TURNKEY VEHICLE DEVELOPMENT
Reliable, single-source engineering partner

GENEVA MOTOR SHOW
SVEN unveiled for the first time

48 VOLT
Optimized energy management for 48V mild hybrid drives

ELECTRIFICATION
Software and testing solutions

GASOLINE ENGINES
200 kW/L with Lambda = 1
Dear Readers,

The automotive industry is changing and new concepts for the "mobility of the future" are presented daily in the media – most based on an electric powertrain. Experts agree that additional e-fuels are urgently needed to achieve a climate-neutral transport sector. In addition, it is always necessary to optimize the entire vehicle system and not just the powertrain.

For this reason, FEV also offers its customers solutions in turnkey vehicle development, and at this year’s GENEVA MOTORSHOW, FEV presented SVEN. This prototype is a purely electrified vehicle designed for the needs of urban carsharing. In this issue of SPECTRUM, you learn more about FEV’s specific expertise in turnkey vehicle development.

In addition, we present you with solutions for operating combustion engines even more efficiently in the future. We furthermore show different performance potentials in the area of electrified powertrains with a powershift capable two-speed transmission for high-performance applications and optimized energy management for 48V systems. We also present software and test solutions in the field of electrification.

We hope you enjoy reading this issue. News and further information can also be found on our online channels, such as www.fev.com.

Dr.-Ing. Norbert W. Alt
Chairman of the Executive Board
FEV Europe GmbH

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FEV assumes responsibility for the complete scope of turnkey vehicle development, as well as for the development of individual modules and for the selective design and calculation scope of individual components. The fact that the development competence for powertrain, transmission and vehicle comes from a single source makes FEV an ideal development partner – also for electrified vehicles. FEV offers particular expertise in the conversion of conventionally powered vehicles into electric vehicles. The ideal results here can be achieved only through the closely integrated and parallel development of powertrain and vehicle.

Some turnkey vehicle development tasks will be introduced in the following:

**Body shell structure**

The body shell structure is the backbone of the vehicle. Over the past few years, the focus of development has been on crash performance and weight. With the future trends of autonomous driving and electrification, the requirements in this respect will change significantly, with electrified vehicles exhibiting lateral pile impact as a critical load case in most cases. The body shell structure has to prevent penetration or severe deformation of the battery case to avoid a short circuit, and therefore a fire, in the battery. In addition to this load case, the structure has to fulfill a large number of other load cases, such as global static and dynamic stiffness, local stiffness and strength, fatigue strength, and much more. The key task in development is the resolution of conflicts between these requirements and the equally important topics of cost and quality.

New vehicle architectures are expected for autonomous driving vehicles. Only in the event of complete connectivity and automation of the vehicle will we expect a reduction of vehicle safety requirements, with the same potential for weight reduction. The early involvement of production forms an important aspect of body shell development. And, thanks to the intensive application of simulation technologies for production, a high degree of maturity is reached in the first test vehicles, avoiding costly, late tool changes. Even standard parts, such as bolts, nuts, clips, standard reinforcements, and holders, have to be defined at the start of the project.

The construction of each part has to match the production requirements from the very beginning. The calculation is the most important tool in this development phase. This is where suggestions for the optimization of parts with regard to crash performance, stiffness, NVH and manufacturability are developed. The designs have to strike the right balance between these requirements.

THE KEY TASK IN DEVELOPMENT IS THE RESOLUTION OF CONFLICTS BETWEEN REQUIREMENTS AND THE EQUALLY IMPORTANT TOPICS OF COST AND QUALITY
Exterior and interior

FEV maps all topics in the fields of exterior and interior. This begins in the earliest concept phase with installation space analyses and various design support topics. Further topics are the creation of technical surfaces in “class A” quality in the field of surfacing as well as tool and series-compatible component development - FEV is a comprehensive partner at the interface of OEM and Tier 1 customers.

Surfacing plays a critical role in ensuring convergence between design and technical development (e.g. surface finish and materials). Compliance with minimum radii in accordance with ECE R26, legal requirements for pedestrian protection and impact crash requirements is a matter of course for the team of specialists. The last development phase in particular is characterized by close cooperation between tool manufacturing, construction and surfacing.

As reflected in automotive megatrends, vehicle interiors are growing rapidly in importance. With the focus for interior development often placed on purely practical considerations, increasing connectivity and new mobility concepts such as carsharing, electric cars and autonomous vehicles are instigating radical changes, with a strong influence on all equipment and interior themes. The construction of car bucks and seat boxes, support with regard to seat modifications, and the conversion of subframes therefore form part of the range of services offered. In addition, all facets and materials are mapped in trim development (leather, synthetic leather, materials, synthetic fabric, Figure 3), and customers are accompanied from sewing and lining work to the integration of heating and air conditioning systems right through to the technical documentation. Rangeing from the procurement of individual steering wheels, gearshift cuffs, central armrests, and vehicle headliners up to the production of complete car seats and complete interiors, FEV has a large-scale operation.

