SPECTRUM
"POWERTRAIN ELECTRIFICATION"

TRANSMISSIONS
Optimized electromotive transmission solutions by FEV

FUEL CELLS
Range extender for battery electric commercial vehicles

E-FUELS MIX
Almost CO2-neutral mobility by optimized e-fuels mix

THERMAL MANAGEMENT
Range extension: clever climate control for electric vehicles
Dear readers,

A primary objective for future mobility solutions is to reduce CO₂, NOₓ and particulate matter emissions to meet global climate targets. This issue of SPECTRUM shows the wide range of solutions for both conventional powertrains and new fuels, as well as partially electrified powertrains and transmissions, which all offer areas for improvement. When it comes to electric powertrains, increasing the range plays a major role in meeting these global targets.

The first chapter of this issue is dedicated to electrified transmissions. We identify solutions that meet our customer’s most diverse requirements – for example regarding component size, performance and costs.

Another focus of this SPECTRUM is on the potential and suitable fields of application for fuel cell range extenders and e-fuel solutions that can further reduce pollutant emissions. We also provide insights into the thermal management of electrified vehicles, a solution that can increase the vehicle’s range.

In addition, with the FEV Ecobrid, we present a partially electrified development for diesel engines which achieves impressively low fuel consumption with increased performance.

We hope this issue offers you the insights needed to be successful and you enjoy reading it. To stay up-to-date on FEV news and for additional information, visit www.fev.com.

Dr.-Ing. Ernst Scheid
Executive Vice President of FEV Europe GmbH
Chairman of the Executive Board of FEV Asia GmbH
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Battery electric vehicles (BEVs) will play a major role in achieving future vehicle fleet targets for emissions such as CO₂, NOₓ, and particulate matter. Especially in big cities, these vehicles may contribute significantly to keeping the air clean. Hybrid electric vehicles (HEVs) will also do their part in major cities, provided drivers charge their batteries via the power grid and not using the internal combustion engine. FEV has already developed transmissions for passenger cars and light commercial vehicles configured as BEVs as well as HEVs.
Transmissions for battery electric vehicles are becoming more complex as the demands placed on them increase. The maximum driving speed attainable using the battery is rising continuously while demands on starting performance remain constant. These conflicting goals can be solved using high-speed electric engines or two-speed transmissions, but experience shows that such transmissions need to be power-shifting. Besides recuperation, there is a new requirement to have a neutral feature for disconnecting the electric engine from the drive wheels. Particularly at high revolutions and with P4 hybrids, the drag torque of perpetually energized electric engines has a noticeably negative effect. In other applications, the parking lock switches from the transmission to the vehicle braking system. Highly demanding vehicle installation spaces require coaxial construction of the electric drive. The product developer’s task is to limit this complexity and the rising product costs associated with it to an absolute minimum. It helps significantly to adopt subsystems from transmissions used in conventional powertrains. FEV takes this approach.

In addition to the one-speed transmissions already in production for BEVs and P4-HEVs, FEV also develops power-shifting, two-speed systems. Figure 1 shows a first-generation drive unit with a continuous output of 70 kW as well as a peak output of 90 kW using a 400-volt battery. The transmission was developed in-house by FEV. Our development partner, YASA, supplied the P400S electric engine, and the inverter was manufactured by SEVCON. Alternatively, the setup can make use of FEV’s own electric engine and inverter. The component that limits the torque is the mass-produced dry dual clutch. The corresponding electromechanical actuator also comes from mass-produced dual clutch transmissions for the powertrains of purely internal combustion engines. Using these commercially available subsystems makes development short and efficient, enabling market launch to take place quickly. The rotational speed at which the clutches rupture and their torque capacity, however, limit the applicability to the ranges indicated. The demand for higher driving performance is leading to a new solution, as illustrated in Figure 2. A planetary transmission with a Ravigneaux gear set is used to allow the electric engine to rotate at higher speeds and provide higher torque. These transmissions are quite common, with corresponding production facilities and equipment already available. In connection with this simple, reduced clutch transmission, two brakes are sufficient for generating two speeds. The exclusive use of brakes was an important criterion in selecting a design because, unlike ordinary clutches, they avoid the use of rotary transmission feedthroughs or slave cylinders to engage the gears, making them significantly more economical. Figure 2 also shows the oil pump and heat exchanger, which not only...
aid the gears but also help cool both the electric engine’s stator and the inverter. The electric engine with a built-in inverter belongs to a new generation of products developed by our partner YASA. The compact axial flow electric engine is also suitable for vehicles that have a narrow track width, such as relatively small construction vehicles and municipal fleets.

On the way to the large-scale introduction of battery electric vehicle powertrains, hybrid drive system technology is crucial to bridging the gap. The section below introduces two solutions offered by FEV for transversely mounted engines.

Transmissions for P2 and Combined Hybrids

The P2 hybrid transmission (parallel hybrid) illustrated in Figure 3 expands FEV’s dual-clutch transmission kit to include variations for input torques of 150, 250, and 350 Nm for the transverse engine. Every transmission uses wet dual clutches and exclusively needs-based actuators. For full hybrids, a power-on-demand actuator is the most important prerequisite for operating the transmission independently of the internal combustion engine. FEV’s experience shows that the P2 hybrid with its numerous functions represents a very good solution. The model shown here, based on the 350-Nm version of our dual-clutch transmission kit, also makes use of transmission subcomponents readily available on the market. The electric engine being used delivers 50 kW of continuous power, plus 100 kW for a maximum duration of 30 seconds. The length of the transmission, extremely important for a transverse engine, is 440 mm. For a six-speed version, the length can be reduced to 415 mm. Six speeds are sufficient for most vehicles because the torque of the electric engine is essentially available from a standstill, enabling selected gear ratios to be higher. However, even a six-speed version is not a solution for vehicles with

» ON THE WAY TO THE LARGE-SCALE INTRODUCTION OF BATTERY ELECTRIC VEHICLE POWERTRAINS, HYBRID DRIVE SYSTEM TECHNOLOGY IS CRUCIAL TO BRIDGING THE GAP

Fig. 3: P2 hybrid expanding on FEV’s family of dual-clutch transmissions
ELECTRIC DRIVE UNITS

extremely tight installation space. That is why FEV has devised another concept that combines the advantages of a P2.5 and a P3 hybrid. These types of hybrids have an electric engine mounted parallel to the electric engine, a big advantage for the package (Fig. 4). With a P2.5 hybrid, the electric engine is coupled with one of the dual-clutch subtransmissions, but it has the disadvantage that the rotor’s inertia needs to be synced up by the gear synchronizers during shifting. The electric engine must be actively synchronized each time the corresponding subtransmission shifts gears. To avoid that, on this kind of hybrid, the electric engine can be disconnected from the subtransmission and connected to the transmission output as a P3 hybrid. This takes place by way of an additional gear shaft with a shifting mechanism. Compared to the P2 hybrid, this combined P2.5/P3 hybrid, with total torque of 350 Nm, is 50 mm shorter than a six-speed, P2 hybrid.

FOR FULL HYBRIDS, A POWER-ON-DEMAND ACTUATOR IS THE MOST IMPORTANT PREREQUISITE FOR OPERATING THE TRANSMISSION INDEPENDENTLY OF THE INTERNAL COMBUSTION ENGINE

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Fig. 4: Combined P2.5/P3 hybrid (also feasible as 48 V version)
CUSTOM-MADE FEV BENCHMARKING NOW MINIMIZES COSTS EVEN FOR HYBRID TRANSMISSIONS

FEV continues to maintain a global leadership position in benchmarking of transmissions. In the early years FEV’s transmission benchmarking was focused on 5-6 speed planetary automatic transmissions and first generation dual clutch transmissions. In 2004, FEV added hybrid transmissions to its benchmarking portfolio. With such transmissions, the propulsion sources were no longer exclusively in front of the transmission, but also incorporated within the transmission – a factor that made novel approaches to the determination of efficiency necessary. With the growing number of conventional and hybrid benchmark projects that encompassed all variants available globally, the results of these projects were used to define FEV scatterbands, representing the state-of-the-art for metrics such as spin losses and loaded efficiency. In 2008, FEV created a standardized level-based benchmarking structure that was enhanced over subsequent years. Over the years, FEV has developed universal transmission control units (UTCU) to enable operation of complex transmissions on test rigs. More than a decade ago, FEV equipped its transmission and powertrain test cells with battery emulation systems and since 2017, FEV has added capabilities to bypass the OEM inverter controls and directly drive electric motors benchmarking hybrid transmissions and electric driveline components. Where necessary, FEV has capabilities to reverse engineer OEM hybrid/EV controllers to test the electric machines and gain insight into the efficiency of the power electronics. In 2018, the standardized transmission benchmark series was updated to cover conventional, hybrid, and electric powertrains enabling customers to evaluate items such as shift quality, strategy, and efficiency-level data on transmissions new to the market in a cost-efficient manner.
The presence of electric machines in hybrid transmissions necessitates development of new methods for benchmarking such transmissions. Regardless of the hybrid transmission type (e.g., parallel vs. power-split) or the architecture (e.g., P0 – P4) and number of electric machines in the drivetrain, various strategies to define representative test points must be taken into consideration. Thus, the test point definition moves away from conventional items such as load, input speed, and gear ratio and shifts toward the consideration of various power flow strategies. Accordingly, not only are the efficiencies of the various gears compared, but there is also an assessment of the hybrid operating strategy related to specific driving maneuvers, e.g., EV mode, power-splitting, load point shifting, generator mode, recharging strategies, and the selection criteria in the use of specific modes.

