SPECTRUM

Technology Highlights and R&D Activities at FEV

Issue 21, September 2002

FEV/GIF-Powertrain
Engine and Transmission Competence for the Development of Future Powertrains

Future powertrains will increasingly be dominated by automatic and automated transmission systems, as well as hybrid systems, all requiring substantial development effort. As a consequence, new challenges are arising within the development of the engine-transmission-vehicle system.

SUMMARY

Continually increasing customer demands and legislative requirements regarding fuel economy, emissions, performance, driveability and comfort need to be met. Automated powertrains including automatic transmissions, CVTs, or automated manual transmissions with/without tractive force interruption require a more and more extending interaction between the engine and transmission, and, hence, a systems approach for the powertrain concept and the vehicle application effort. Particularly for future vehicle concepts, electrical management, starter-generators, and other hybrid concepts need to be considered. The necessities of the vehicle's dynamic stability and safety controls should also be included.

The strategic partnership between FEV Motorentechnik GmbH and GIF Gesellschaft für Industrieforschung mbH offers a new combined engine and transmission development service to the automotive industry and its suppliers. The two companies are cooperating in the development of automated powertrains, in order to offer a competent development service for the complete powertrain in a vehicle, combining the

PREFACE

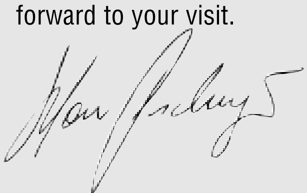
Dear Readers,

Drivetrain performance demands with respect to fuel consumption, dynamics and comfort continue to increase. As a consequence, not only the engine but also the transmission must be continually developed. In addition to classical manual and automatic transmissions, CVT's and, above all, automized manual transmissions, which will be increasingly accepted with future integration of double clutch transmissions without torque interruption (Figure), are gaining increasing prominence.

In addition to the development of the transmission, sensor technology and actuator technology, this brings a special meaning to the tuning of the shift event and the shifting strategy. Electronic engine and transmission controls, as common components of the vehicle drivetrain management, communicate over a CAN bus and must be tightly integrated using appropriate software and application/integration effort. Therefore, the software necessarily contains the driving and adaptation strategies, the diagnostics as well as the safety functions.

The development cooperation FEV/GIF-Powertrain bundles the resources of both companies and allows the combined resource to offer a single point-source for drivetrain development consulting resources from concept through the prototype stage and including driveabilty calibration. The offered services will also include NVH and emissions development as well as proof of durability.

Come visit with us and you'll be surprised by our capabilities. We are looking forward to your visit.



Prof. Dr.-Ing.
Stefan Pischinger
Executive Vice President

Fortsetzung Titelseite

significant expertise and knowledge in engine and transmission development, as well as powertrain integration.

In all cases, development engineers can rely on a high number of proven analytical tools, test equipment, test facilities and test tracks for engines, transmissions and vehicles. The potential synergies of bringing the expertise, CAE and test equipment together motivated the cooperation of FEV and GIF as a combined system development source for automated powertrains with:

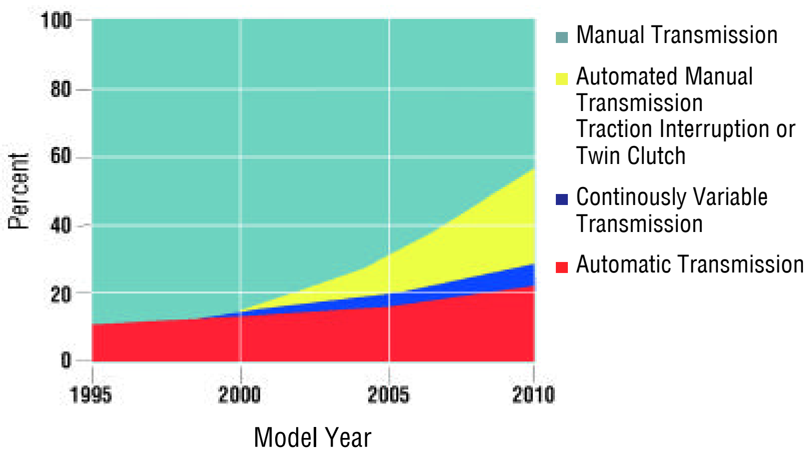
- Availability of development resources (qualified personnel, development and test facilities),
- Complete project support for powertrain development,
- Powertrain integration and vehicle application.

