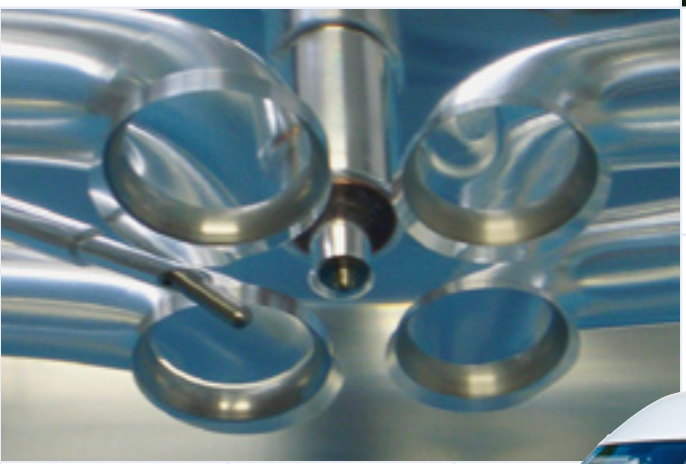
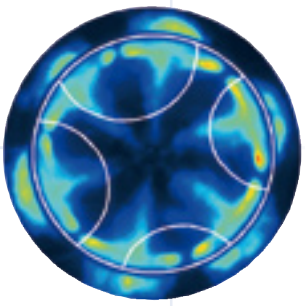
MANAGE THE DIESEL –
FULL SCALE DIESEL DEVELOPMENT SERVICE





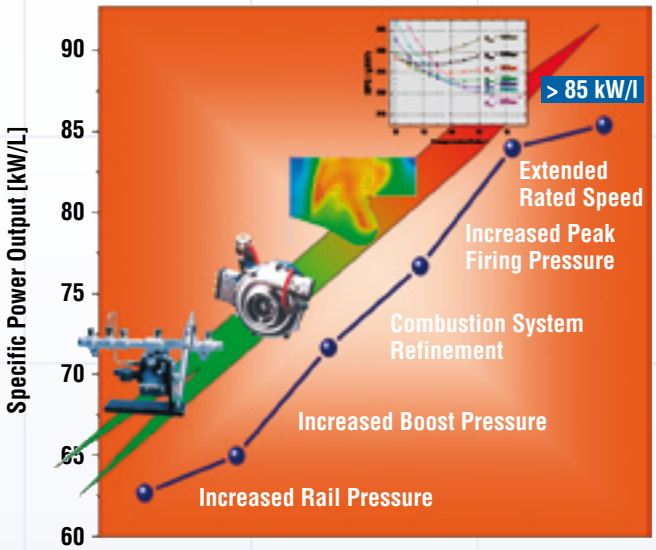
FEV®

Combustion System Development

For more than 20 years, FEV has been the partner of choice to the automotive industry for the development and improvement of diesel combustion systems. FEV was the first independent engineering company to develop a high-speed 4-valve DI diesel for passenger cars. Today, FEV is developing and refining diesel combustion systems for a wide range of applications:

- HSDI diesel engines for compliance with worldwide emission standards (e.g. European, Euro-5, and the, U.S. EPA Tier 2 Bin 5, emission standards)
- Racing/High-performance Applications
- Heavy-duty and Off-road Engines

The combustion system development approach that is utilized by FEV lends itself to repeatable results. FEV's approach ensures high air utilization of the injected fuel with sufficient air mass (boost pressure) and a high EGR acceptance to ensure both lowest engine-out emissions and high specific power output.

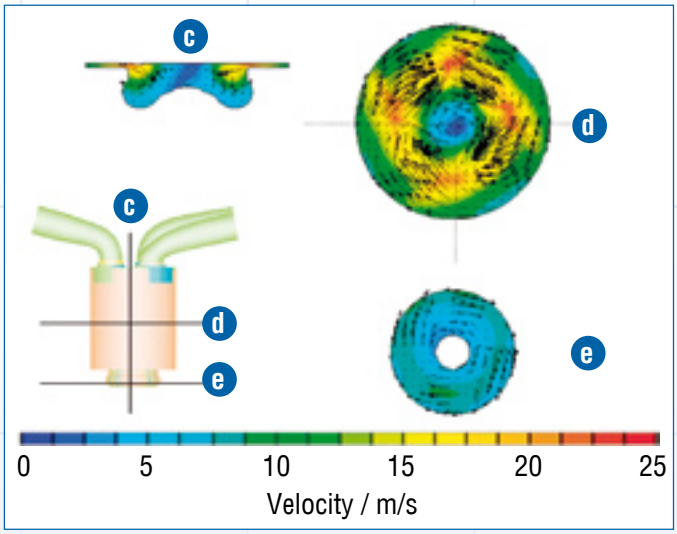


Development Steps for High Specific Power

FEV uses a combined experimental and CFD-based optimization approach to optimize a combustion concept with respect to:

- Boosting system
- Charge motion
- Bowl layout
- FIE system and nozzle layout
- Gas exchange
- EGR system (pressure losses and cooling capacity) layout

FEV has been a pioneer in the application of CAE tools within the field of combustion system development. For the combined layout of the combustion bowl, charge motion and nozzle configuration, one-dimensional thermodynamic post-processing (burning function and heat release calculations) and fuel spray penetration computations are employed. These methodologies have proven beneficial for accelerating the development process. FEV also routinely uses CFD calculations with great success in the supporting combustion system development. The combination of closely correlated data from theoretical and experimental methods is particularly useful in understanding the phenomena of mixture formation and combustion behavior. In the end, faster development processes are possible as a result of the use of analytical tools.



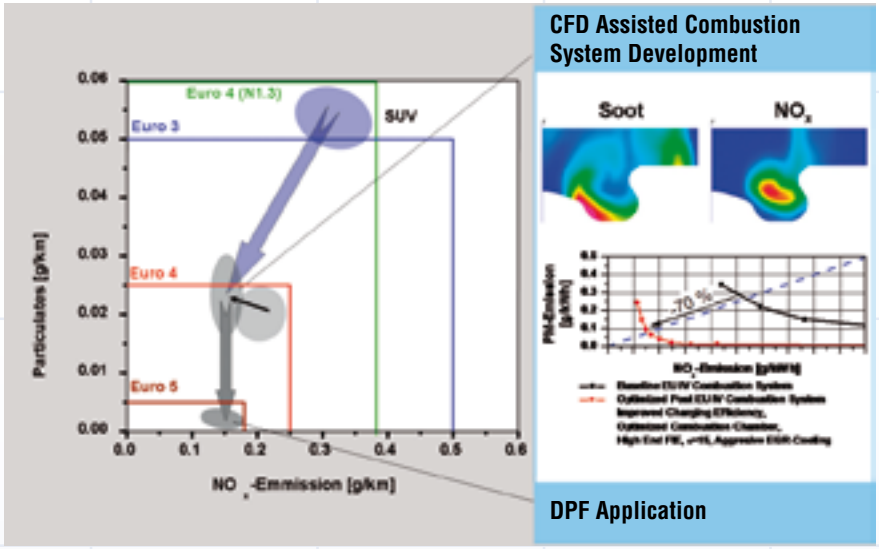
CAE Flow Layout

The combined analytical and empirical approach considers all aspects of combustion development and offers significant potential for improving emissions with increased power and lower combustion noise.

In addition to diesel combustion systems development for high fuel efficiency and low emission engine concepts, FEV provides special services, such as engine certification and emission deterioration factor evaluation programs.

The challenges for heavy-duty and industrial engine optimization lie in finding an economical means of meeting emission requirements, while maintaining low fuel consumption. FEV has developed procedures and methods to combine state-of-the-art technology and services with the specific requirements from our heavy-duty and industrial diesel engine customers.

In parallel with its automotive engine capabilities, FEV also offers a full range of engineering services for large bore engines. FEV has developed a specialized large-bore single cylinder research engine that is adaptable to different engine configurations (e.g. bore and stroke). The engine can be operated with a wide range of fuels from distillate fuel to heavy fuel oil and to a variety of gases.