Of utmost importance for the gain in overall efficiency using the electric components is energy regeneration which, in the FEV benchmarking process, is assessed with regard to the utilization of the kinetic energy potential and the proportion of regenerated energy – in relation to the overall cost.

From a drivability perspective, additional focus has been added on understanding the use of electric machines for automatic engine starts, launch behavior enhancement, and shift quality improvement, bearing in mind the influence of items such as SOC of the HV battery.

At the component level, the thermal management strategy and its impact on performance and drivability, are also assessed. A general consideration of the system with regard to efficiency, costs, performance, NVH, and drivability form the overall impression of a vehicle to the customer. Overall, FEV has operating data from testing on approximately 70 different conventional transmissions and upwards of 40 hybrid/EV variants. This data is stored centrally in a database and is available for the creation of FEV scatterbands that allow for specific comparisons.

Standardization of the Benchmarking Program

FEV offers a level-based benchmarking process to our customers. As an example, Level 0 is related to creation of “features and specification” documents where relevant information is gathered from publications and distilled to align with the focus of specific customers. These documents typically include research on components/subcomponents and highlight their influence on the system performance.

In “Level 1” a basic level of standardized instrumentation is included to provide a cost-effective vehicle assessment in a relatively short time, focusing on high-level attributes such as fuel consumption during legislative and real-world cycles, performance, and shift quality. In “Level 2” the instrumentation from Level 1 is enhanced to include more details such that customer-specific areas of focus can be addressed. Examples of details in Level 2 include vehicle-level loss analysis, energy management, and overall operating strategies under a variety of driving maneuvers. The use of personnel with long-term
experience in such measurements is critical to ensuring that the right level of detail can be included in the instrumentation plan so that results with appropriate level of accuracy can be obtained. The information obtained in Level 2 can be compared to relevant scatterbands from FEV’s database so that appropriate conclusions can be drawn. In “Level 3” FEV focuses on component-level evaluations. Such tests can be at the transmission or electric motor levels on corresponding test rigs, but can also include sub-systems such as oil pumps. Further, the component-level investigations can include “strip-friction” type measurements where the contribution of individual sub-components are documented relative to the overall system quantifying their share of the overall parasitic losses. All the information gathered in Level 2 is utilized to ensure that the component-level tests are conducted with vehicle-representative control strategies and boundary conditions (such as temperature, system pressures, etc.) to provide the most representative measurement results. As market innovations happen, FEV’s benchmarking processes...
continuously evolve to develop appropriate techniques and methodologies. As an example, FEV has developed component test benches with capabilities to drive electromechanical actuators with our own BLDC motor control units, so that clutch and shift controls can be evaluated. FEV is able to align our standardized benchmarking process and test protocols to meet our customers’ goals with maximized efficiency in a cost-effective manner.

Innovations in External Transmission Measurement – UTCU

With the increasing interconnectedness of powertrain components, it has become significantly harder to operate transmissions in isolation on component test benches. Vehicle immobilizers, complex counters, and the rise of encrypted and/or exclusive communication bus systems have complicated or suppressed the use of the simple CAN bus. The workaround of using cable harness extensions and restbus, sensor, and actuator simulations to “trick” the TCU into thinking it is in the vehicle, is disproportionately time-consuming and expensive – and, does not always achieve the intended objective. To combat this challenge, FEV has continued to develop innovative approaches. As an example, beginning in 2014 FEV developed a new overall process that ensures that the transmission on the test bench experiences exactly the same conditions and controls as in the vehicle. Part of this process is the development of the UTCU (Universal Transmission Control Unit). Its core is a rapid prototyping control unit, to which an electronic module was added for issuing control signals. In some ways, the UTCU takes the place of the original TCU and completely replicates its control signals. CAN bus communication with the test bench can enable automated 24/7 operation on our test benches, so that a measurement with several thousand load and rotational speed points can be completed in the most time and cost-efficient manner. The UTCU has modular software in which the controls for almost all transmission types can be stored. The UTCU can be utilized either as the sole control unit or also as a subordinate actuator within a given drivetrain.

The modular approach allows not only the operation of classic solenoid actuator systems with PWM and associated carrier frequencies, but also that of BLDC actuator systems, which are used in modern transmissions.

Specialized Instrumentation

Another pillar of FEV’s global benchmarking expertise is the creativity to develop and use specialized instrumentation to meet specific project goals. FEV routinely employs torque sensors at various points in the driveline, e.g., flexplates, driveshafts, in addition to pressure measurements in clutch circuits, non-intrusive solenoid monitoring sensors (to avoid controller
faults), and 3-phase power measurements in relevant portions of electrified drive-trains. Since standard instrumentation calibration approaches don’t always offer the required measurement precision, where relevant, FEV uses calibration processes that take load and temperature dependency into account, and minimize uncertainties in the measurement chain to prevent implausible measurement results.

FEV defines a set of transducers that is consistent with the goals of a given project and associated measurement situations. In addition to the use of suitable data acquisition tools, the measurement data is processed to yield the required information depending on the required measurement scenario, online or via post-processing. The application of this determination process guarantees the use of a measurement setup that fully meets the precision requirements while avoiding unnecessary, expensive precision measurement technology that may not be absolutely necessary for achieving the defined precision required for a given project.

**FEV Benchmark Series**

In 2018, FEV will implement a standardized transmission benchmark series in which conventional automated transmissions as well as CVT and hybrid or DHT transmissions will be examined. The goal is to determine the efficiency and drag losses (under appropriate boundary conditions), operating strategy,
shift quality and evaluation of unique and special characteristics/features (as appropriate). FEV is working to convert the detailed benchmarking services for advanced transmissions to standardized work plans, with the goal of offering our customers significant added value compared to conventional transmission benchmarking for a moderate additional price.

The program includes vehicle and test bench based measurements. For vehicle measurements, the shift quality is determined objectively and a tool-based measurement of the shift strategy is performed. In addition, the information required to optimize the UTCU is entered automatically to enable operations for test bench measurements relating to drag torque and loaded efficiency. The results are presented on an absolute basis as well as in the context of scatterbands from FEV’s global database.

**Fig. 4: V-P2: Vehicle Instrumentation**

**Torque Instrumentation BSG shaft**

**BSG SHAFT INSTRUMENTATION WITH STRAIN GAUGE**

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**Benchmarking**
HOLISTIC CALIBRATION: FEV OFFERS COST BENEFITS BY SOLUTIONS FROM A SINGLE SOURCE

As the technical complexity of modern electrified powertrains is increasing significantly, the effort for systems engineering, function development, system calibration, and system validation will increase. For the specification of the system requirement FEV has developed a structured approach of system analysis and controller design that helps to identify system requirement parameters and reduces the time and associated costs for function development and calibration.
The powertrain calibration engineer must have deep systems knowledge to be able to calibrate modern electrified propulsion systems. FEV has qualified resources to develop and calibrate these kinds of modern powertrains with over 1,000 experts possessing "e"-powertrain know-how & the mindset to work in interdisciplinary teams to bring these "e"-powertrain to the streets. All powertrain application activities are integrated within FEV's vehicle application centers, in which all vehicle-related activities and departments work together.

Effective Transmission Calibration Process, Tools and Methods

The complexity of modern control units, the increasing diversity of powertrain applications and the need for shortened development cycles require novel approaches towards powertrain calibration. A model-based calibration process to transfer major parts of the calibration activities from the vehicle to the calibrator's desktop is an answer to these contemporary challenges.