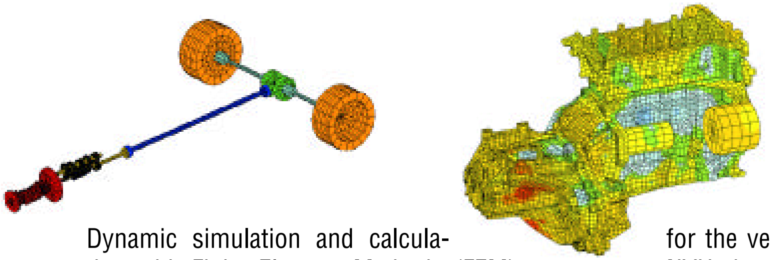
The cooperation enables the complete process of powertrain development for vehicle application. The development of powertrain concepts and their control strategies are supported using cycle simulations, with the goal of achieving the continuously increasing targets for emissions, fuel economy and customer demands.

Powertrain Development Engineering

- Concept/Simulation/Calculation
- Benchmark and Assessment
- Functions Testing
- Long Term Durability Testing
- NVH Powertrain and Vehicle
- Calibration Powertrain Control
- Software Development
- Hybrid Powertrain

Share of Advanced Transmissions in Vehicle Model Year, West Europe





CAE in Powertrain Simulation

Dynamic simulation and calculation with Finite Element Methods (FEM) and multi-body systems (MBS) offers the prediction of system interactions for all components of the powertrain system, their vibrational behavior and durability evaluations. Measurements, analysis and evaluations of powertrains and their components are conducted using extensive experience from competitive benchmarking.

Methods of Powertrain Analysis

- Powertrain Torque Measurement
- Continous In-Vehicle Measurement
- Engine Analysis and Powertrain Component Testing
- Complete Drive-Train or Vehicle Testing
- Determination of Powertrain Friction Losses
- Driveability Evaluation, Shift Quality
- Virtual Calibration (HIL)
- Official Test and Real World Driving Cycles
- Endurance on Public Roads/Flights Recording

To support the powertrain and vehicle development work, a broad range of test facilities, evaluation methods and specialized equipment is available at FEV and GIF for functional investigations, efficiency measurements, and durability testing.

A particularly important role is the NVH engineering, and the application/calibration of the functional controls within a powertrain development program. The simulation of the drivetrain dynamics, the engine mount tuning and vehicle interior noise simulation build a foundation for a state-of-the-art systems approach to component development including structural analysis, vehicle NVH and driving comfort. NVH powertrain test cells are used for powertrain measurement and verification and their components; for the vehicle this effort is conducted either in an NVH chassis dyno or with free-field measurements.

Testing Facilities Powertrain and Vehicle

- NVH Test Benches
  - Engine, Transmission
  - Powertrain (FWD, RWD)
- Anechoic Chassis Dynanometer
  - Pass-by Measurement
- Transient Powertrain Test Benches
  - Emission Calibration
- Emission Chassis Dynamometer and Climate Test Chambers
- Test Cells (Function, Efficiency, Durability)
  - Transmission
  - Powertrain (FWD, RWD, AWD)
- Test Track
- Fleet Testing
- Packaging- and Prototype Workshop

Integration of the powertrain into the vehicle is one particular focus of the services provided. All of the required application work for steady-state and transient operation of the vehicle are conducted in consideration of the individual components/systems and mechatronics development.

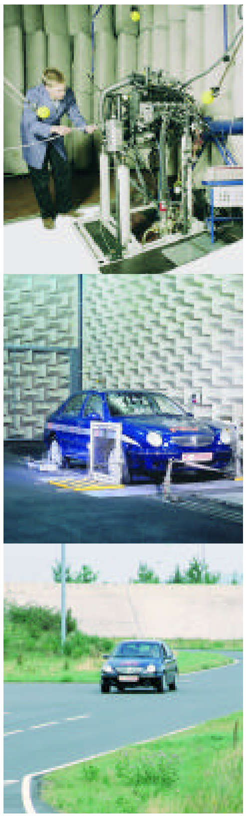
The key elements of the vehicle integration and application are the development and availability of the drivetrain management and the necessary software development.