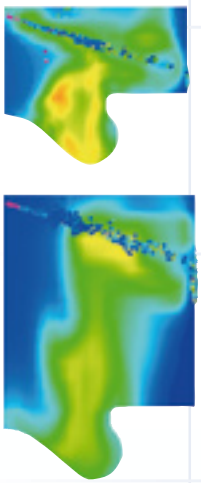


Combined CAE and Experimental Combustion Layout lead to lowest Engine Out Emissions

Exhaust Gas Aftertreatment

FEV offers extensive experience in the development and application of diesel exhaust gas aftertreatment technologies for passenger car, light-duty, heavy-duty and stationary diesel engines, including:

- Screening and benchmarking of exhaust gas aftertreatment components (DOC, DPF, SCR and NO_x Adsorber catalysts)
- Exhaust aftertreatment system concept layout
- Exhaust aftertreatment system sensors
- Control strategies/development of software functionalities
- Exhaust gas aftertreatment calibration
- Setup of demonstrator vehicles
- Development for production



CFD Simulation Post Injection

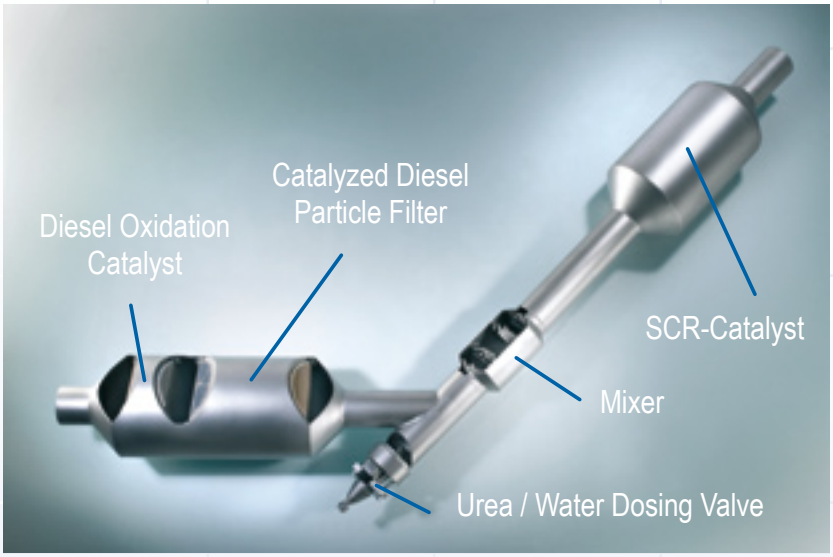
Diesel Particulate Filters (DPF)

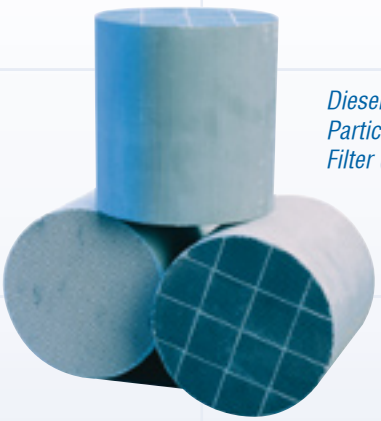
FEV has successfully completed a large number of Diesel Particulate Filter (DPF) technology projects. One such project involved development support of the PSA FAP-system, which became the first production DPF system on the market.

FEV has been actively developing DPF technology for more than 15 years. FEV's current DPF development activities include:

- DPF system components assessment/ benchmarking
- Detailed investigations on local soot deposition in DPF
- Calibration and vehicle assessment/ benchmarking
- Layout of DPF systems
- Modelling of DPF systems
- Innovative regeneration strategies
- External diesel fuel injector applications
- Reliable and robust regeneration calibration
- Oil dilution
- Development of DPF-related control strategies
- Vehicle calibration with regard to regular production, including various climatic conditions

Today, FEV engineers remain deeply involved in NO_x aftertreatment programs, including Selective Catalytic Reduction (SCR) and NO_x Adsorber technology. These programs target production readiness, and address stringent U.S. and future European exhaust emissions regulations.





Diesel Particulate Filter (DPF)

NO_x Adsorber Catalyst Technology

Current developmental activities at FEV in the field of NO_x Adsorber Catalyst (NAC) technology include:

- NO_x Adsorber Catalyst (NAC) assessment/benchmarking
- Aftertreatment system conceptual layout
- Robust rich engine calibration
- Lean/rich transitions
- Sensor demands for NO_x Adsorber Catalyst systems
- Application of external diesel fuel injectors/diesel fuel reformers
- Development of control strategies
- Desulfurization strategies
- Vehicle calibration for regular production

Selective Catalytic Reduction (SCR) Technology

FEV's development of SCR technology led to the creation of an alternative solid SCR system based on ammonia carbamate. This system features substantial packaging and maintenance benefits. The concept feasibility has already been proven in several demonstration vehicles, including passenger car and light-duty applications with significant space constraints.

FEV's developmental activities for SCR technology:

- SCR catalyst assessment/Benchmarking
- Aftertreatment system conceptual layout
- SCR system calibration
- Sensors for SCR systems
- Alternative SCR system concepts
- Development of SCR closed-loop control strategies
- Production vehicle calibration

Emission Measurement

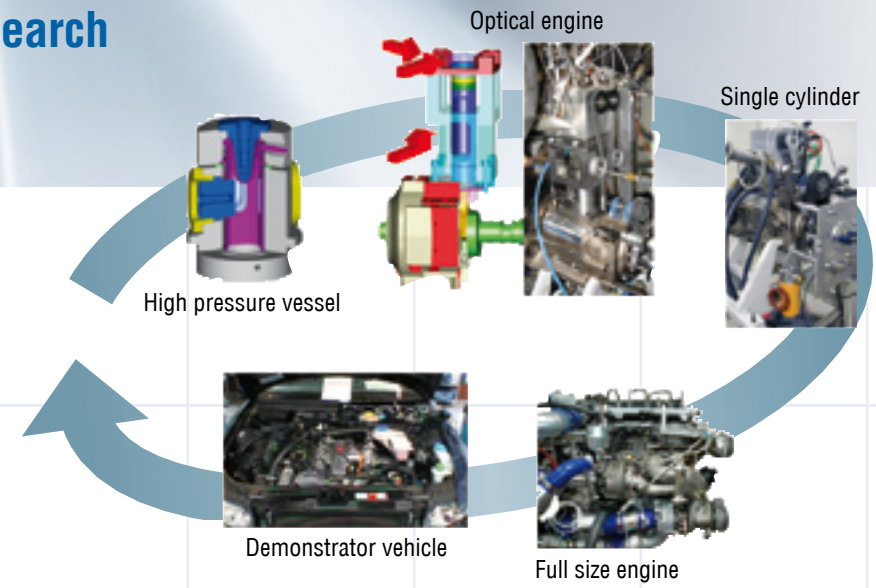
As tailpipe emissions begin to approach the level of background emissions, detailed characterization of exhaust emissions becomes increasingly important with regard to the future of exhaust aftertreatment systems and regulations. FEV provides special services with regard to particular questions and is experienced with the application of suitable measurement tools or analysis methods.

Measurements and Analyzing tools:

- FTIR
- Mass spectrometer
- Alternative NH3 measurement devices
- PAH/Aldehyde analysis
- Detailed particulate analysis (SOF, NSOF, Sulfates)
- Particle size distribution measurement (SMPS and Berner impactor)

LDV Demonstrator Vehicle with FEV Solid SCR System based on amonia carbamate

Basic Research



Full Scale Support for Diesel Engine Research and Development

FEV offers single cylinder research engines in various bore sizes (400 cc to 15700 cc), as well as a number of full-size engines (passenger car and heavy-duty) and demonstration vehicles that complete the FEV portfolio for basic research and combustion investigations. In addition to our own fleet of demonstration vehicles, FEV also builds up new demonstration vehicles that allow our customers to evaluate and demonstrate their developmental technologies.