Against this background FEV has developed tools and processes for efficient powertrain calibration. Typical tools and processes that are used by FEV in the field of transmission calibration are:

- For efficient driving mode calibration FEV developed the TOPEXPERT Transmission Calibration Expert toolset (TraCE). This calibration tool is used for calibrating accelerator pedal maps, shift lines, variograms, driving resistance and e-powertrain functions such as load-point shifting, boost, sailing and regeneration operation. This model-based calibration tool reduces the required time for transmission control function calibration significantly and increases the calibration robustness.
- To increase the vehicle testing and calibration efficiency, FEV has developed the TOPEXPERT Vehicle Test Automator (VTA), a unique solution that’s able to transfer the automation approaches from the test bed environment to vehicle calibration.
- A requirement-based parameter management system is used for effective handling of calibration datasets in projects with numerous vehicle variants. This tool is based on physical system dependencies. Depending on these physical dependencies the transmission control unit (TCU) parameters are assigned to powertrain components. If a calibration parameter that is assigned to a component needs to be changed the change will be valid for all vehicle variants which are assigned to this particular component. At every calibration release the calibration maturity will be compared to the agreed program targets.
- FEVcal makes the powerful Design of Experiment (DoE) technique easily applicable for a calibration engineer. The state-of-the-art global modeling techniques based on Gaussian processes have been adapted to also address the specific characteristics of transmission and powertrain modeling.
Transmission Calibration Process

The combination of above mentioned processes and tools allows FEV to deliver a high quality dataset for all possible applications and variants. FEV has the experience from numerous projects with AT, CVT, AMT, DCT, modular hybrid, DHT and EDU transmissions to handle multi-variant production transmission calibration projects. Therefore, FEV has developed an in-house calibration process that allows a secure and reliable project management. Main features of the calibration process are:

- Clear change management of calibration parameters based on a web server to enable project traceability and risk management that’s completely transparent to our clients.
- Defined maturity levels for datasets to track the actual status of calibration level of TCU functionality and the overall calibration.
- Easy adaptation to customers processes to support the needs of different customers.
- With this level of organization FEV has the capability to take over production calibration projects with turnkey responsibility including project management, supplier handling, homologation support and after production assistance.

Transmission Calibration by Design of Experience

One of the developed methods for efficient shift quality calibration is based on the Design of Experiment approach (DoE). Shift quality calibration means, regulating the clutch torque capacity control and engine control parameters to ensure a comfortable shifting behavior in every driving situation with respect to the customer-defined requirements. The DoE approach is used to predict the shift quality of the system, based on calibration parameters. The shift quality is characterized by various objective physical metrics from FEV’s objectification toolbox (FEVos). Examples of such metrics are the Vibration Dose Value (VDV) and the Low Frequency Percentage (LFP). The clustered calibration parameters, which form the input for the creation of DoE measurement plans and for the DoE model in the TOPEXPERT Tool FEVcal, are restricted within certain boundaries in the operating range of the system. These calibration parameters are then optimized based on the DoE model outputs which describe the shift quality objective ratings.

Finally, the optimized calibration parameters are tested at the vehicle level to validate the results of the shift quality calibration with subjective and objective ratings.

For several production applications FEV has optimized “problem areas” using the DOE method. An example of results from a 6-speed production automatic transmission calibration program is shown below.

In this example the shift quality improvement was also confirmed via subjective evaluation by an experienced calibration engineer. The calibration test runs are performed by the TOPEXPERT VTA tool.

Vehicle Test Automator for Efficient Transmission Calibration

To increase the vehicle testing and calibration efficiency, FEV has developed the TOPEXPERT Vehicle Test Automator (VTA), a unique solution to be able to transfer automation approaches from the test bed environment to vehicle calibration. It allows the calibration engineer to plan experiments at the desk using a comfortable graphical workflow editor. With libraries of calibration-specific blocks and the open environment for custom evaluation algorithms, VTA provides a platform to easily document, transfer and standardize calibration expertise. On this basis the use of model-based calibration approaches can be expanded to vehicle calibration. The generated test descriptions can be executed in the vehicle, either guiding the calibration engineer through the maneuvers or completely taking over vehicle control and to collect appropriate data in a structured way.

For transmission calibration and validation FEV has developed rating sheet workflows which will guide the driver through the maneuvers. After the VTA run is started the calibration engineer will be guided by the tool through graphical interfaces. The calibration engineer can monitor the important signals and will be guided through the defined set of maneuvers. If the maneuver is driven successfully VTA will save the recording. The recording...
will only be saved when all pre-defined boundary conditions are fulfilled (e.g., vehicle has to be stationary, accelerator pedal position within a bandwidth, air conditioning must be switched off, engine must be running, etc.), otherwise the recording will be rejected and the tool will ask the driver to repeat the maneuver. Accordingly, the tool collects data from only those maneuvers which are performed in a right way which makes offline analysis and dataset improvements highly efficient. At the end of the procedure the tool will request the calibration engineer to provide a subjective rating value to the maneuver. All important data will be stored in the measurement file comment or the measurement file name to make the documentation complete.

Drivability Improvements With Electrified Powertrain

To be able to use the advantages of modern electrified powertrains with increasing technical complexity the engineer will be challenged to find smart solutions. FEV has experienced system engineers to develop electrified powertrain concepts and use the advantages of these systems. For example, a dedicated hybrid transmission in combination with a P4 system can improve the shift quality by providing torque support during the shift by the electric machine in the transmission and by the electric machine at the rear axle. At the inertia phase of the shift the belt starter generator (BSG) can regenerate energy by compensating the internal combustion engine (ICE) inertia torque. To achieve the optimum shift quality all the sub-systems needs to be controlled and calibrated by considering the whole system.

To be able to calibrate these modern electrified powertrains FEV has developed an efficient calibration process in combination with smart tools and methods to achieve optimum energy management, fuel economy, emissions, NVH, and drivability.

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Power on up Shift Support

![Power on up Shift Support Diagram]

Drivability Improvements With Electrified Powertrain

![Drivability Improvements With Electrified Powertrain Diagram]
The transportation of goods, a key element of economic development, enables trade between producers, wholesalers, retailers and customers. However, for instance because of its emissions it causes global challenges that call for solutions. One adequate approach is the fuel cell range extender which is explained in more detail in the following.
Transport services will rise at even higher rates than the growth in population, especially due to increasing e-commerce, as seen in Figure 1. The growth of commercial vehicles (CV) is also differentiated by specific markets. These trends are major obstacles to achieve the required reduction of global greenhouse gas emissions (GHG), a mandatory reduction to meet and keep the UN target limit of 2 °C in global warming. Local air pollution by transportation in densely populated urban areas is another driver towards zero emission technologies. Therefore, battery electric commercial vehicle powertrains, preferably those in combination with regenerative production of the electric energy, are strongly promoted. As stated by the United Nations, "electric drive vehicles [...] need to represent 35 percent of global sales in 2030".

In the light duty segment, e.g. postal and courier parcel distribution, the transportation of goods by battery electric vehicles (BEV) has already become reality. This trend is expected to penetrate into the larger vehicle segments, reinforced by prohibitive legislation in urban areas. Currently, the first field tests with battery electric medium and heavy duty trucks are ongoing. Of course, this transition will only be possible if cost efficient coverage of daily changing transportation tasks is maintained. This requires flexibility, which may not allow a strict limitation in range due to battery size for larger vehicles. Shift operation is especially difficult to realize with a battery electric powertrain, as known from material handling applications.

Considering today’s battery electric passenger car market, the number of announced BEVs worldwide will amount to 300 vehicles in nearly all segments by 2025. While most of the currently available BEVs enable driving ranges of about 250 km, the next generation will be equipped with larger batteries with a range of more than 500 km. This range seems to be a good compromise between customer expectations, battery cost, volume and weight. For lithium-ion batteries, energy related costs of roughly 100 €/kWh and energy densities up to 300 Wh/kg are expected. The range of the vehicle is defined by the battery size, energy consumption of the propulsion system, and the accessory loads of the low-voltage electrical systems. Depending on the equipment of the car, including electronic devices for safety and comfort reasons, the power consumption can increase up to several kW peak power and an average power of about 500 W. For BEVs, auxiliaries such as heating or air-conditioning devices are powered by electric energy, which also reduce the real world driving range. The energy consumption for propulsion is strongly influenced by the weight of the vehicle. Analyzing current vehicles in the NEDC driving cycle, the power consumption is roughly 750 Wh per 100 kg weight and 100 km driving range. Using this simplified value, a 1.5 ton vehicle needs 60 kWh usable energy to achieve a NEDC range of 500 km, as seen in Figure 3. This leads to a nominal energy content of approximately 65 kWh. The weight of such a battery pack will increase the vehicle weight by roughly 200 kg. To carry this
additional weight, the battery size must be increased by 20 percent again, if it cannot be compensated by weight reduction of other vehicle components. Upcoming battery electric trucks provide a range between 100 and 200 km. Exemplary data from a distribution truck fleet in the Cologne-Aachen area over a selected timeframe of 10 days, reveals that approximately 50 percent of all day trips are within the range of up to 120 km.
It can be noted that the pure electrically driven truck, which is part of the fleet, was used only for shorter trips. In order to substitute conventionally powered vehicles in distribution truck fleets with BEVs, electric ranges higher than 200 km are needed. As an example, a commercial vehicle with a maximum gross vehicle weight of 7.5 tons or more and a range of 500 km is considered. The battery causes additional weight or loss of payload of more than 1 ton, and additional costs of more than 30,000 €, as seen in Figure 3.

In order to increase flexibility of these vehicles, fuel cell range extenders can be applied instead of increasing battery capacity. Proton-exchange membrane (PEM) fuel cells can be operated with hydrogen and the hydrogen tank can be refueled within a few minutes. During operation, only water is emitted.