Today, in a typical powertrain calibration, individual functional elements such as engine, transmission and vehicle dynamics controls (which, in some cases, are using the same sensors and actuators) need to communicate via data networks. This becomes increasingly difficult with the growing complexity and networking of the individual components. Therefore, systems evaluation of the complete powertrain with individual subsystems including engine controls, transmission controls and vehicle controls is becoming more important as a means of complying with the increasing complexity of functional features, the integration of control tasks, the optimum performance characteristics, and the comfort demands of the customer.

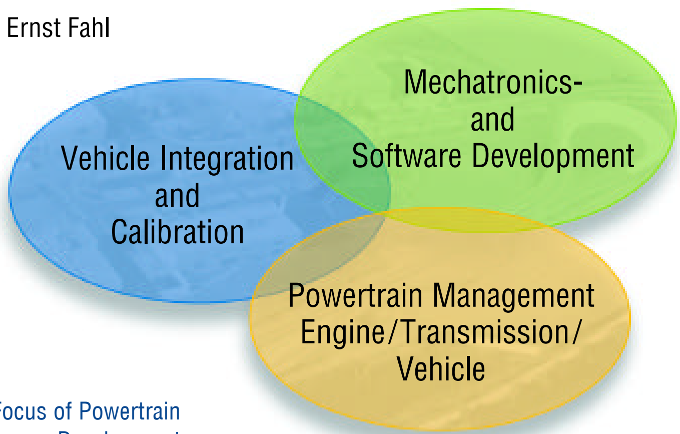
The optimum operation of the engine/transmission-system with driver dependant behavior for drive comfort, performance, overall efficiency and emissions present extremely high demands on the engine controls and the transmission, as well as the optimization of shift events, clutch actuation and driveaway behavior.

The FEV/GIF Powertrain cooperation offers complete development services supported by the experience of many successfully completed development and production projects.

Dr.-Ing. Ernst Fahl



NVH Testfacilities



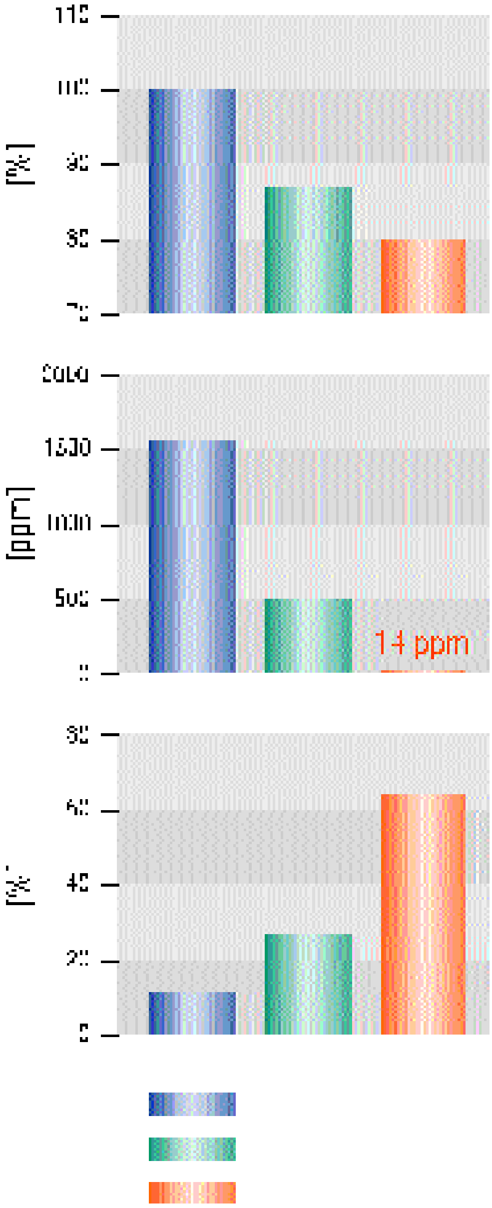
Focus of Powertrain Development

Controlled Auto Ignition

Before Nicolaus August Otto made his pioneering invention 125 years ago, many of his efforts failed due to uncontrolled self ignition. Since then, one of the primary postulates in developing SI engines has been to avoid any form of self-ignition. Nevertheless, as a result of recent developments, the auto-ignition of fuel-air mixture is now being pursued as one of the most promising future concepts and much effort is being undertaken to gain control of this form of ignition.

