance, emission analyzers and test bench operating system as well as engine control unit and will automatically scan the complete map, but will not reduce the number of measurement points. Design of Experiments, a test planning methods based on regression modeling and involving statistical analysis is another way to reduce the measurement load. As always the modeling here depends very much on the experience of the calibrating group and incorrect planning can lead to wrong or deficient regression modeling. The best practical approach is a combination of both, see fig. 2: In a multiple model approach run automatically on test bench the error can be minimized. The idea is to do regression modeling only in a sub space of Rn. Influencing factors are divided in groups of more linear ones or those with only one extreme point and other ones showing higher polynomial or even unknown behavior. The DoE planning is thus restricted to the areas that are more easily to be described by polynomial approaches.

To give an example: A gasoline engine mapping is therefore limited to only small speed areas, but extended over a larger load range. The reason for that is that a gasoline engine air charge or torque as a function of intake pressure has a similar behavior upon load. Upon speed different intake and exhaust wave dynamics will lead to non linear behavior upon speed and increase the error in the regression model.

![Figure 2. multiple models in Design of Experiments](image)

The described methodology can also be used effectively in emission optimization. The high number of injections with a direct injection engine is especially usefull after cold start and during catalyst heating. The catalyst heating period is characterized by an operation aiming at supplying maximum exhaust enthalpy with low Hydrocarbon emission. Fig 3 shows a variation, where as well the engine speed is kept constant and injection number and injection timing is varied to find optimum parameters. In a prestudy it was found that the camshaft timing had no or little interaction terms with the injection pattern in this area and thus allowed to separate the optimization process.
Figure 3: Regression analysis in catalyst heating operation point

The emission as well as drive ability quality depends on the combustion properties. For a gasoline engine the mixture should be kept in an optimum range as lean as possible but avoiding misfire and minimizing NOx. The experienced calibrator will include his knowledge and try to calibrate a mixture air to fuel ratio close to one on the rich side and increasing this enrichment towards very low lambda values for extremely cold temperature. The control units model and measure different temperatures characteristic for the intake system and combustion chamber wall film and ignition delay effects, normally coolant temperature in the engine block. In the intention to combine advanced tools with easy handling, FEV developed a number of tools in a software platform called TopExpert. Fig. 4 gives as an example the warm up calibration aid by TopExpert: Based on the measured values for lambda the TopExpert will analyze a deviation pattern, e.g. an error to a desired lambda as function of engine run time and coolant temperature. The model can offline in desktop environment predict an improved lambda control assuming a different calibration upon input parameters. The calibrator can then search for the maps and calibrate in the desired way. A graphical use interface allows the engineer to do the optimization easily.
Figure 4: Predicted lambda in desk top analysis to improve control unit calibration

To avoid an excessive number of expensive emission tests on chassis dyno TopExpert has a vehicle tracer tool, see figure 5. The tool can be used as add on to any vehicle calibration interface or even using direct vehicle speed signal inputs. The tool was developed in collaboration with calibration engineers. It allows to use the calibrator's laptop as driver's guidance to run standard or any other programmable speed profiles. It supplies the calibrator with tolerance bands, drive error statistics and provides statistical analysis as e.g. dwell times in configurable map areas, etc. Together with experience based pre calibration it allows to do a good part of the job on simple chassis dynos or on test track.
On Board Diagnostics (OBD) legislation requirements are also being tightened in Brazil with the new PROCONVE6 regulation. The requirements are now broader compared to the beginning of OBD legislation. Only to give examples of global trends: US legislation included comprehensive components failure diagnostics. A comprehensive component does not belong to the aftertreatment system in any way, but a malfunction could interfere with emissions and therefore has to be monitored. US and European legislation oblige the manufacturer to monitor the activity of the monitoring function. A statistical minimum of successful OBD diagnostic function runs per trip has to be carried out and documented to the authority, the rate based monitoring.