The battery capacity and the fuel cell range extender power can be tailored for the main use case to reduce investment cost and total cost of ownership. The battery costs are dependent on the capacity and finally on the battery electric range. The fuel cell costs depend on the power demand, and in cases when it’s used as a range extender, costs depend on the average power demand of the vehicle. Because of that, applications for urban use and distribution tasks are suitable fuel cell range extender applications. Use cases such as a delivery vehicle, a distribution truck or a city bus have a low average power demand compared to required peak power due to many downtimes and lower average speeds. In addition, a light duty CV for the discussed use cases has a lower maximum speed requirement. Currently, FEV is developing a scalable fuel cell system for its customer, ElringKlinger. The fuel cell system is equipped with an ElringKlinger NM series fuel cell stack. The fuel cell stack and its system can be scaled for different CV applications between 5 to 100 kW of electric power. The fuel cell system can be adapted for different CV applications ranging from light duty commercial vehicles to trucks and busses.

**Fig. 3: Battery mass for 200 and 500 km battery electric range for different applications**

![Battery mass for 200 and 500 km battery electric range for different applications](image-url)

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ALMOST CO₂-NEUTRAL MOBILITY BY OPTIMIZED E-FUELS MIX

Using power to x, synthetic fuels can be produced from hydrogen and carbon. Ideally, the hydrogen is produced by means of electrolysis using renewable electricity. CO₂ taken from the atmosphere or organic matter should be the source of carbon. Using these kinds of fuels in internal combustion engines would achieve virtually CO₂-neutral mobility [1,2]. Because of their optimized molecular structure, they also offer a means of reducing exhaust emissions. However, to achieve a quick reduction in the amount of CO₂ emitted by the transportation sector, these alternative fuels would need to be compatible with the existing vehicle fleet and infrastructure. Oxymethylene ethers are incompatible with some materials, making fuels, methane and dimethyl ether gases only partially suitable. Fischer-Tropsch (FT) products are very similar to fossil fuels and can be added to them without any problems [3].
Today's FT processes are designed to yield as many long-chain, saturated hydrocarbons as possible. Alkanes and alkenes with medium-length chains could also be obtained using a high-temperature Fischer-Tropsch (HTFT) process. Adding a hydroformylation process to the end of production makes it possible to create new types of composite fuels (alkane/alcohol mixtures) using robust and easy-to-control technologies. Before a synthesizing plant begins operation, it cannot be predicted what the exact composition of the product will be because the alkanes and alcohols of differing chain lengths are formed only with the likelihood of polymerization. To cover the broad range of possible fuels, two extreme fuel mixtures consisting of C7 to C12 alkanes and C6 to C8 alcohols were chosen for engine testing.

The first fuel defined, hereafter referred to as “Fischer-Tropsch Fuel 1” (FTF1), represents a non-reactive fuel with a rather short chain and a very high concentration of alcohol at 40 percent m/m. By contrast, FTF2 creates a highly reactive fuel with a low concentration of alcohol at 10 percent m/m and longer molecules. In addition to these two FT alcohol fuels, we examined blends with fossil diesel fuel, with the concentration of FT alcohol fuels in each being 20 percent (with FTF1, referred to below as “Blend1” and referred to as “Blend2” when combined with FTF2).

Challenges for Engine Control

Despite the similarity of these fuels to fossil diesel fuel, there are some major differences in their combustion characteristics especially when an engine controller is used based on an engine map (Fig. 1). The combustibility of FTF2 is clearly seen in a very short ignition delay. By using EGR, the difference further increases to as much as 10° compared to diesel. Blend2 also shows this tendency.

Engine control systems based purely on engine mapping cannot exploit the full potential of e-fuels. Even customized calibration of the engine maps for a specific number of predefined fuels is not helpful because of their diversity, which results from the production process and mixture rate. Therefore, out of necessity, we use a control system that enables us to maintain the desired form of combustion regardless of the fuel being used.

![Fig. 1: Comparison between fuels for reference injection (Rotational speed: 1,500 1/min., PMI: 6.8 bar)](image-url)
A new type of control system based on an approach called “digital combustion rate shaping” (DiCoRS) may provide a solution. Especially in light of the unpredictable fuel compositions, this approach continues to guarantee reliable control of all target values without the need to know the fuel composition, neither during initial engine calibration or during subsequent vehicle operation.

The key difference between DiCoRS and conventional control systems built into engines is the control variable they use. Unlike a combustion-phased or PMI controller, no optimization of previously calibrated injection processes is performed in order to control individual parameters. Instead, DiCoRS controls combustion at a completely predefined crankshaft angle. This means that DiCoRS takes advantage of the maximum degree of freedom of combustion control.

From this operating condition-based standard of optimum combustion, a pre-control algorithm automatically calculates the proper injection rate necessary, including the number of injections, the electric trigger times, and the amounts to be injected. At this point, it should be noted that this approach causes a shift in conventional engine calibration from defining the process of injection to specification of an ideal process of combustion. At the same time, the time and effort required for calibration is reduced drastically and the desired thermodynamic optimum is achieved more reliably [4].

### Experimental Results

The engine testing impressively demonstrates that the control algorithm developed can control acceptable combustion with a wide variety of fuel mixtures, even without calibration for varying fuel specifications. Through the use of DiCoRS, it is also possible for the first time to compare different fuels at a fixed, constant rate of combustion. This enables statements to be made about fuel emissions that are virtually independent of the form or phase of combustion.

Figure 2 shows an excerpt of the test results. At all EGR rates, the target progressions of the burn rate were easily achieved.

---

#### Table 1: Properties of FTF1 fuels tested

<table>
<thead>
<tr>
<th>Material</th>
<th>Molecular formula</th>
<th>Mass percent</th>
<th>Density @ 25°C/kg/m³</th>
<th>Lower heat value /MJ/kg</th>
<th>c/h/o /-</th>
<th>Kin. viscosity @ 25°C/mm²/s</th>
<th>Boiling range /°C</th>
<th>Cetane rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTF1</td>
<td>C_{17.58}H_{32.04}O_{3.87}</td>
<td>0.18/0.82</td>
<td>808</td>
<td>42.9</td>
<td>0.86/0.13/0.01</td>
<td>2.92</td>
<td>172.0-360.8</td>
<td>57.4</td>
</tr>
<tr>
<td>Diesel</td>
<td>C_{13.8}H_{25.8}O_{0.08}</td>
<td>1</td>
<td>741</td>
<td>41.05</td>
<td>0.79/0.15/0.06</td>
<td>2.84</td>
<td>98.4-195.2</td>
<td>44.9</td>
</tr>
<tr>
<td>Blend1</td>
<td>C_{20.20}H_{20.20}O_{0.18}</td>
<td>1</td>
<td>742</td>
<td>43.31</td>
<td>0.84/0.15/0.01</td>
<td>2.59</td>
<td>174.2-245</td>
<td>63.6</td>
</tr>
</tbody>
</table>

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*Fig. 2: Comparison between fuels at three different EGR rates (rotational speed: 1,500 1/min., PMI: 6.8 bar)*
There is a clearly noticeable shift in the injection rates in accordance with the fuels’ combustibility. At this load point, the reduction in soot emissions is quite pronounced thanks to use of the FT alcohol fuels. With FTF1, there is a reduction of up to 80 percent, and with FTF2, the amount was lowered by as much as 50 percent compared to fossil diesel fuel (Fig. 3).

The particulate/NOx trade-off is illustrated in Fig. 4 for two load points. The alternative fuels shift the curve so that a more optimal solution can be reached. The strong advantage of soot can mainly be seen as higher EGR compatibility of the alternative fuels. In future calibration strategies, this could allow the EGR rate to be increased in order to reduce the NOx emissions, while still inside the engine.

## Summary

In this examination, we assessed the potential for creating innovative e-fuels based on the Fischer-Tropsch process and by adding hydroformylation to the end of production. There is large variation in fuel composition possible because of the production process. The use of such FT alcohol fuels thus enable the CO2 footprint to be reduced considerably by increasing the concentration of regenerative energies in the transportation sector using existing engine technology and infrastructure. Thanks to their optimized physical and chemical properties, it is also possible to further lower pollutant emissions, especially particulates and nitrogen oxides, at the same time.

Based on the results, a statement regarding the emissions potential of the fuels with the same rates of combustion and, thus, the same combustion noise levels through the use of the controller can be achieved.

With respect to the effectiveness of the DiCoRS approach to control, we achieved excellent quality across all fuels, load ranges and EGR rates. In each case, the controller was able to make adjustments for the specified target combustion rate. It is conceivable that the system may be expanded to include an external control loop to complete the integrated e-fuel control system. Additional injection pressure and EGR controllers could take optimal advantage of the demonstrated lowering of the particulate/NOx trade-off. Depending on the fuel mixture and associated potential to produce particulates, the injection pressure or even the EGR rate can be subsequently adjusted online as needed to find an ideal compromise.