In Germany alone, around 100 FEV employees are currently working on full interior development (headliner, pillars, floor/insulation, trunk space/cargo management, center console, door trims and instrument panel).

Light and sight

In automotive development, the field of “light and sight” assumes a central role at the interface of design, comfort and safety. Thanks to its years of experience, FEV offers its customers comprehensive support, with advance development projects, right through to series management. Its particular specialization is in the calculation, design and production-friendly construction of headlights, taillights, and side and interior lights. Be it laser light developments for headlights or transparent OLEDs for taillight applications, FEV is a leader in setting new standards. The company has a broad range of expertise and skills in the field of micro-optical components, such as MLA technology and REALEYES 3D technology. With the bionic approach of
Test and validation

Vehicle development is shaped by strict customer and market requirements. In addition to innovation, safety, and economic efficiency, reliability is an important prerequisite that has a direct impact on the follow-up costs. Country-specific legislation lays out the basic requirements of a complete vehicle. These are defined as the basis for each development project and thereby define the development process. An important step here is the validation that proves these requirements have been met.

The term validation covers the topics fatigue strength, function, and performance. For this, FEV has comprehensive test options, as well as extensive knowledge of the necessary target parameters. The fatigue strength of the powertrain, chassis components, and the vehicle structure is validated during the endurance test drive. In a validation test program for the planned range of applications, all the accumulated routes are divided proportionally into various sections of the journey, representing urban traffic, high-speed driving and driving on country roads, and include roads with poor surfaces and mountain roads. Hot and cold climate testing is also included. Each section poses a different challenge for the powertrain and the overall vehicle.

However, these test scenarios do not yet take into account the special features of ADAS/AD vehicles. New scenarios are defined that test the control units on various levels to develop a suitable test program for these vehicles. These new scenarios depend more on the surroundings of the planned route, such as traffic lights, road markings, and other road users, than the route itself. The influence of these surrounding elements and their monitoring must be examined systemically with regard to the performance of the control units. It is important to take into account that a significant amount of these elements is subject to change over time and depending on location. With the FEV Advanced Road Rating System (ARRS), the tests for ADAS/AD vehicles are based on objective assessment criteria to enable a comparison of the various test routes. The focus of the ARRS approach is on objective and efficient robustness tests for ADAS/AD systems in the real world. This enables FEV to develop test methods for the validation of future technologies, such as ADAS/AD systems, systematically and efficiently.

Noise Vibration Harshness – NVH

Inner vehicle noise and vibrations are experienced firsthand by the end customer and therefore represent an important, often subconscious decision-making criterion for the purchase of a vehicle. On the one hand, they should be perceived as pleasant, but on the other hand, depending on the vehicle class, they should also express the dynamics and match the brand. The ambient noise of the vehicle is subject to legal provisions. On the one hand, pass-by noise is limited to reduce the strain on other road users and residents, and on the other, warning sounds are required of potentially very quiet electric cars for pedestrian protection (Figure 7). Acoustics and vibrations have to be taken into account consistently, across the complete vehicle development process, to achieve these NVH objectives. This begins with a decisive definition of the target values at the overall vehicle level. These are then used to derive target values for individual components, such as the engine, transmission, bodywork, and engine mounts, based on experiences with the predecessor vehicle, competitive comparisons, and the systematic assessment of noise transfer paths.

In the early phase of the development process, simulations support the design of the full concept and the detailed layout of acoustically relevant components. This includes, for example, the multi-body simulation of the powertrain and the finite elements simulation of the bodywork. With the hardware’s increasing degree of maturity, the achievement of acoustic objectives will be checked with the execution of measurements and subjective assessments in the later course of the project if applicable, necessary optimizations are reported to those responsible for the part (see Figures 5 and 6).

This established process is facing new challenges due to the current trends in the automotive industry, such as electrification and autonomous driving, increasing number of electronic systems are finding their way into vehicles. In addition to the ABS and ESP systems as well as provides an explanation for the importance of the chassis for modern vehicles, as well as an explanation for the importance of chassis in the automotive industry, such as electrification and autonomous driving, as well as provides an explanation for the importance of chassis for modern vehicles. These new systems. FEV’s active role in the development of new systems.