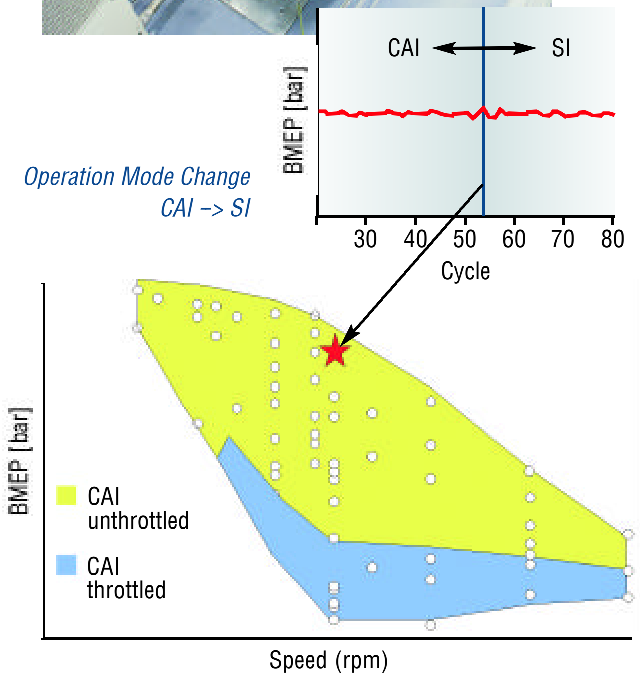
Self-ignition is not the primary target of the development effort; the goal is the possibility of reliably inflaming even extremely diluted cylinder charges and to burn them quickly and efficiently. This effect is made possible when combustion starts simultaneously at many different locations in a thermally pre-activated mixture. The result is unthrottled engine operation, lower process temperatures and extremely low raw emissions. The NO_X adsorber technology that is necessary for exhaust gas aftertreatment of lean stratified engine concepts is no longer necessary.

Ideally, the necessary conditions for Controlled Auto Ignition (CAI) are created with exhaust gas recirculation. Hot recirculated exhaust gas increases the charge temperature, causing cylinder temperatures to reach auto ignition temperature at the end of compression. In this process inhomogeneities between the fresh charge and residual gas are desired because the temperatures resulting in EGR-rich zones of the combustion chamber are higher than those attained in a completely homogeneous cylinder charge. The air-fuel mixture will ignite at the boundaries of these EGR-rich zones.



Fuel Consumption and Emissions, 2000 rpm Part Load

Emission Chassis Dynamometer



Operation Mode Change CAI –> SI

For this reason, the particular form of exhaust gas recirculation has a key influence on the CAI process.

FEV's extensive background with different forms of variable valve actuation was a key element in the successful implementation of this new combustion process. The real challenge, however, is the ability to control the process during transient engine operation, where changes between Controlled Auto Ignition and conventional SI operation must be realized without noticeably negative effects on the engine load. Based on current results, a valve train featuring cycle synchronous control of each valve timing event is very helpful in this regard.

FEV has gained widespread experience in the implementation of this combustion process within the execution of numerous internal R&D programs as well as via commercial projects. The initial results from a test vehicle that has been equipped with fully variable valve actuation are very promising and document the impressive potential of this alternative combustion process of achieving a highly effective, environmentally friendly and affordable future gasoline engine.