**REFERENCES**


In order to increase the attractiveness of the electric mobility, neither the comfort nor the driving range of the vehicle may suffer under extreme ambient temperatures. Optimized thermal management helps to meet customer comfort requirements, while at the same time reduces energy demand [1]. In this article, the structure and the validation of a new developed simulation model are explained. Based on the model, measures to reduce the energy demand with regard to cabin temperature control are investigated. Finally, the results, as well as a summary of the energy saving potentials are presented.
The generated vehicle simulation model consists of several modular components, as depicted in Figure 1. Each of these objects represents a subsystem of the electric vehicle. With this model, it is possible to simulate different driving profiles, as well as ambient conditions. Thus, various thermal management measures can be assessed regarding their influence on system efficiency [2, 3]. For the validation of the simulation model, measurements were carried out on both, the component and system level.

![Fig. 1: Submodels of the CVSM](image)

Conducted Investigations

Various cabin measures are investigated regarding their energy saving potentials with the created simulation model. All simulations were conducted during the WLTP driving cycle for 30 minutes at an ambient temperature range from -20 to +20 °C. At the same time, the cabin is heated from the respective ambient temperature to an average cabin temperature of 20 °C and the total energy demand is determined. In addition, to the energy savings for a particular ambient temperature, the energy saving potential in annual means is calculated. Therefore, climatic data from Europe is used [4]. The results, which are referred to as Reference in the following, show the energy consumption of the electric vehicle when the cabin is heated up only with the PTC-air heater. Under these conditions, the vehicle has an energy demand of 31.4 kWh/100 km at an ambient temperature of -20 °C. This result is also used as a reference point for the calculation of the energy savings. Furthermore, the energy consumption of the vehicle without heating the cabin is shown in all diagrams. It is 22.2 kWh/100 km at an ambient temperature of -20 °C and is therefore, significantly below that of the heated vehicle, as seen in Figure 2. A promising approach for saving heat energy is a reduction of the fresh air rate in the air conditioning of the cabin. In contrast to fresh-air operation, a large proportion of the required heating energy can be saved in recirculation mode. At an ambient temperature of -20 °C, the total energy demand is reduced from 31.4 kWh/100 km to 27.9 kWh/100 km, which corresponds to a saving of 11.1 percent, as seen in Figure 2. Averaged over the year, this results in a saving of 3.1 percent. As a further measure to reduce heating energy demand during winter operation, radia-
tion surfaces are considered, as seen in Figure 3. Through the use of radiation heat surfaces, the air temperature inside the cabin can be lowered with a comparable sensation of comfort of the occupants. For the corresponding comfort tests, six electric radiation surfaces were installed in the driver and passenger foot wells (three on each side). In the simulation, the result of the previous measurements were confirmed. The energy demand at -20 °C can be reduced from 31.4 kWh/100 km to 30.1 kWh/100 km by the use of radiation surfaces. This corresponds to an improvement of 4.1 percent, as seen in Figure 2. Averaged over the year, an energy savings potential of 3.8 percent can be realized. The generated heat is sufficient to heat the cabin completely without the PTC-air heater from an ambient temperature of 10 °C or higher and without reducing the comfort for the occupants. In order to reduce the heating energy demand even further, targeted heating of the driver is chosen as another measure. The total energy demand at -20 °C can be reduced from 30.8 kWh/100 km or by 1.9 percent from 31.4 kWh/100 km, as noted in Figure 2. Averaged over the entire year, a savings of 0.5 percent is achieved.

**THROUGH THE USE OF RADIATION HEAT SURFACES, THE AIR TEMPERATURE INSIDE THE CABIN CAN BE LOWERED WITH A COMPARABLE SENSATION OF COMFORT OF THE OCCUPANTS**

By integrating a heat pump into the vehicle, the energy demand can be reduced additionally. With the heat pump, heat can be absorbed at lower temperature levels and discharged at higher temperature levels. The amount of heat emitted is thereby much higher than the work expended [5]. For an ambient temperature of -10 °C, the energy requirement can be reduced from 27.5 kWh/100 km to 23.7 kWh/100 km or by 13.8 percent, as depicted in Figure 2. The energy savings potential is reduced for rising ambient temperatures. The heat generated is not sufficient to heat the cabin to 20 °C at an ambient temperature of -20 °C due to the integrated compressor. For this reason, Figure 2 shows only the energy demand at ambient temperatures from -10 to +20 °C.

In addition, combinations of the individual measures were also considered, as noted in Figure 4. By combining the individual measures, the energy saving potential can be increased even further. The starting point for the comparison of the different combinations is the energy consumption of the vehicle in recirculation mode. Combination 1 describes the expansion of the recirculation mode with the use of radiation surfaces. The energy demand at an ambient temperature of -20 °C can be reduced from 31.4 to 27.1 kWh/100 km. This corresponds to a saving of 13.7 percent. The average energy consumption over the year can be reduced by 5.6 percent. If the system is extended by targeted heating of the driver (combination 2), 2.3 percent of the energy can additionally be saved at an ambient temperature of -20 °C. This results in an energy consumption of 26.4 kWh/100 km and thus a saving of 15.9 percent. For the targeted heating of the driver synergy, effects with other individual measures can be seen. Over the entire year, 6.4 percent of the required energy can be saved. Finally, combination 3, an expansion of combination 2 by a heat pump operation, is considered. The simulation shows that a total of 22.9 percent of the energy can be saved at an ambient temperature of -20 °C compared to reference operation. The energy demand is reduced from 31.4 kWh/100 km to 24.2 kWh/100 km. Averaged over the year, an energy savings of 7.2 percent can be determined. Using combination 3, the energy demand at -20 °C of 24.2 kWh/100 km is only 9.0 percent higher than that of the vehicle without cabin heating. Without any measures, the energy consumption with cabin heating was 41.4 percent higher than without, as seen in Figure 4.

![Simulated energy consumption of the individual measures investigated](image-url)
Summary and Conclusion

In this article, various measures for the cabin air-conditioning have been introduced using a vehicle simulation model that reduces the energy demand of the electric vehicle at low ambient temperatures. By combining the individual measures, the shown energy savings potential can be increased even further. Throughout the year, 7.2 percent of the total energy can be saved. This saved energy can be used to increase the range and thus directly contribute to an improvement in the acceptance of electric vehicles. Intelligent operating strategies for the individual components of the thermal management system could result in a significantly higher saving potential. These operating strategies and the use of the heat pump as a refrigerating machine at high ambient temperatures will therefore be the subject of further research.

A TOTAL OF 22.9 PERCENT OF THE ENERGY CAN BE SAVED AT AN AMBIENT TEMPERATURE OF -20 °C COMPARED TO REFERENCE OPERATION

REFERENCES


ELECTRIC TREATMENT FOR DIESEL ENGINES: FEV ECOBRID PROVIDES CLEAN AIR IN CITY TRAFFIC

Improving air quality while simultaneously reducing CO₂ emissions requires a significant modification to drive systems. In 2021, newly approved vehicles will need to reach 95 g/km of CO₂, and following this first milestone a further reduction of 15 percent per year is planned for 2025 to 2030. In order to achieve these goals, the electrification of the powertrain is critical. The hybridization on a 48 V basis, in this context, offers significant potential, while simultaneously avoiding extensive reconstruction.
The efforts of reducing greenhouse gas emissions results in stricter testing cycles for the determination of CO2 emissions. The expansion to real driving emissions (RDE) means a massive tightening of the requirements. In regards to the global efforts of CO2 reduction, it cannot be excluded that, in the future, other climate-relevant exhaust gas components, such as CH4 and N2O, will also be subject to regulation. The study of the CO2 norm shows that the required reductions cannot be achieved with the optimization of conventional powertrains alone, but that a change in technology is necessary. This means that, in addition to the introduction of electrically operated vehicles (Battery Electric Vehicle - BEV), conventional drives must also be electrified.

The EU market is characterized, among other things, by compact vehicles that offer various versions on one platform. The compact car segment (C-segment) covers the classic second vehicle with short-distance traffic on one hand, and serves as family vehicle on the other. In light of this background, the potential analysis for partially electrified drives was carried out with regard to:
- Lowest emissions; especially in urban operation
- CO2 reduction in real operation

The basis was a EU6b vehicle with CO2 emissions of 100 g/km in the NEDC. For modifications in light of the above-mentioned goals, a targeted adjustment of the technical package was carried out:

<table>
<thead>
<tr>
<th>Measure</th>
<th>Primary Function Funktiohn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opt. combustion methods (FIE, ETC, EGR, etc.)</td>
<td>CO2 + EU6d / EU6+</td>
</tr>
<tr>
<td>Opt. air system (VVA, eCompressor)</td>
<td>EU6d / EU6+</td>
</tr>
<tr>
<td>Opt. EA system (DeNOx)</td>
<td>EU6d / EU6+</td>
</tr>
<tr>
<td>48 V belt starter generator (BSG)</td>
<td>CO2</td>
</tr>
</tbody>
</table>
A matrix-based selection of the components was carried out with regard to these objectives. The powertrain configuration examined represents a pMHEV concept with a 48V BSG, meaning that a Diesel engine with improved functional characteristics was partially electrified in a P0 layout.