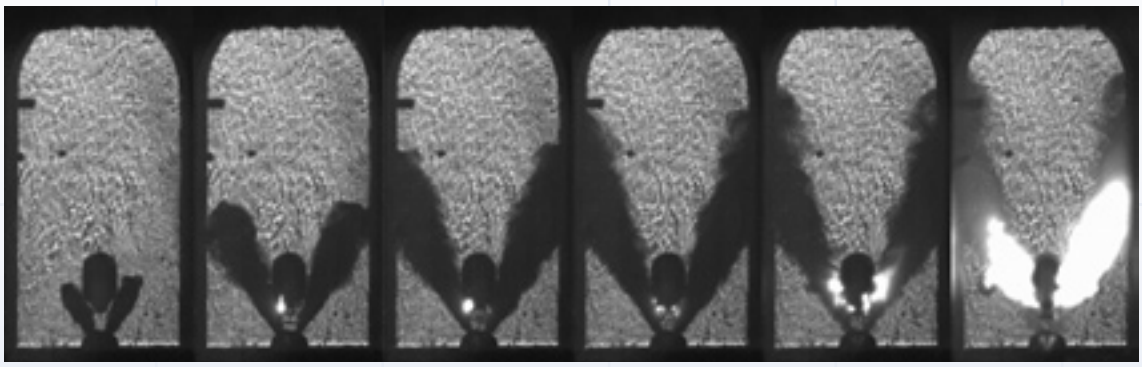
As new technologies are developed and put on a path towards advanced development and production intent, comprehensive knowledge and expertise regarding fundamental physics and thermodynamics is essential to effectively support the ongoing development activities. FEV maintains a full range of basic research facilities and capabilities that can be leveraged to support fundamental studies and research activities with respect to charge motion, fuel injection, mixture formation, internal combustion and exhaust gas aftertreatment.

To support fundamental research on combustion phenomena, FEV has developed a high-pressure vessel and innovative transparent engines. Optical measurement techniques are routinely used to perform a fundamental analysis of spray penetration and evaporation, ignition, combustion and exhaust gas evaluations.

The following optical measurement techniques can be applied:

- Particle Image Velocimetry (PIV)
- Mie-Scattering
- High Speed Extinction/Schlieren Visualization
- Laser-Induced Incandescence (LII)
- Laser-Induced Fluorescence (LIF)
- Droplet Sizing (Laser Diffraction or Phase Doppler Anemometry)
- Fast Gas Sampling Valve

Example: Spray Penetration and Ignition under Cold Start Conditions



FEV's unique high pressure vessel is capable of:

- Maximum Gas Temperature: 600°C
- Maximum Gas Pressure: 60 bar
- Modifications:
  - Application of piston bowls
  - Heated and cooled wall inserts (-25°C / 130°C)
  - Swirl and turbulence generator

Key technical features of the transparent HSDI Diesel Engine:

- Single-Cylinder 4V-CR-Test Engine
- Technical Specifications:
  - VStroke = 390 cm^3
  - Bore = 75 mm, Stroke = 88.3 mm
- Optical Accesses:
  - 3 Side Window
  - Glass Piston Bowl
- ω- shaped Piston Bowl
- Fast Gas Sampling Valve applicable
- Modern CR Injection System, variable in:
  - Injection Pressure
  - Begin and Duration of Injection
  - Pilot-, Main-, and Post Injection
- Injector: Conventional or Piezo (> 19 mm)
- High load capability extended to IMEP > 10 bar

Catalyst Test Bench:

FEV has developed a catalyst test bench for benchmarking and screening of catalysts for closed-loop exhaust aftertreatment control. This new resource is being used for investigations on Diesel Oxidation Catalyst (DOC); Selective Catalytic Reduction (SCR), NO_x Adsorber Catalysts and Diesel Particulate Filter (DPF) systems. The test bench utilizes small catalyst or DPF samples with full length, which can be prepared by FEV.

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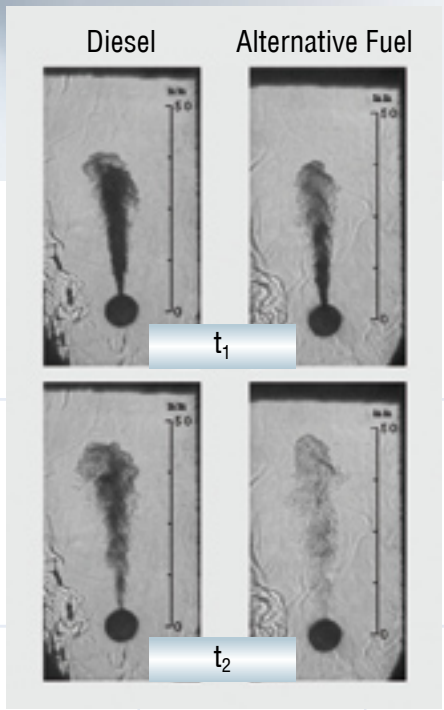
Typical Applications of the Catalyst Test Bench include:

- SCR catalyst NH3 storage
- SCR catalyst NO_x conversion
- DOC light-off performance
- Soot regeneration by NO_2
- Soot regeneration by O_2
- Impact of single exhaust components on catalyst performance under real engine exhaust conditions

Catalyst Test Bench

Alternative Fuels



Spray Visualization

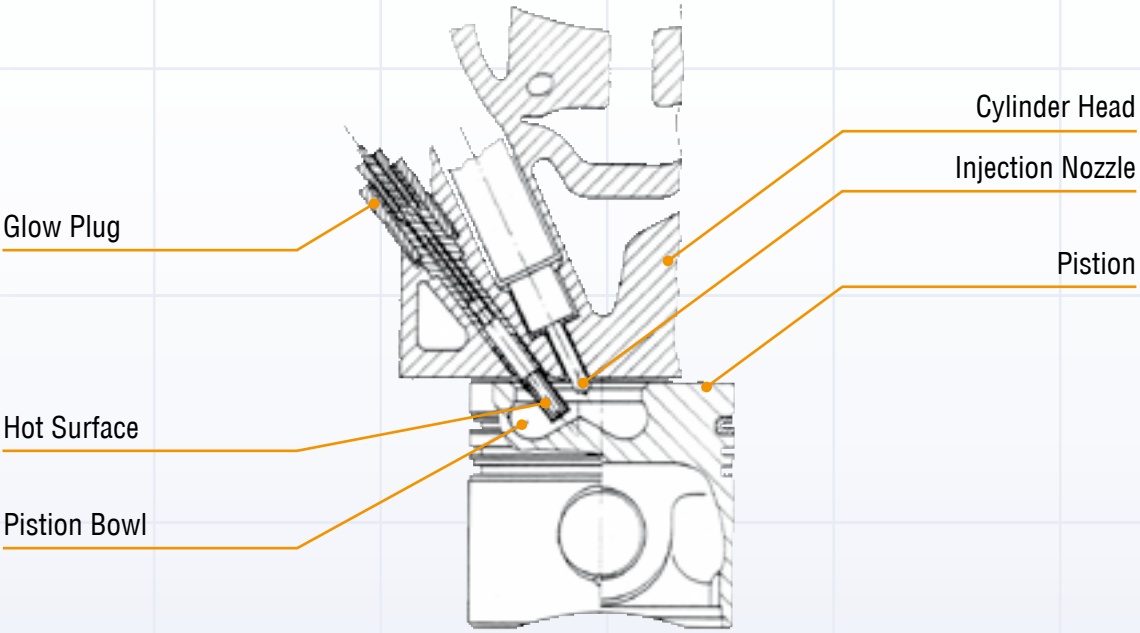
Since the late 1970's, FEV has been a global leader in alternative fuels research and development. Several generations of FEV engineers has fine-tuned specialized competence in the evaluation and optimization of alternative fuels technologies.

A broad range of experience has been gained over the years from many successful programs. Today, that knowledge base is available to our customers as they work toward diesel combustion system integration and calibration for:

- DME (Di-Methyl-Ester)
- FAME (Fat acid methyl ester)
- Methanol
- Synthetic diesel fuels (XtL)
- Ethanol and alcohol diesel fuel bends
- Biodegradable fuels like rapeseed oil and water emulsified fuels
- Gaseous fuels

The ongoing global discussion about reducing oil imports and achieving substantial reductions in CO_2 emissions has increased the demand for research and development into alternative fuels.

FEV offers both the knowledge and experience that is essential for developing and adapting diesel combustion systems for alternative fuels.