Dr.-Ing. Peter Wolters
Dr.-Ing. Wolfgang Salber

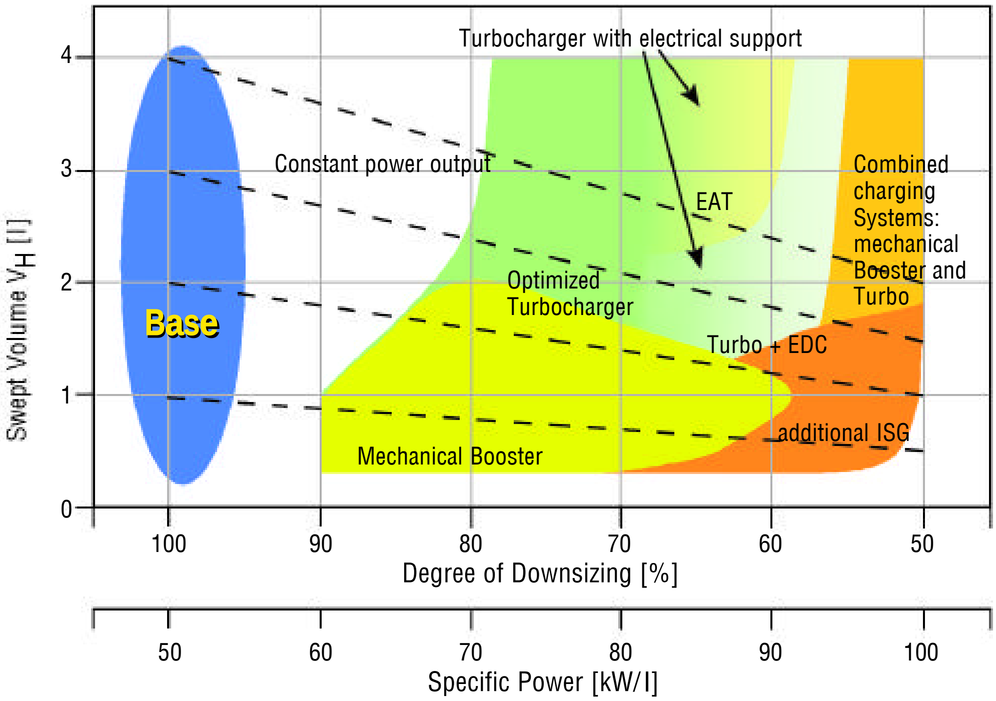
Boosting Systems for Downsizing Engines

Currently, turbocharged DI Diesel engines are recognized as the state-of-the-art. However, in the future, gasoline engines will increasingly use this measure to achieve further fuel consumption reductions via "downsizing", especially in combination with direct fuel injection (see previous Spectrum 19). The primary boosting technologies that are available on today's market are turbochargers and mechanically driven superchargers.

As specific power outputs of both Diesel and gasoline engines rise, the low end torque behavior of such engines is becoming increasingly critical. This is primarily a result of the various characteristics of turbochargers and the engine itself. The low-end torque response of direct injected gasoline and Diesel engines is mainly influenced by the heat losses in the exhaust manifold, whereas, for homogeneous gasoline engines, the low turbocharger speed is more significant.

In the future, VNT's will play a larger role in the development of dynamic behavior and extended mass flow range for gasoline engines, as well. Discussions about the use of an electrical or mechanical booster in addition to the turbocharger are becoming more relevant. Electrical systems, such as the electrically assisted turbocharger or electrically driven flow compressors use a battery for peak power demands. This development is concentrated on devices with electric power < 2 kW at 12 V. The challenges presented by the vehicle electric network requirements, the battery and control unit as well as durability issues at full load all show drawbacks for these systems. Additionally, the practical speed limit of the electric motors determine the minimum volume of these units.

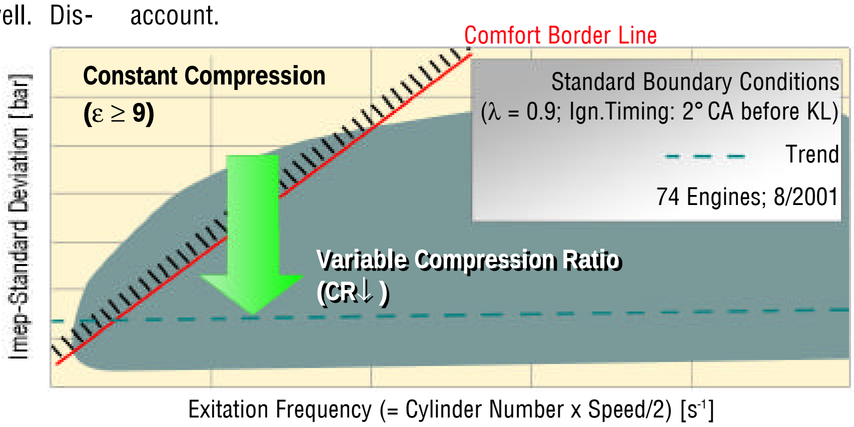
The addition of a mechanical supercharger (e.g. Roots blower) that is directly driven by the engine represents a potential alternative. The flow characteristics of these units are closer to the engine's behavior and allow the realization of high boost pressures even at low engine speeds. In combination with a clutch, the supercharger can be activated only in the low engine speed range. Using high gear ratios leads to the use of compact superchargers. The small speed range makes it possible to match the charger to the engine within the best possible charger efficiency range.