Chassis and driving dynamics

For vehicles of all types, the chassis establishes the connection to the road, making it the assembly that transfers the force and torque which affect the vehicle. The chassis’ key task is therefore to always guarantee this contact, as otherwise the transfer of force is not possible. The fact that the road is never smooth and straight, as well as still having various friction coefficients, makes this task so demanding. Overall, the chassis is responsible for driving safety, driving comfort, and dynamic vehicle behavior, which can be broadly divided into longitudinal dynamics (brakes), lateral dynamics (steering) and vertical dynamics (suspension/absorption). There are conflicts of objectives, particularly in the conflict area between driving comfort and driving safety, which have to be resolved in the field of chassis design. FEV also covers the complete development process in chassis and driving dynamics development. FEV is able to integrate its experience and skills into projects – from the development of new concepts and target values to the construction of parts and modules, right through to the testing and final approval of prototypes.

A team of trained drivers is on hand for the tuning of dynamic driving properties to assess and optimize the vehicle subjectively and objectively with the aid of corresponding measurement technology. The close proximity of FEV to the ATC Testing Center in Aldenhoven (Germany) represents a major advantage here. An increasing number of electronic systems are also finding their way into vehicles. In addition to the ABS and ESP systems legally in force today, many advanced driver assistance systems affect the road holding and stability of the vehicle via the chassis. This again underlines the importance of the chassis for modern vehicles, as well as provides an explanation for FEV’s active role in the development of these new systems.
Alternative drive concepts with one or more electric engines offer a means of developing new chassis concepts that were previously impossible due to the installation space in conventional combustion engines.

Passive safety development

For years, there has been particular focus on passive vehicle safety in terms of development and is also in the special interest of buyers, as life and health depend on it in the event of an accident. In addition to legal provisions that have to be met for the registration and maintenance of a car (homologation), there are consumer protection organizations, such as EuroNCAP (European New Car Assessment Programme), which go beyond the minimum legal requirement – for instance, to assess the passive vehicle safety of cars.

In the past, the Consumer Protection Rating became increasingly important, causing the requirements for achieving a high rating (five stars) to increase steadily. The speed at which new test methods, test equipment, and crash dummies are introduced presents huge challenges for vehicle manufacturers every year. Globally active vehicle manufacturers not only have to meet different legal requirements worldwide, they also have to achieve a top rating in the different regional consumer protection ratings – for example, JNCAP in Japan, C-NCAP in China, US-NCAP in the US and Bharat NCAP in India.

The introduction of the pedestrian protection leg impactor (aPLI) is a representative example of the rate of change of EuroNCAP for the implementation of new test specimens. The decision in favor of this new impactor was made in February 2019, resulting in the development strategy for projects already started with SOP 2022 having to be changed. However, the leg impactor currently exists only in the form of a physical impactor, with a virtual development model for the simulation expected to become available for the first time in the second half of 2019.

Thanks to the knowledge and the network of experts at FEV, customers can make the right adjustments to their projects at an early stage in order to implement far-reaching development strategies in their development projects as soon as possible. FEV also provides the functional design during development in the field of passive vehicle safety. In addition to virtual crash simulations, part, component, and overall vehicle tests are organized, performed and evaluated. FEV facilities can be used for part and component tests. The company is working together with longstanding partners in the field of overall vehicle crashes. The integration of safety-relevant components, such as airbags, is also managed by safety experts – constant and close communication between the virtual functional design, system suppliers, and construction is a given here.

GLOBALLY ACTIVE VEHICLE MANUFACTURERS HAVE TO MEET VARIOUS REQUIREMENTS AROUND THE WORLD

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The increasing tightening of global emission legislations promotes the further development of gasoline engines with the aim of clean engine operation under all real driving conditions. At the same time, performance requirements are growing. Gasoline engines compete increasingly with electrical components for package volume, and the displacement of high performance engines is reduced to lower the CO₂ emissions. This article covers the trade-off between increasing specific power and switching to Lambda = 1 throughout the engine map.

**Why Lambda = 1 throughout the engine map?**

Components in the exhaust gas flow of gasoline engines are currently protected from excessive thermal stress at high performance by mixture enrichment (Lambda < 1). At the same time, such an operating strategy is linked to the cross-influences:

- The fuel consumption at high engine output is disproportionately high.
- The CO engine-out emissions are increased considerably by the mixture enrichment, and outside of the operating window with Lambda = 1, the three-way catalyst only provides very low conversion rates.
- CO emissions under RDE conditions are not limited by the Euro 6d legislation, but they are measured and recorded (“monitoring”).
- Apart from the monitoring of CO in the homologation process, non-government organisations also record CO emissions under RDE conditions.
- Since the introduction of RDE Package 4, so-called AES (Auxiliary Emission Strategies which influence emissions as e.g. mixture enrichment) can only receive a time-limited approval.