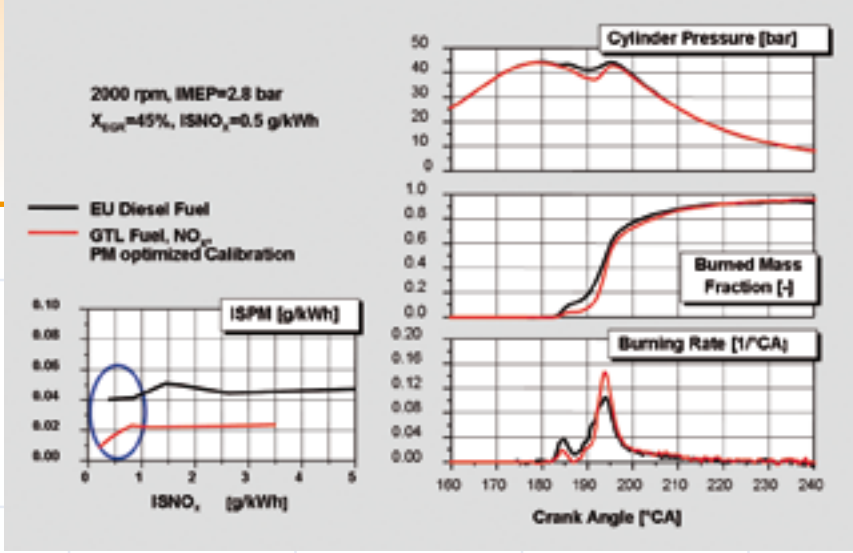
Methanol Combustion System

Our development support capabilities for alternative fuels include:

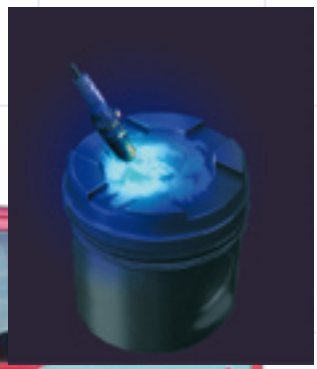
- Spray visualization (high pressure vessel and optical engine)
- Detailed CFD analysis
- Detailed fuel analysis
- Single cylinder and full size engine for thermodynamic investigations
- Demonstrator vehicle
- Detailed exhaust gas analysis

We also support our customers in the field of function development for fuel detection and calibration.

If you're looking for world-class facilities and capabilities, combined with a corporate culture that promotes new ideas and innovation, you need not look any further than FEV. Contact one of our experts today.



Synthetic Fuel and Combustion Benefit



FEV ATAC Demonstration Vehicle and Combustion System

Fuel Injection System Technology

One of the main drivers for improving the characteristics of diesel engines is fuel injection technology. For many years, FEV has been involved in the development of Fuel Injection Equipment (FIE) technologies.

Injection System Development

Over 20 years ago, FEV was a pioneer in the development of piezo-electrically actuated injection systems. Initially, these systems were used for identifying Fuel Injection Equipment (FIE) related requirements in combination with advanced combustion system concept development.

More recently, FEV has also been one of the key developers of modern production piezo injection systems. In addition to typical diesel injection systems, FEV has continued to develop and investigate gasoline-tailored injection systems, as well as dedicated injectors for exhaust aftertreatment devices or fuel cell systems.

We offer the expertise to deliver key support in the following fields of fuel injection system technology:

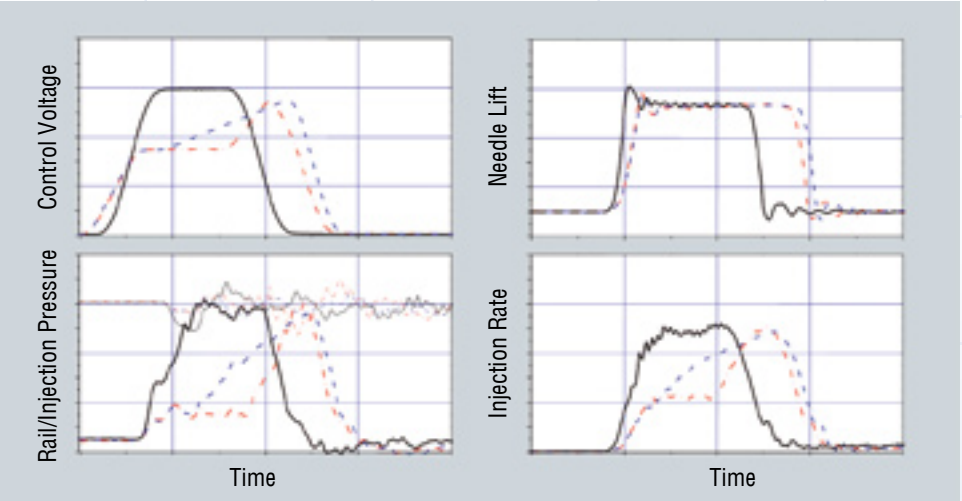
- Injection system development
- Production system investigation
- Special sensors for fuel injection system analysis

FIRST is a significant example of FEV's prototype injectors for combustion system development. *FIRST* uses a conventional spring-loaded nozzle needle, which allows a much higher opening and closing velocity of the nozzle than that achieved by current-production common-rail systems. The higher velocities are possible because the rear side of the nozzle is not pressurized by the rail pressure.

The *FIRST* injector also integrates the common-rail system's degrees of freedom regarding injection pressure and multiple injection capability with flexible formation of the injection rate and minimized nozzle seat throttling.

FIRST Injector

Flexible
Injection
Rate
Shaping
Tool



FIRST Injector

Production System Investigation

Typical production engine development projects are supported by dedicated fuel injection system investigations. In addition, FEV engineers perform innovative research work on unique prototype injection systems.

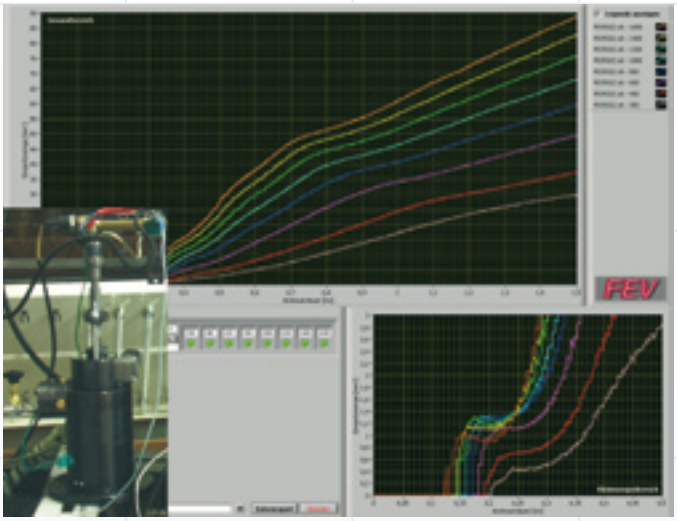
Using computerized injection test benches, the performance of the injection system is automatically measured and documented by a variety of means:

- Injected quantity vs. energizing duration
- Standard deviation of injected quantities
- Influence of the intervals between pilot, main and post injection
- Injector stability (aging and coking)
- Full system durability investigations

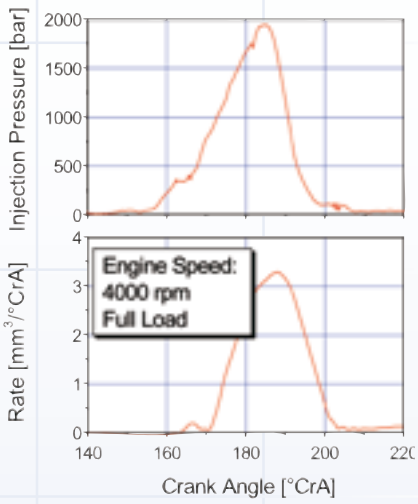
Special Sensors for Fuel Injection System Analysis

The size and the dynamic and environmental boundary conditions of fuel injection systems often require the application of specially developed sensors since, typically, such sensors are not commercially available. Since the addition of sensors can have the undesired effect of altering injection system performance, this job must be done with great care and precision. Some examples of special sensors that have been developed by FEV include:

- Nozzle needle and/or valve lift sensors
- Pressure measurement in a servo control chamber or at the nozzle side
- Dynamic pump drive torque and/or power consumption
- Temperature measurement
- Actuator force measurement



Measurement of Injection Characteristics



Injection Pressure Measurement with Strain Gauges

Benchmarking and Engine Assessment

In a rapidly moving marketplace, understanding what it takes to produce a best-in-class powertrain is essential to the success of our customer's development projects. In support of this effort, FEV maintains one of the world's largest databases of competitive powertrains that can be made available to support our customers with target setting and assessment.