The magnitude of the effort for such a system can be restricted by adopting an optimized supercharger/ clutch design.

NVH-Improvement by Variable Compression Ratio VCR

Such systems will support the acceptance of turbocharged engines. However, for gasoline engines, the knocking behavior, which is influenced by the higher boost pressure levels, must also be taken into account.



Here, the use of variable compression ratio (VCR) leads to the possibility of combining optimized torque characteristics with the best possible part load fuel consumption.

Downsizing Strategy (Basis: NA Engine 50-55kW/l)

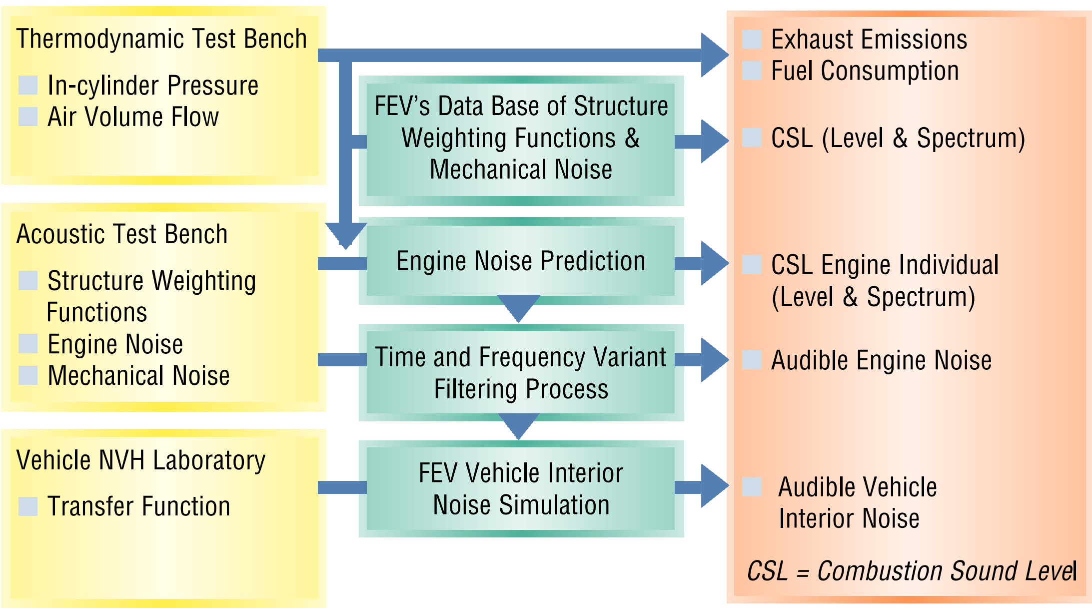
Dr.-Ing. Knut Habermann
Dipl.-Ing. Oliver Lang

Economic, clean and silent! Engine noise prediction as an integral part of combustion system development

Combustion system development at FEV includes simultaneous optimization regarding a combination of the thermodynamic and combustion noise targets. Therefore, engine noise prediction tools, based on in-cylinder pressure data, are applied as soon as experimental development becomes available from the thermodynamic test cell. Noise prediction may include:

- Engine noise level & spectrum
- Audible engine noise
- Audible vehicle interior noise

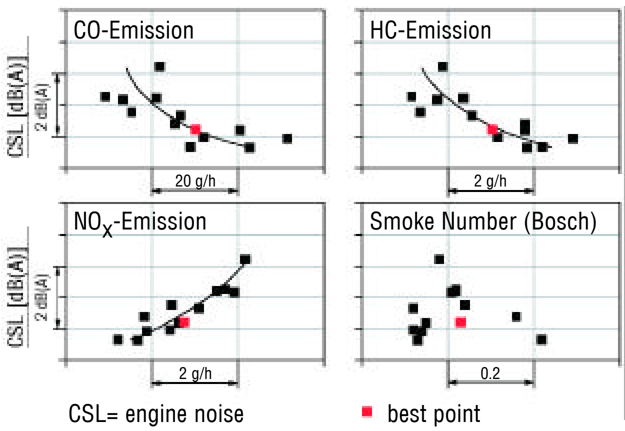
The noise prediction methods are based on engine noise estimation (Combustion Sound Level - CSL) derived from thermodynamic data from the cylinder pressure indication system. The CSL includes mechanical noise (including accessory noise) and load-dependent combustion noise (CN). The CN incorporates direct and indirect combustion noise and flow noise. They are obtained by the combination of thermodynamic parameters and appropriate structural weighting functions related to noise transmission.