The core elements of engine optimization are the new 2,500-bar CR system and a newly specified exhaust turbocharger with variable turbine geometry (VTG). In addition to an eCompressor and cooled multiple exhaust gas recirculation (M-EGR), the new engine version also has a 48 V BSG. By way of an immediate torque increase, the eCompressor enables a reduction in emissions in highly dynamic cycles and an improvement in responsiveness. Two configurations were investigated for the exhaust aftertreatment system:

- **Topology A**: Combined DeNOx system with a nitrous oxide catalytic converter installed close to the engine, DPF, and underbody SCR unit.
- **Topology B**: Electrically heated catalytic converter (E-DOC) with SDPF installed close to the engine and active underbody SCR system (incl. 2nd dosing)

In light of stricter air quality requirements, there was a focus on the optimization of urban operation. Since the BEV is considered to be locally emission-free, the “almost emission-free” attribute must be formulated for conventional vehicles to maintain market acceptance.

With regard to CO₂ reduction, a target range of ≤115 g/km was defined for real operation, derived from:
- CO₂,Current: NEDC:100 ➤ CO₂,Current: WLTP:110 ➤ CO₂,Target, WLTP:~100 ➤ CO₂,Target, RDE: ≤115 g/km

The functional results were evaluated using RDE driving profiles from the extensive FEV database.

**Holistic Powertrain Optimization Approach**

The significantly increased complexity of a Diesel-hybrid powertrain requires a systematic optimization process that follows the flow shown in Figure 2.

At the start, the parameters of the operating strategy and the powertrain are reduced on a weighted basis, including catalytic converter volumes or temperature thresholds. This allows the system characteristics to be optimized simultaneously with the operating strategy.

A specific DoE approach is elaborated for each layout using these combinations. This leads to a statistical overall model and the identification of the key parameters. The optimizations are then evaluated and validated for benchmark driving cycles using FEV SimEx software, a virtual test environment for the powertrain which takes into consideration the EA system functionality. The model has a modular construction, so that layouts, cycles, and strategies are calculated flexibly and can then be used again for validation.

For implementation, a pMHEV concept with dual influence was selected through the targeted addition of electric components to the engine. The integration of the 48 V BSG was carried out to guarantee the following functions:
Engine support and phlegmatization
Start/stop functionality, especially combined with variable valve actuation
Recuperation and optimized battery management in combination with an e-catalytic converter

In addition to this step, the inclusion of the following is essential:
- eCompressor for:
  ▶ Accelerated charge pressure for attractive driving behavior
  ▶ Reduction of NOx and PM peaks
- E-catalytic converter in an EA version

For a hybrid concept, the operating strategy is key for potential maximization. When stationary, the torque distribution between the engine and the e-machine is determined based on the torque requirement at the transmission input, the engine or transmission rotational speed, and the state of charge (SOC) of the battery. For heavy loads, the BSG system helps to avoid high NOx emissions during operation. In case of a low SOC, additional sets of parameters determine the conditions under which load shifting is required. This field is limited by defined efficiency increases and the NOx increase. In transient operation, BSG is also in control for a moment to avoid engine exhaust soot and NOx emission peaks.

For the cold-start phase or at low speed, a dedicated heating strategy is selected that includes a more aggressive load switch-point and stronger transient support. This heating strategy is active until the EA system has reached an adequate conversion level. The operating strategy selection is carried out as a rule-based optimum between NOx emissions in low-load cycles and CO2 emissions in the overall cycle.

Operating Behavior

The achievement of challenging target values requires a systematic approach in the specification of the systems for the reduction of exhaust emissions. This is made possible by the application of an internal methodology with a high prediction share, such as FEV XiL. The use of virtualized routines enables the efficient management of high system complexities, while effort and expenses are reduced. At the start, requirements for emission-critical scenarios are identified and the scenarios are evaluated in a multi-dimensional DoE campaign. Then, the virtual system optimization geared toward robustness is carried out. Finally, the system behavior is validated extensively in a second DoE campaign.

The high performance of the selected technology components is evident in Figure 3. Since the variable heating performance represents a powerful degree of freedom, the e-catalytic converter version has an advantage in future requirements.

Vehicle acceptance is also determined by driving and comfort attributes. In this context, the combination of additional drive torque via the BSG and the "multiplier function" for the engine torque from the electric compressor can provide impressive values. Combined with the model-based control algorithms, advantages in CO2 values and emissions can also be obtained.

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**Strategy Setup**

<table>
<thead>
<tr>
<th>P/S</th>
<th>Hybrid Topology</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Operating Strategy</td>
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**Case Definition**

<table>
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<th>Feature 1</th>
<th>Feature 2</th>
<th>Feature 3</th>
<th>Feature 4</th>
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<td>✓</td>
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</table>

**Powertrain Optimization Approach**

**DoE**

- Cycle 1
  - Low + Mid

**Optimization**

- Low NOx
- Delta SOC

**Validation**

- Step 1
- Simulation
- Step 2
- Time

**Fig. 2: Optimization methodology**
FOR HEAVY LOADS, THE BSG SYSTEM HELPS TO AVOID HIGH NOx EMISSIONS DURING OPERATION

**FEV DEMONSTRATOR**
Even 48 V hybridization offers significant potential in emissions reduction. Multi-level DeNOx systems enable almost “zero NOx” emissions as soon as the catalytic converter start-up temperature is reached. The very low NOx emissions can be achieved with the selected combinations, but driving at a reduced speed remains the biggest challenge. Electrically heated catalytic converters offer a degree of freedom with additional reduction potential. A partially electrified diesel engine is, and will be in the future, an attractive drive concept, and makes a convincing argument against inner-city restrictions on the operation of vehicles with combustion engines.

By:
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LOW CONSUMPTION AND LESS POLLUTANTS: OPTIMIZATION POTENTIALS OF COMMERCIAL COMBUSTION ENGINES

As the global population continues to grow, the need for increased logistics, infrastructure and agricultural production do also. As a result, improving commercial diesel powertrain efficiency, and reducing its climate and emissions footprint has become a major topic of focus. Using typical commercial applications from the market, we will discuss efficiency enhancing and promising technologies.
Due to the sheer number of units, on-road applications contribute significantly more energy consumption, as well as pollutant emissions, compared to mobile machinery. Until 2040, commercial on-road vehicles are forecasted to increase energy consumption by 1.4 percent year-over-year. During this time, a majority of the transportation will be sourced by liquid fuels.

Increasing efficiency in basic engine development

Based on several projects and comprehensive studies conducted by FEV & FEV Consulting GmbH regarding powertrain development and optimization, researchers are working on developing current and future requirements for the base engine, which are summarized in Figure 1. Most optimization measures have been available on the market for some time and became established features for reducing fuel consumption. In the near future, we can expect new measures to be launched and others are being intensively researched.

“Downspeeding” and “downsizing” represent effective options for reducing fuel consumption through lowered friction. The goal is to shift the vehicle’s engine operating point close to the optimal Brake Specific Fuel Consumption (BSFC) area in the engine performance map. The average fuel consumption improvement potential is near 2-3 percent. As an alternative approach, FEV investigated the influence of the cylinder swept volume and the number of cylinders, keeping the engine displacement constant. Based on this, different medium-duty (MD) and heavy-duty (HD) six-cylinder inline engines were analyzed and then transferred to four cylinder engines with more than 2 L/cylinder. In addition to weight and package advantages, fuel savings of 3 percent are possible (Figure 2).

Several other known and established measures can also be applied. For example, cranktrain optimization involves adjusting the crankshaft bearing and journal dimensions, with a potential fuel savings of up to 3 percent. Additionally, advanced coatings can be applied. Reducing the parasitic losses from demand-controlled oil and water pumps, controllable thermostats and switchable piston cooling jets (PCJ), can generate additional improvements of nearly 2 percent. Optimized air path and further increase of the boost pressure using a high efficient turbocharger.

“DOWNSPEDING” AND “DOWNSIZING” REPRESENT EFFECTIVE OPTIONS FOR REDUCING FUEL CONSUMPTION THROUGH LOWERED FRICTION

![Fig. 1: Improvement potential in fuel consumption compared to additional engine costs](image-url)

Specific Fuel Consumption (BSFC) area in the engine performance map. The average fuel consumption improvement potential is near 2-3 percent. As an alternative approach, FEV investigated the influence of the cylinder swept volume and the number of cylinders, keeping the engine displacement constant. Based on this, different medium-duty (MD) and heavy-duty (HD) six-cylinder inline engines were analyzed and two-stage charging are also applied. In regards to thermal management, a variable valve train system with a cam phaser on the outlet side has the potential to raise the exhaust temperature, and improve Diesel Particle Filter (DPF) regeneration and warm-up time. Such advantages were verified specially on delivery trucks and off-road machines under, low ambient temperatures and low engine loads.
downstream the EATS. EATS are necessary in determining the exhaust gas temperature and mass flow. In order to not negatively influence the emission reduction, the ORC is placed after the exhaust after treatment system (EATS). Therefore, the simulation of the heat losses between the turbocharger and the EATS are necessary in determining the exhaust gas temperature downstream the EATS.