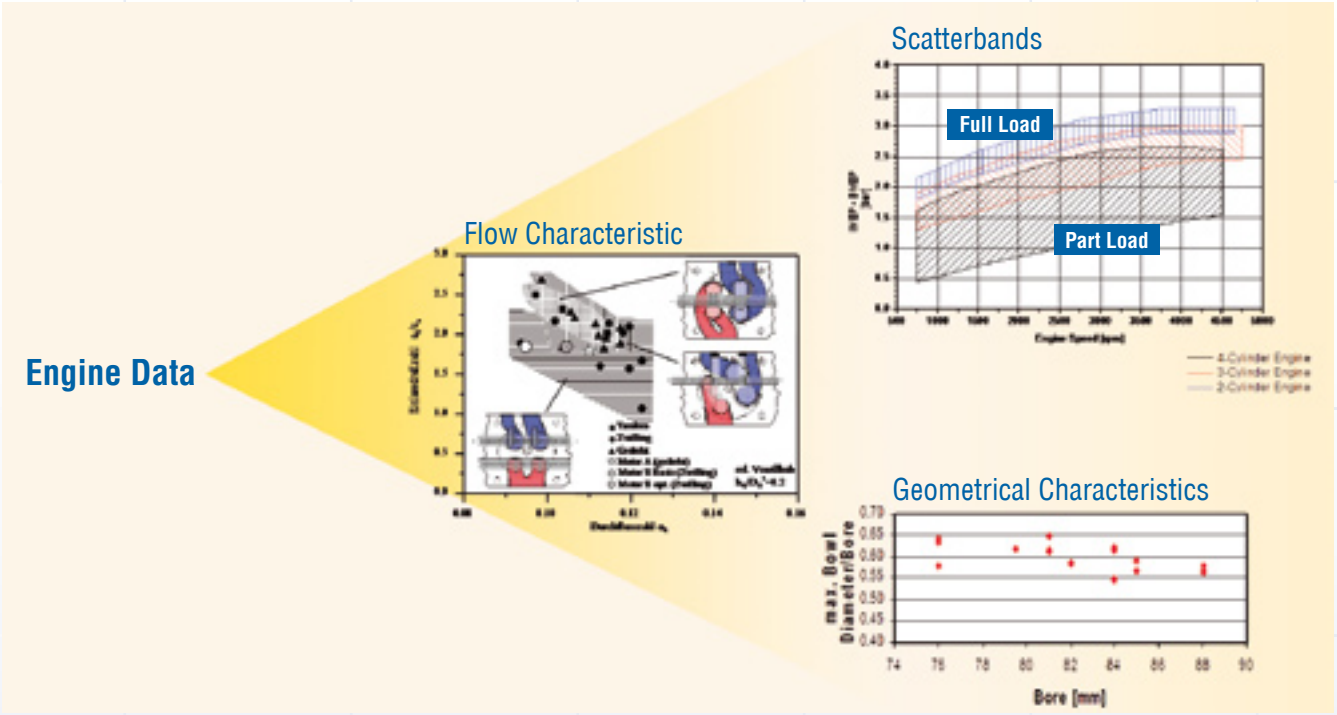
With the support of this database, detailed engine benchmarking and assessment programs can be conducted for a wide range of vehicle applications. Benchmarking and engine assessment cover both engine and vehicle investigations and typically include an analysis of weak areas and recommendations for engine improvements and upgrades.

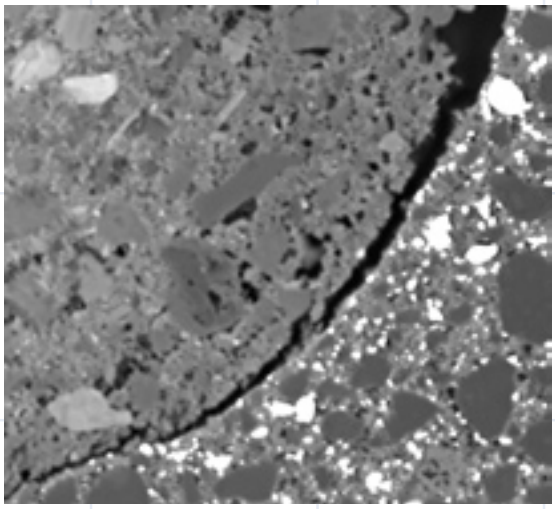
The results of an FEV benchmark program provide a detailed view of the operational behavior of modern engines from a global complement of market areas, including state-of-the-art HSDI engines, and allow the prediction of future development trends. FEV benchmark data is available for a wide range of applications.

Due to it's long-term experience, FEV benchmarks 10 to 12 new production and pre-production engines each year and conducts a large number of complete vehicle assessments as well.

FEV's benchmark database contains data from nearly 70 representative diesel engines, ensuring a strong foundation for statistical comparisons.

Engine Benchmark and Assessment





Detailed Coating Analysis

FEV also offers services to support its customers with detailed benchmarking programs for Diesel Oxidation Catalysts (DOC), Coated Diesel Particle Filters (CDPF) as well as SCR and NO_x adsorber catalysts. These efforts typically include:

Geometrical data:
- length/diameter, volume
- position in exhaust system
- cell density, wall thickness
- substrate porosity

Catalyst performance data:
- Light-off performance
- CO-/HC conversion efficiencies
- NO/NO_2 conversion efficiency
- Impact on particulate emission (SOF, NSOF)
- NO_x conversion efficiencies (for SCR and NO_x adsorber catalysts)
- NH3 adsorption behavior (for SCR catalysts)
- NO_x adsorption/NO_x reduction performance (for NO_x adsorber catalysts)

Diesel Particle Filter (DPF) related performance data:
- Filtration efficiency (including particle size distribution measurement)
- Back pressure performance
- Regeneration performance
- Behavior under thermal shock regeneration conditions
- Balance point

Detailed characterization of coatings and substrates.:
- Porosity and specific surface area (e.g. by BET)
- Coating structure (e.g. by XRD, SEM, EDX)
- Elemental composition (e.g. by ICP, XRF, EPMA)

FEV customers receive detailed scatterbands, representing the latest state-of-the-art technologies. Scatterbands can be developed for a number of different parameters, allowing a detailed assessment of a particular technology. Some investigations are conducted on special test bench setups; in addition, a catalyst test bench for detailed catalyst and DPF investigations is available for in-depth investigations.

If requested, FEV can also provide a state-of-the-art DI Diesel engine (in-house development) with full access to all ECU parameters. Based on FEV´s experience in catalyst and DPF benchmarking, additional standardized procedures have been developed that allow efficient project completion under repeatable boundary conditions

Start of Production Calibration

FEV's Start of Production (SOP) diesel calibration knowledge is based on many years of production calibration experience with a variety of OEM's and other clients. This broad base of project experience offers FEV engineers the opportunity to work with many different project requirements and as well as applications in a variety of target markets. That experience contributes to FEV's recognition as a proven development partner for production calibration and solutions at all levels.