FEV's in-cylinder pressure based noise prediction tools

A third-octave selective addition of CN and mechanical noise is used to estimate the engine noise (CSL) with regard to noise level and spectral content. This procedure enables comprehensive combustion system development on a thermodynamic test bench with respect to fuel consumption, exhaust emissions and engine noise (CSL). The figure shows an example of the "best point" achieved for idle at cold start condition (<< 20°C) for a direct-injected Diesel engine.

Simultaneous Process Optimization of Acoustics and Combustion System (Idle<< 20°C)



To provide a prognosis of the "audible" engine noise, acoustic measurements are required at an early stage in the combustion system development process. NVH test bench data at a "rough" calibration stage is sufficient for this purpose. Based on the spectral comparison of measured "base noise" and predicted engine noise, a time and frequency variant filtering of the "base noise'" is performed. This allows the subjective evaluation of various development stages using sound comparisons.

If the vehicle air-borne transfer function is available, the impact of calibration modifications on the vehicle interior noise level and quality can also be predicted. The engine noise serves as input for the FEV vehicle interior noise simulation (VINS). In-cylinder pressure based noise prediction tools, developed by FEV, make possible a comprehensive combustion system/calibration optimization with respect to thermodynamic and NVH targets.

NVH tests with a "rough" calibration stage, early in the combustion system development, allow for engine specific structural weighting functions (alternatively from FEV's database) and subjective noise assessment. In this manner, the impact of calibration modifications can already be evaluated with respect to the noise level and quality early in the development process, saving time and cost during final vehicle integration and calibration.

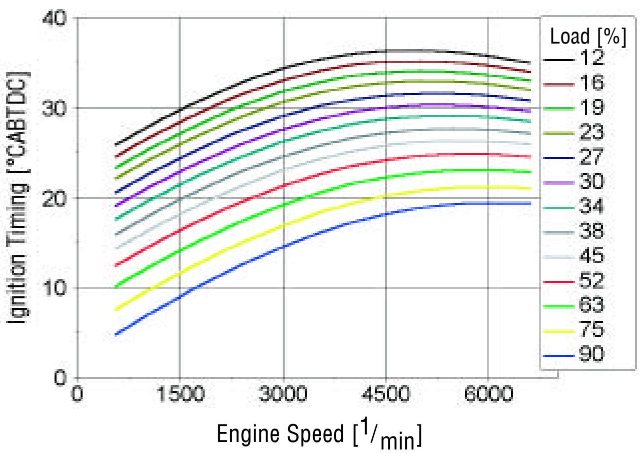
Dipl.-Ing. Jakob Nehl

DoE During Engine Management Application

During calibration on the stationary test bench, extensive maps are filled with optimum values for specific operating points. Hereby experience is used to interpolate certain areas. With increasing variability of the engine concept (e.g. continuously variable valve timing for intake and exhaust for a $\lambda = 1$ engine, or the numerous number of variables for a DISI engine), it is even for the expert hardly possible to predict the ideal combinations. The effort for a full grid measurement in all base points is extremely high. A possibility to reduce the measurement effort is the utilization of designed experiments (DoE) and regression analysis.

Often this method is applied to determine the ideal combination of the variable parameters for one specific operating point. In a subsequent step valid maps without major discontinuities for all engine speeds and loads must be generated.

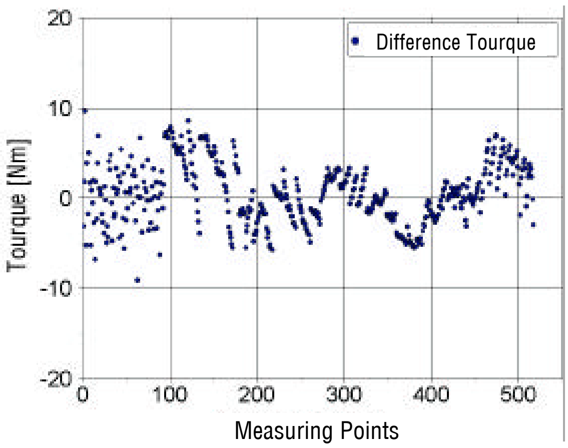
Under certain circumstances it is possible to generate complete maps with DoE directly. The following examples show how the effort to obtain the torque data for a torque-based EMS of a $\lambda = 1$ SI engine can be reduced significantly.