In addition to the engine-internal measures, the further use of the exhaust gas energy represents an additional potential for the improvement of overall vehicle efficiency and therefore, fuel consumption.

Organic Rankine Cycle (ORC) is the most promising technology for waste heat recovery in commercial vehicles because it has the highest power output in comparison to other technologies. In an ORC, a fluid is condensed isobaric, compressed isentropic, evaporated isobaric and expanded isentropic to convert heat into work. Because of their low boiling points, organic fluids are best suited for medium heat sources, as is the case for exhaust gases from internal combustion engines. One of the major challenges for mobile applications are packaging and added cooling demand.

Pre-analysis, based on computational simulation, is a prerequisite for the specific concept decision and integration of such an application. Therefore, FEV developed a holistic investigation and simulation platform, based on established software products. The vehicle model generates the speed and torque information to define the load points out of the engine performance map. These are generated with a physical and scalable engine model, which simulates the combustion process and the according losses. The ORC model is then fed with information about the exhaust gas temperature and mass flow. In order to not negatively influence the emission reduction, the ORC is placed after the exhaust after treatment system (EATS). Therefore, the simulation of the heat losses between the turbocharger and the EATS are necessary in determining the exhaust gas temperature downstream the EATS.

To evaluate the fuel savings potential for the ORC system which includes, a piston expander, and ethanol, the simulations were performed on a 40-ton on-road HD truck with an 11l, 345kW Diesel engine. The Long Haul cycle, which is an upcoming CO₂ certification cycle for HD trucks in the EU, is the basis for the transient simulations. The net power output – expander output reduced by the power needed to drive the ORC pump – was used to determine system performance. The maximum net power output was nearly 14 kW, with an average of 4.46 kW. The ORC had its highest impact on the fuel consumption mainly at high load points during the second half of the cycle, resulting in a simulated fuel consumption reduction of 3.8 percent.

### Waste Heat Recovery Through Organic Rankine Cycle

As we know from passenger car powertrains, the benefit of hybridization or electrification lies in the possible recuperation of mechanical work and the use of regenerative energy sources to charge electric energy storage systems. At the same time, depending on the topology of the powertrain and its application, the corresponding potential can be leveraged by optimizing the configuration of different energy storage systems and drive sources.

For example, Figure 4 presents the results from a study conducted with a 40-ton semi-trailer. In terms of hybrid concepts, the “mild hybrid” concept was examined first. This concept enabled extended start-stop operation with support from the combustion engine in transient operations. “Full hybrid” concepts were also examined, which allowed for maximum recuperation of braking energy and, on top of that, facilitated all-electric driving. This means a correspondingly strong electric machine with roughly 200kW output will be required. The storage size of the electric battery has to be designed based on the desired driving distance. The “Full Hybrid II,” for example, can travel 20 km, or nearly 12.5 miles, on electric power. As shown below, a moderate improvement in fuel consumption of 1-3 percent in the Mild or Full-Hybrid I can be achieved, while improvements of up to 18 percent are possible for short-distance city driving. However, in comparison, emissions disadvantages in the “Full Hybrid I”, due to the cooling down of the exhaust system, have been found. The use of such concepts in long-distance HD trucks is not particularly economically feasible due to the cost and net-weight load capacity disadvantages caused by the high voltage system, the battery package and its overall weight. However, this depends largely on the cost trends in electric systems and the economy of scale.

Taking a serial hybrid concept into account, the energy savings potential is dependent on the load profile/driving distance and primary energy source of about 20 percent (Well-to-Wheel). This compared to base combustion engines was calculated at 100 km/day, power mix.

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**Fig. 2: Influence of the cylinder swept volume while retaining the engine displacement. MD commercial vehicle is used as an example**
Summary and Outlook

Based on worldwide scientific and business researches, it is clearly forecasted that internal combustion engines – specifically the diesel engines – will play a major role in the sustainable economic and society development in the future. Therefore, it is mandatory to continue to develop advanced powertrain system technologies and drive concepts, which include internal combustion engines, in parallel with electrification. Technology measures reducing engine friction and parasitic losses have been discussed and have been already widely introduced in modern powertrains by many manufacturers. Therefore, this paper highlights two technology measures, WHR and electric hybridization, which shows major potential when integrated in the complete powertrains. Figure 5 provides an overview and outlook for the technologies discussed in this paper.

By:
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The introduction of stricter particulate number (PN) limits in Europe and China is complemented by the measurement of Real Driving Emissions (RDE) on public roads at arbitrary boundary conditions. This creates a challenge to meet the PN limits and a clear trend for all OEMs to apply GPF systems in order to comply with current and future RDE legislations.

Up until now, automotive manufacturers have been able to meet the EU6d-TEMP PN limits for standardized driving cycles, such as the NEDC with the Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP) without having to depend on a GPF. The left side of Figure 1 supports this statement, showing PN emissions of approximately $3 \times 10^{11} \text{1/km}$ without a GPF for a J-class vehicle with a turbo DI gasoline engine in a WLTC test. The implementation of a GPF with an efficiency of around 75 percent leads to a further significant PN reduction.

The right hand side of Figure 1 shows influences that are valid under RDE conditions, which can lead to substantially higher particulate emissions compared to nominal WLTP conditions. The first factor shown, is the decrease in the share of the ethanol content in the fuel, e.g. from 10 vol-percent (EU6 fuel respectively “nom. Cond.”) to 0 vol-percent (EU6 worst-case fuel), which is caused by the reduction of the fuel’s oxygen share. Secondly, and also a fuel-related topic, a strong knock resistance of high aromatic content comes with a high particulate formation potential. A payload increase, caused by luggage and/or passengers, leads to engine operation with higher speeds and loads, which further increases the PN output (dark blue bar). Moreover, a sporty or aggressive driving style causes increased particulate numbers, especially when combined with the other illustrated influences. [1]

Considering these multiple aspects and all their possible combinations, the extensive integration of GPFs will become mandatory. Consequently, a need to develop suitable tools and methods becomes important, which enables the consideration of all GPF impacts and interactions in an early development phase. The following article discusses the simulation-supported RDE testing and highlights the current GPF hardware trends and calibration subtasks for ultra-low temperatures. It concludes with results of an accelerated GPF ash loading procedure.

Fig. 1: PN emissions with and without GPF
THE FEV WORSE-CASE RDE SIMULATION ENABLES AN EVALUATION OF THE FULL RANGE OF BOUNDARY CONDITIONS
Simulation-Supported RDE Testing

Often, the investigation of all influencing boundary conditions for the determination of RDE values requires consideration of several cycles and driving scenarios. If a large number of different cycles need to be tested, this leads to cost and time issues. Figure 2 shows the main RDE boundary conditions and a comparison of the WLTC chassis dyno cycle with an on-road RDE test (conducted on the FEV Aachen RDE track). In addition, a simulation-supported, tailor-made worst-case RDE driving scenario, conducted on a chassis dyno, is depicted. The on-road Aachen RDE test is compliant with the law and covers sections in an average mountain range. The best-case condition of each criterion is marked by the center of the diagram, whereas the worst-case condition is marked by the outer border.

As seen in Figure 2, the WLTP covers quite severe speed conditions, and medium v* apos and vehicle weight values. The v* apos number describes the positive acceleration multiplied by the vehicle speed and is a first characteristic number to evaluate RDE driving. However, the influences of full load acceleration, cold start and positive altitude gain or temperatures are not covered completely. The RDE-compliant FEV Aachen RDE track covers significantly more of the diagram. But, only the FEV worst-case RDE simulation enables an evaluation of the full range of boundary conditions. It is clear that only a holistic simulation approach is able to cover all of these boundary conditions in one cycle.

GPF Hardware and Calibration Overview

Another fact supporting the trend of simulation-supported testing is the wide variety of GPF applications on the market. Figure 4 displays current technology and market trends for GPF applications based on FEVs in-house analysis. Despite the fact that 75 percent of actual GPFs are coated, FEV expects a long-term trend of uncoated GPFs due to their backpressure advantages [3]. Besides, most GPFs are located in close-coupled position in order to utilize the high exhaust gas temperatures for soot regeneration.

The integration of GPFs into a gasoline powertrain brings a number of additional calibration tasks. The major tasks are soot model calibration, monitoring of soot loading (simulation and DP sensor) and safety function calibration. All calibration tasks aim at minimizing the customer impact of the GPF implementation. Typical ECU calibration tasks are listed in Figure 2.