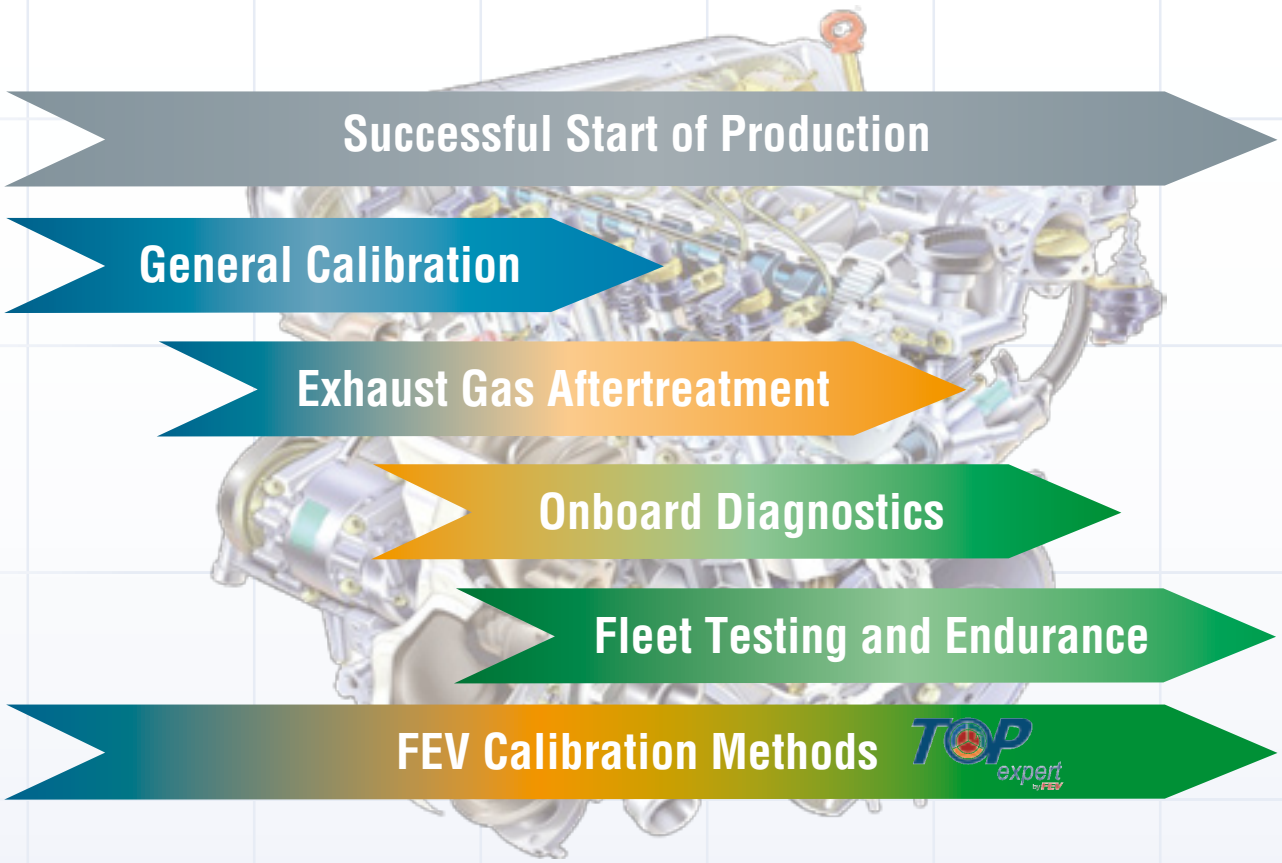
A standard Start-of-Production (SOP) calibration process can be subdivided into four technical areas:

1. **Base calibration**
2. **Exhaust gas after treatment**
3. **On-Board Diagnostics (OBD)**
4. **Fleet Testing and Endurance**

In order to provide robust production calibration results that move quickly into engine/vehicle production, the global application process needs to be continuously monitored. In addition, FEV improves timing, cost and quality through the use of FEV-developed calibration methods (TOP Expert), which support the accelerated development cycles.

1. Base Calibration

FEV uses standards and tools for the base calibration task that ensure an effective, robust and cost-efficient calibration process. The base calibration concentrates primarily on the items identified below in the figure, "Diesel Base Calibration".



Calibration Process

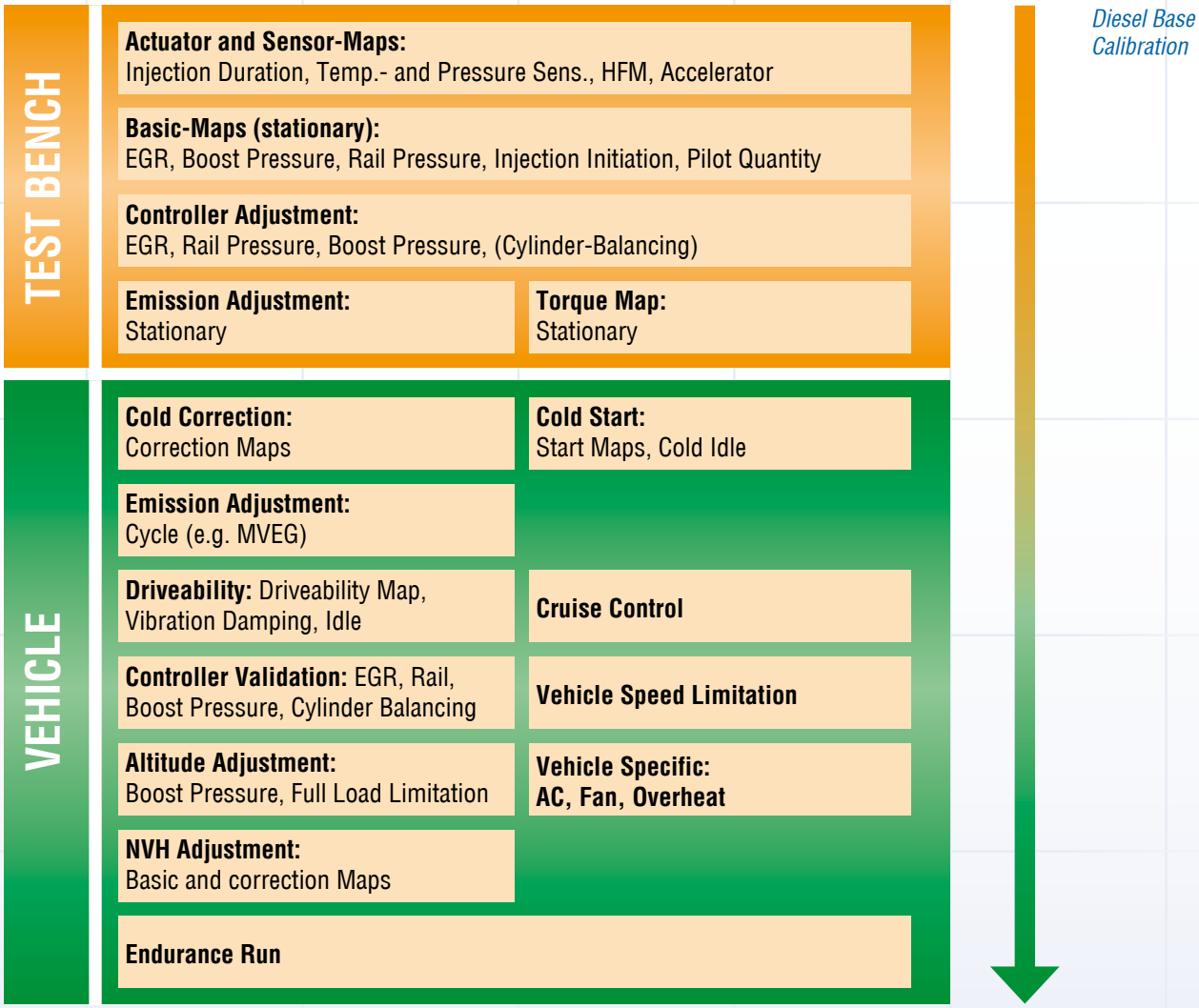
Design of Experiments (DOE) methods are used to calibrate the emission relevant engine map area.

Global optimization parameters for the base calibration include:

- Regulated emissions
- Fuel consumption
- Combustion noise
- Calibration stability
- Interactions between different calibration parameter

FEV's development strategy ensures a proven level of calibration quality, which leads to success with the final homologation.