We could verify with existing data that D-optimal designs yield good results and I-optimal designs perform even better. The design of the experiments, the regression and the residual analysis were done with specific DoE software.

The optimization and generation of the maps are semi-automatically carried out by Microsoft Excel macros. The ignition map in the first figure is an example. All other maps necessary for the torque calculation in the EMS were generated similarly.

The following experiment illustrates the time saving potential at the stationary test bench due to the utilization of DoE. In the past a minimum of 500 measurement points was necessary to determine the torque data. Now with DoE only 100 tests are planned, run and evaluated as described. The second figure shows the difference between the conventionally obtained and the calculated torque data. The first 100 points were used for building the regression model, the other 420 points were ignition loops which were checked with the obtained regression model. The difference between prediction and measurement was less than 10 Nm with a maximum engine torque of over 400 Nm.



Besides the determination of torque data, DoE can be utilized in large areas of the engine operation range for the following calibration steps:

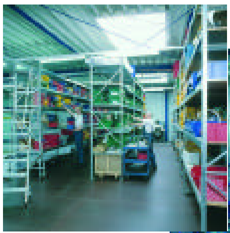
- Exhaust gas recirculation (EGR)
- Exhaust gas temperature model
- Boost control
- Camshaft phasing control
- Transitional mixture compensation

With the good results of DoE based application of conventional SI and Diesel engines, we now also address the application of advanced engine concepts such as DISI and EMVT with DoE. Due to the abundant parameters (EGR, lambda, injection timing, fuel rail pressure, etc.) the use of DoE promises impressive gains in effectiveness.

Dipl.-Ing. Georg Lütkemeyer
Dipl.-Ing. Michael Heinen

Upgrade and Extension of Engine Assembly Workshop

With the expansion of FEV's complete engine development activities in the 1990's, a separate engine assembly workshop was constructed with a total production capacity of 250 engines per year (assuming one-shift operation). In addition to the engine assembly capability, the facility upgrades included attached storage capacity for engine components as well as special test rigs (e.g., leakage checks) and cleaning devices for engine components.



In connection with the ongoing expansion activities at FEV's headquarters in Aachen a completely new engine assembly workshop recently was commissioned. This new engine workshop supplies the engine assembly capacity that is required for the ever-increasing number of engines that pass through the test cell and laboratory areas at FEV as part of a diverse complement of ongoing project work.

Currently, the new engine assembly area includes a total of 12 distinctly separate so-called assembly islands. Additionally, a flexible work zone separation was inserted, which permits the combination of several assembly islands into an assembly zone. This concept incorporates the possibility to simultaneously assemble engines from different programs in one workshop without the risk of exchanging engine components between different programs. Adittionally, this concept guarentees the secrecy between the different programs without a loss of synergistic effects in the assembly workshop.

In addition to the engine assembly islands, component storage capacity was significantly increased, so that today a 400 m^2 storage facility is available with generously sized storage cribs. The storage is located directly above the assembly area and incorporates its own additional commissioning area. The short distance between assembly and storage enables the workshop staff to pick up requested parts directly from stock without loosing time for transport, etc. A computer-based part handling system assists FEV employees to retain the required oversight and control of parts inventories for the individual projects.

The engine assembly workshop is now located directly adjacent to the test bench assembly workshop that was also newly constructed over the past year. Within this workshop, engines that have been assembled in the assembly workshop are completely instrumented and checked for test bench operation. In the case of questions or technical problems, it is possible for technicians and engineers from the engine assembly area to directly work together with their coworkers in the test cell line-up area to clarify any open issues with the shortest possible reaction time.

These ongoing improvements and upgrades provide FEV with integrated, highly efficient engine assembly and test cell assembly areas that are very well prepared for future customer requests and projects.

Dipl.-Ing. Peter Stommel

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