<table>
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<th>Calibration Task</th>
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<td>Active regeneration calibration</td>
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<td>Execution (lambda, temperature, torque)</td>
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<td>Soot oxidation modelling</td>
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<tr>
<td></td>
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<tr>
<td></td>
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<td></td>
<td>GPF replacement</td>
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Fig. 2: Calibration tasks
The most important input for GPF calibration is an engine-out soot map. For that, the base engine calibration must be in a mature state, including optimized particulate emissions. The soot map is usually based on worst-case fuel, as these conditions serve as a main driver for the initiation of active regenerations. Tests for GPF loading and (active) regeneration take place at the engine test bench. It is necessary to determine the critical specific soot mass for the filter to prevent thermal shock during regeneration. Furthermore, the corresponding tests generate input data for soot loading and oxidation models, as well as for the back-pressure model. With the definition of the critical specific soot mass, the calibration of GPF monitoring and safety functions are possible. Both are of high importance for the impact on drivers. [4]

GPF and Cold-Start Conditions

As the worst-case fuel plays a central role within GPF calibration, FEV applied their fundamental fuel research experience regarding the impacts of ethanol or aromatics content in the fuel to a complying fuel. Since there is no fuel quality sensor in current series applications, the ECU must always consider worst-case fuel.

Figure 5 displays the GPF soot load after ten repeated cold starts at different temperatures. For EU6 certification, fuel with 10 vol-percent ethanol and the chosen SUV with a turbo DI engine, ten cold starts at -20 °C result in a soot load of approximately 0.9 g/l. For the same conditions, the FEV worst-case fuel produces about 50 percent more soot. A reference fuel shows the same behavior.

Ten repeated cold starts at -30 °C led to a specific soot load of 2 g/l, which is the threshold to trigger an active regeneration for the specific application. Considering two cold starts per day, a temperature of -30 °C may become critical regarding the GPF soot loading after only five days of client operation. Thus, it is mandatory to implement an ECU function for active filter regeneration.

A HIGH NUMBER OF PARAMETERS REQUIRES SIMULATION-BASED TESTS

Figure 3: Testing at RDE boundary conditions

- full load acceleration
- positive altitude gain
- maximum speed
- temperature
- vehicle weight
- average motorway speed
- average rural speed
- average urban speed
- cold start influence
- v*a'pos

**FEV worst-case RDE simulation**
**FEV Aachen RDE track**
**WLTC**
Accelerated Ash Loading

In order to consider the aging effects during calibration, accelerated GPF ashing is carried out on the burner test bench. Figure 6 illustrates two oil-based fuel doping experiments on the burner test bench. However, since this aging method is known to produce ash with very high backpressure, the burner hardware has been modified to precisely control the ash properties. The modified hardware can optimize the ash formation and significantly reduce the backpressure, which leads to ash properties comparable to vehicle ash. This improvement was achieved without limiting the shortening factor and full utilization of the potential is still in development.

Thus, the burner ash generation is a cost- and time-effective tool for end-of-lifetime investigations with respect to the wide range in which field ash varies for different customer applications. Especially in early development stages, where no durability runs are finished, the burner aging enables GPF aging-effect calibration.

Summary

Due to the future measurements of real driving emissions, an entire new range of influencing factors of vehicle calibration must be considered in order to be certification compliant. This makes a GPF application mandatory. Currently, test cycles do not include RDE worst-case conditions. FEV developed a simulation tool that generates worst-case cycles in order to develop calibrations that guarantee RDE compliance under all boundary conditions. An FEV market analysis confirms the
increasing trend to GPF applications, but also shows that there are a variety of technologies and installations for different vehicle applications available. As the GPF affects the engine operation, new calibration tasks arise. In order to minimize the related calibration effort, the simulation-supported testing is combined with worst-case fuels and cold start conditions. As a result, the soot modelling and regeneration calibration tends to be on the safe side. Accelerated ash loading on the burner test bench addresses the evaluation of aging impacts and allows end-of-life GPFs at a very early development stage.

Fig. 6: Ash loading results
SERIAL PRODUCTION OF POWERFUL VCR RODS: FEV AND HILITE FORM PARTNERSHIP

The FEV Group and automotive parts supplier Hilite International are partnering to develop and manufacture a two-stage, variable compression ratio (VCR) connecting rod. The goal of this partnership is to leverage synergies in the development of the product and devise a cost-efficient solution for serial production.
This collaboration is mutually beneficial for both parties. FEV will provide the development and systems expertise, while Hilite, an established systems supplier on the market, has vast experience in production. Furthermore, the company, based in Marktheidenfeld, Germany, can produce large quantities of the components and is therefore a strong partner in the final development phase of the VCR connecting rod – the know-how can be ideally bundled. VCR connecting rods are an important technology for the future of the internal combustion engine to considerably reduce CO₂ and exhaust emissions in real operation. FEV’s solution has the advantage that it can be incorporated into nearly any engine without an entire redesign.

The VCR technology meets the challenges of downsizing and the associated increase in combustion pressure by enabling optimal adjustment of the compression ratio at any time. This innovative approach is a reasonable complement to the wide variety of future powertrain solutions for affordable, personal mobility. The optimized internal combustion engine will continue to play a major role alongside purely electric drives – in particular, for long-distance travel – and in hybrid vehicles. That claim is even more valid when considering that the properties of future, renewable fuels (referred to as “e-fuels”) encounter favorable conditions within a VCR engine.

The two-stage, VCR connecting rod developed by FEV is already being used in multiple demonstration vehicles. The company also has prototypes for heavy-duty and large engines, which have already proven their performance in a comprehensive series of tests.

VCR-RODS OPTIMIZE THE COMPRESSION RATIO IN COMBUSTION ENGINES AND REDUCE EMISSIONS

About Hilite

Since it was founded in June 1999, Hilite International has grown into a global automobile parts supplier. The focus is on the development and production of systems and components for improving fuel consumption and reducing emissions. The company demonstrates its comprehensive experience and vast expertise with advanced products for engines and powertrains.

Hilite has just under 1,600 employees at eight locations in Europe, North America and Asia.
FEV SPECIALIST CONFERENCE
“ZERO CO₂ MOBILITY” TAKES ROOT AS A PLATFORM FOR DISCUSSION

FEV will once again provide an important expert platform for emission-free mobility with the second international specialist conference, “Zero CO₂ Mobility”, in Aachen, Germany. After the successful premiere last year, with more than 140 participants, the topic will once again be considered from different perspectives this November.
The goals for emissions reduction in Europe, as defined in the Paris Climate Agreement, require significant CO₂ reductions in the transportation sector by the year 2050. However, experts are already warning that although electrification alone is an important means of achieving climate-friendly mobility, it is by no means sufficient in the foreseeable future. In order to discuss general conditions and potential solutions with expert speakers, FEV is holding an international conference in Aachen from November 13 to 14, 2018. Presentations and panel discussions with a focus on the reduction of CO₂ in mobility are on the program. Participants will include leaders from the automotive, fuel and energy industries, research and development specialists, and the German Federal Ministry for the Environment.

As the organizer, FEV is leading by example and reducing emissions. The atmosphere label confirms that the conference is a climate-friendly event. To this end, among other things, FEV is carrying out CO₂ compensation for environmental projects in various developing countries in Africa, South America, and Asia. These projects were verified by the Clean Development Mechanism Executive Board of the United Nations with regard to their environmental friendliness. The event location, the Pullman Aachen Quellenhof, has previously certified sustainability programs.
MEET MORE THAN 5,000 FEV EXPERTS IN OUR INTERNATIONAL ENGINEERING AND SERVICE CENTERS

UPCOMING EXHIBITIONS AND EVENTS

MAY

03.–04.05.2018  8th International Conference Simulation and Testing – Virtual Product Development  Berlin, Germany
07.–09.05.2018  VI-grade Users Conference – 2018  Lainate, Italy
08.–09.05.2018  Body Construction Conference 2018 – 16th ATZ Conference  Hamburg, Germany
08.–09.05.2018  Conference on Future Automotive Technology (CoFAT)  Fürstenfeldbruck, Germany
16.–17.05.2018  SIA Powertrain 2018 – International Conference and Exhibition  Rouen, France
16.–17.05.2018  12th International CTI Symposium USA  Novi, Michigan, United States
23.–25.05.2018  JSAE Automotive Engineering Exposition 2018  Yokohama, Japan
JUNE

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<td>Electric &amp; Hybrid Marine World Expo 2018</td>
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JULY

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JOIN OUR UPCOMING FEV CONFERENCES

**DIESEL POWERTRAINS 3.0**

3 – 4 JULY 2018, COVENTRY / WEST MIDLANDS, UK

**ZERO CO2 MOBILITY**

13 – 14 NOVEMBER 2018, HOTEL QUELLENHOF, AACHEN

For more information please visit: [fev-events.com](http://fev-events.com)

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