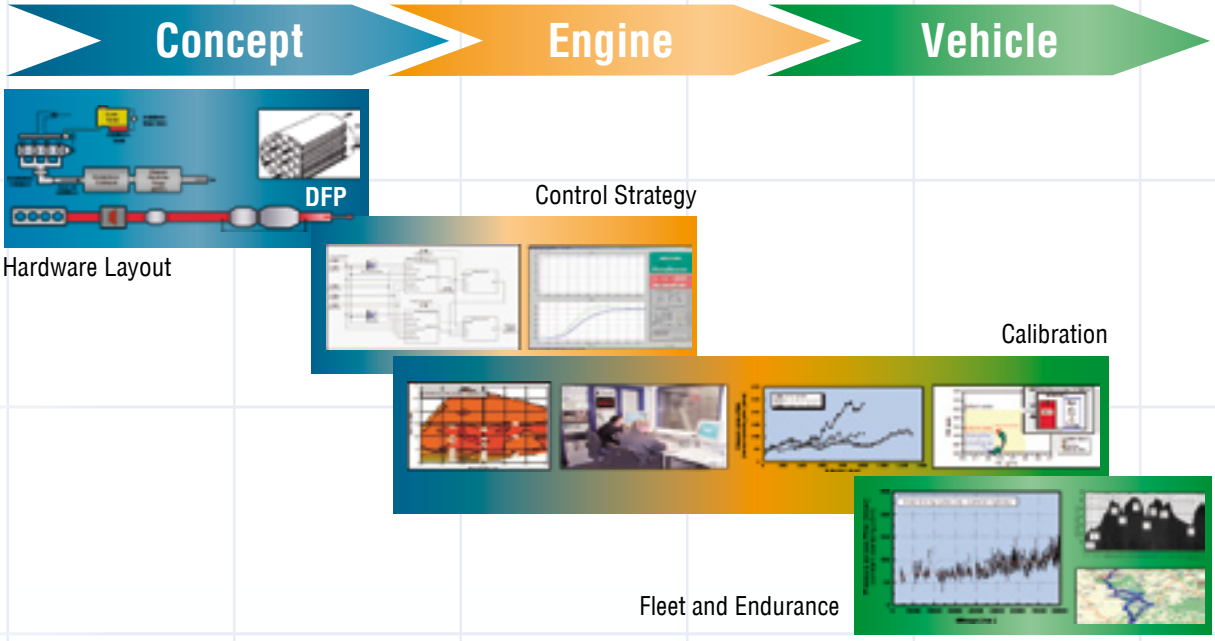
FEV's base calibration effort focuses on the optimization of the controller, with regard to the engine's performance and drivability characteristics, while maintaining all of the other given targets. FEV engineers successfully employ appropriate calibration tools in support of these efforts. In addition to the calibration of control strategies using today's standard software architectures, FEV has also developed advanced controller concepts in conjunction with its partners.



Start of Production Calibration

2. Exhaust gas aftertreatment system

Independent of whether the system is a Particulate or NO_x-reduction unit, FEV's experts offer the know-how and expertise to provide critical and timely support to accelerate the required calibration processes.



The key features of FEV's strategy to provide cost-effective aftertreatment applications are:

- Hardware Layout

A detailed layout of the exhaust gas aftertreatment system always represents a compromise between functionality, vehicle packaging and cost. FEV assists its customers as they develop optimal configurations by using CFD models and leveraging substantial expertise that is based on a broad base of application experience and extensive benchmarking background

- Control Strategy

Sophisticated control algorithms are required to maximize the efficiency of exhaust aftertreatment devices. Aftertreatment strategies must be developed to monitor and control the complexity of an exhaust gas aftertreatment system. A well developed strategy can assist in overcoming system limitations and providing safety functions to protect the aftertreatment components. FEV has extensive experience in developing control strategies for Diesel Particulate Filters (DPF), Selective Catalyst Reduction (SCR), NO_x Adsorption Catalyst systems, and can rely on a wide range of available control functionalities.

- Test Bench and Vehicle Calibration

The predominant task in the calibration of an exhaust gas aftertreatment system is test bench and vehicle calibration. FEV has accumulated extensive experience in vehicle and test bench calibration for DPF and De NO_x systems and provides innovative and reliable capabilities that have been proven over a large number of OEM projects.

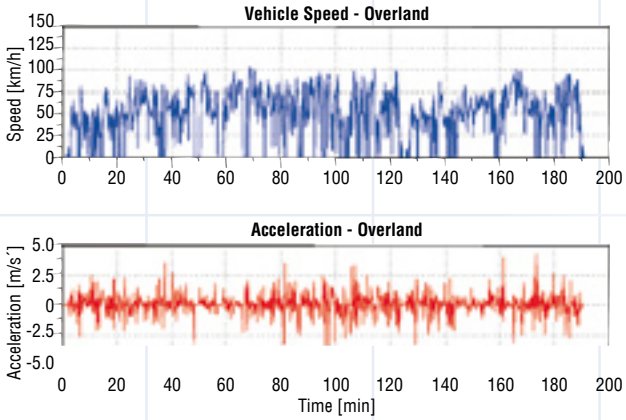
3. On-Board Diagnostics (OBD)

FEV offers significant knowledge and experience in diesel-specific OBD calibrations for any type of vehicle, engine management system and/or market. As customer requirements to reduce project timing increase, in combination with the effect of continuously decreasing availability of test hardware, it becomes more important that the entire application process be managed with efficiency and flexibility.

4. Fleet Testing and Endurance

Over the years, many customers have benefited from FEV's capabilities in fleet testing and endurance investigations, which culminates the calibration development effort.

FEV can also accommodate special customer needs. Different test procedures with a variety of vehicle test profiles are available. All of these activities are supported by methods and tools developed for these purposes, to ensure effectiveness and quality.



Test Profile-Endurance Testing

Data Acquisition

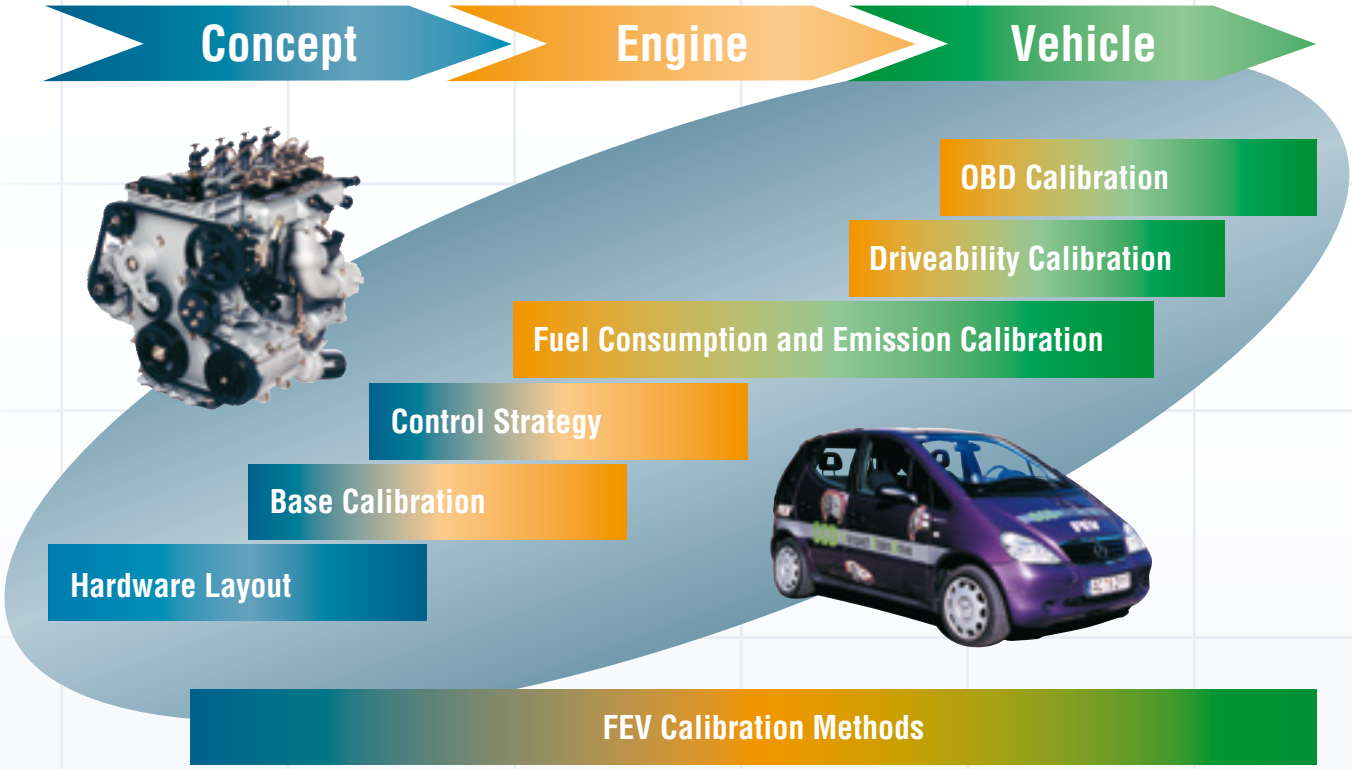
- General Data
- Status of Endurance Test
- Overview Mileage Specific Data
- ECU Data
- DPF Ash Loading
- Fuel Consumption
- Hardware Evaluation
- Oil Dilution
- Average Regeneration Time
- Number of Regenerations
- Faults/Error Management

Calibration Methods and Tools

FEV's broad base of experience with many different types of engines from many different markets and customers represents a unique resource that is available to our customers.