Still the main intention is the diagnostic of the catalyst or catalyst system itself. The diagnostic procedure based on oxygen storage capacity degradation has long experience and sufficient correlation to be used even for lowest emission levels. The oxygen storage capacity is monitored with two lambda sensors, one upstream catalyst and the other on downstream. The monitoring uses single rich lean jumps or oscillations rich lean forced by the CEU control. The downstream lambda sensor will react delayed or in a damped characteristic. The delay or damping effect correlates to the oxygen storage and therefore the ageing of the catalyst. Aged or poisoned lambda sensors can also show a delayed signal. Therefore Brazilian legislation requires a diagnostic of the lambda sensor upstream catalyst. FEV supplies a Diagnostic Failure System electronic device (DFS) that is to be connected within the lambda probe wiring loop and that can fully disturb the lambda sensor signal in order to simulate the failure. Different malfunction patterns as delay or slow signal or offset voltage can be induced, see fig. 6. The parameter setting is easily done via a graphical user interface. The DFS device can be used for all types of current lambda sensors as binary types or wide range sensors.
Another TopExpert based software tool with specific hardware is the high resolution ECU I/O signal recording system that is used for start and stop signal analysis and calibration as well as all other crank angle based signal evaluation as injection timing for direct injection engines. The device allows a time and crank based analysis of all signals, see figure 7. The crank angle and camshaft phase signals are used as base for the calculation and can also be made visible on the analysis sheet. The tool has a graphical user interface for engine parameter information input as e.g. valve timing input for intake and exhaust opening and closing or duration. The tool is very useful to be used in areas where the typical calibration interfaces do not give direct insight to signal accuracy. Examples for applications are injection and ignition pattern analysis during cold start. Also the synchronization process can be evaluated in high resolution. The device will calculate an engine speed on crank angle based resolution and thus allow the analysis of every single combustion – without pressure indication system. The highly dynamic start process can also be calibrated very efficiently as well as injection split.
The next step to automated ECU parameter calibration is the use of Hardware-in-the-Loop (HiL) benches, see figure 8. The ECU can be connected with the wiring harness. A computer is basically simulating the engine and vehicle reactions to the ECU output signals and generates input signals corresponding to the engine sensor readings. In principle the complexity of the models used in the HiL computer is not limited. The current mainstream calibration depth is signal input and output check, OBD signal checks as well as plausibility monitor calibration. Also synchronization and state machine routine calibration is effectively done as well as any CAN or control interface calibration.

FEV could successfully use advanced models for Knock detection and knock control per calibration inducing measured knock sensor patterns from the engine. Another area that was successfully calibrated is mode transitions for advanced combustion cycle consistent valve controls, only to mention some examples.
CONCLUSION

The new engine generations of turbocharged direct injection gasoline engines as also modern Diesel engines have seen an exponential increase of base map parameters. This is due to the fact that new variability increased the parameter
amount. The testing and programming of the ECU parameters and maps did not only increase for base testing, but also for emission optimization and drive ability development. New methods and tools have to be used in order to keep the time schedule. The ideal approach is a balanced methodology with simulation in engine map areas with more linear characteristics and well known system reaction combined with the calibrator's expertise and understanding. FEV's TopExpert toolbox supplies a number of desktop calibration tools which use the base vehicle test data instead of complex system simulation and simulate only small deviations to the setpoint and therefore try to stay in a linear range.

Hardware based tools help the calibrator in the vehicle. With high resolution measurement the dynamics in engine start and stop can be analyzed. The vehicle speed tracer can serve as driver's guidance. The Diagnostic Failure Simulation can avoid to replace the lambda sensor by an aged one and allows a number of different malfunction patterns.

One further step of advanced calibration tool is the Hardware-in-the-Loop test bench. OBDI and II as well as synchronization routines and state machines are already calibrated here. Future calibration will try to transfer more and more calibration work from the final vehicle.

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