We are a valuable and proven development partner that supports the development process through the use of standardized methods and the application of unique tools in all areas of engine development. These tools are continuously adapted for the complex needs of current and future diesel development programs.

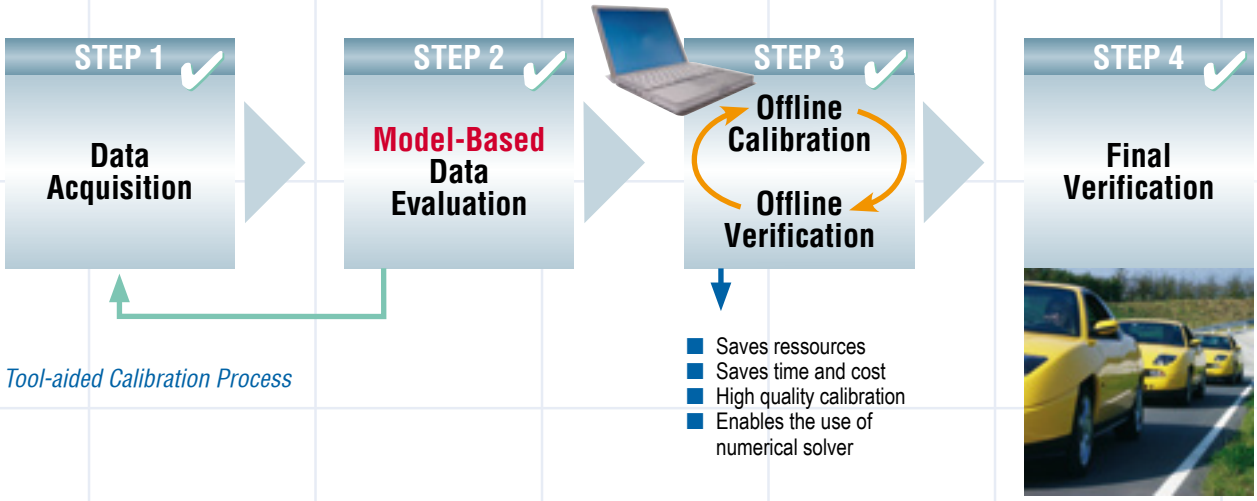
We develop unique approaches that integrate many years of diesel engine knowledge to form intelligent solutions that are utilized by all of the technical departments within FEV's diesel group. FEV remains flexible and ready to meet customer needs for future development efforts. FEV applies the same standards, methods and tools that it uses in customer projects within our own development activities. Therefore, all of the tools that are offered by FEV are tested and proven under real-world operating conditions before being integrated into FEV's TOPexpert program. The integrated and tool-supported development result in saving resources, time and expenses through the growth of off-line activities that enable high quality.



Development Process

calibration methods by FEV

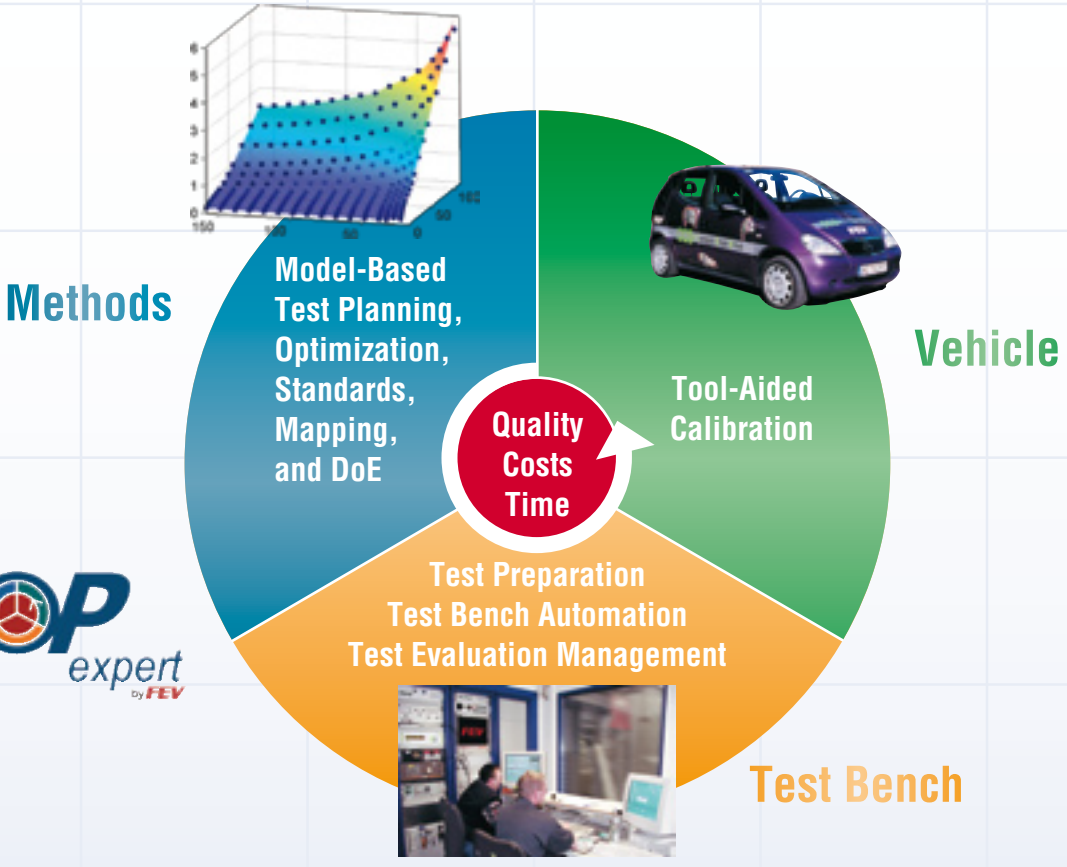
TOP expert by FEV



Tool-aided Calibration Process

FEV's integrated and tool-supported development process results in efficient use of resources and time, as well as reduced cost.

FEV engineers continually apply these tools to support the engineering process. By integrating such tools into the development activities, our customers can be confident that their quality and performance targets will be achieved.



Methods and Tools for Calibration

TOP expert by FEV

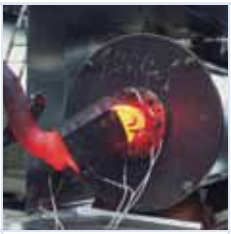
CONTACT

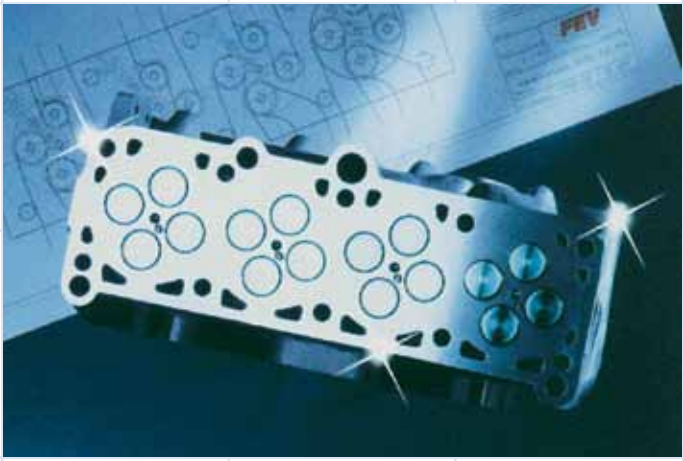
FEV GmbH
Neuenhofstraße 181
52078 Aachen · Germany
Phone +49 (0) 241/56 89-0
Fax +49 (0) 241/56 89-119
E-Mail marketing@fev.com

FEV Engine Technology, Inc.
4554 Glenmeade Lane
Auburn Hills, MI 48326-1766 · USA
Phone +1 (0) (248) 373-60 00
Fax +1 (0) (248) 373-80 84
E-Mail marketing@fev-et.com

FEV China Co., Ltd.
No.35 Xinda Street Qixianling
High Tech Zone · 116023 Dalian · China
Phone +86 (0) 411/84 82-16 88
Fax +86 (0) 411/84 82-16 00
E-Mail fev-china@fev.com

Internet http://www.fev.com





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