The switch to Lambda = 1 leads to a loss of performance and reduces the specific power of current representative technology packages of gasoline engines to ~ 65 kW/L. It results in the increasing introduction of technological measures which improve the specific power at Lambda = 1. These include:

- Integrated exhaust manifold (iEM)
- High temperature-resistant turbocharger turbines
- Miller cycle combined with corresponding boosting procedure as variable turbine geometry (VTG) or electrical turbocharger (eTC)
- Cooled exhaust gas recirculation (cEGR)
- Variable compression ratio (VCR)

For volume segments from 85 to 100+ kW/L can well be achieved. The development of drive systems for high performance vehicles allows more freedom with regards to cost and applicable technology. FEV has investigated the following question: “Are 200 kW/L at Lambda = 1 possible?”

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**Fig. 1: Technologies with Lambda = 1 for vehicles in the volume segment**

**Fig. 2: Degrees of freedom for the development of high performance vehicles with Lambda = 1**
Combustion process for 200 kW/L at Lambda = 1

The realization of the specific power of 200 kW/L at Lambda = 1 requires a break-up of the conflict of interests between supercharging and knock tendency. Water injection in the intake port represents the key technology. The reduction of the mixture temperature associated with the high evaporation enthalpy of water at the end of compression allows for a significant increase of the efficiency of the high pressure cycle. Figure 3 shows a variation of the water-fuel ratio (WFR) at a speed of 7800 min⁻¹ and stoichiometric engine operation. With the selected compression ratio of 9.3:1 the brake mean effective pressure (BMEP) can be increased with the growing water share at only a slight delay of the center of combustion to 30 bar, so that the value of 200 kW/L is achieved at a WFR of 55 percent. An absolute boost pressure of approx. 3.3 bar is required, which can be supplied with a single-stage compressor.

The position of the water injector in the intake port has been optimized with the help of 3D-CFD simulations. For the distance that is furthest away from the valve, the wall film share is too high, because the water can wet the largest area. For water injection closer to the valve, the share decreases significantly, whereby the improvements for a distance of less than 60 mm are minor.

An analysis of the temperature distribution in the combustion chamber shows that the 60 mm position is preferable to the 30 mm position despite the same mean temperature.

With respect to the high mass flow rate and boost pressure demand, the requirement of a low throttle effect of the intake valves is in contrast to the objective of a high charge motion. Figure 5 shows how 3D machined valve seat rings are used to achieve a high charge motion with simultaneously increased flow coefficient.

Design for high mechanical and thermal stress

An engine design for a specific power of 200 kW/L must withstand high thermal stress and high mechanical load. The turbine wheel is manufactured from MAR 246 and withstands a maximum temperature of 1,050 °C. In addition to the exhaust gas turbocharger, the exhaust valves are exposed to particularly high thermomechanical stress. Therefore, sodium-cooled exhaust valves are used. An optimized solution is used which directs the sodium into the valve disc and at the same time largely maintains its structure.

The aluminium cylinder block is a rigid closed-deck design with a bed-plate and cast iron cylinder liners. An aluminium spray coating guarantees a good connection between cylinder and crankcase. The high thermomechanical stress with the corresponding pronounced cylinder deformation is addressed with free-form honing.

High performance boosting and periphery

The system is equipped with an exhaust gas turbocharger on each cylinder bank. The turbine is equipped with a variable turbine geometry without wastegate. The use of the entire exhaust gas mass flow for the generation of the compressor drive power lowers the turbine pressure ratio and therefore also the pressure upstream of the turbine. This means that lower gas exchange losses and exhaust gas temperatures can be reached at rated power.

Secondly, the added hot wastegate mass flow downstream of the turbine with the associated inhomogeneous thermal stress on the catalyst due to insufficient mixing is eliminated. The compressor is equipped with a variable trim, the turbocharger with an electric motor on the shaft to improve the transient behaviour.
Powertrain architecture and electrification

The high performance engine is embedded in the drive system. It consists of:

- Internal combustion engine 600 kW
- Electric motor EM1 30 kW (peak 90 kW) in P1 hybrid architecture
- 2-speed double-clutch gearbox
- Electric motor EM2 55 kW (peak 160 kW) as electric drive unit (EDU)
- High voltage battery 120 kW and 4.0 kWh

The combustion engine and the electric motor EM1 power the rear axle. The electric motor EM2 is configured as an electric drive unit. For reasons of weight reduction, the high voltage lithium-ion battery is designed as a small unit with a capacity of 4.0 kWh. At the same time, it delivers an output of 120 kW at a high C-rate of 1.0. The torque characteristics of all three engines are shown in Figure 10.

In high-speed range, the combustion engine is the dominant drive source. It delivers more than 85 percent of the total system power of 710 kW. The maximum speed is reached in the sixth gear and is limited to 350 km/h. Acceleration from 0 to 100 km/h is achieved without gear change in less than three seconds and is traction limited by the high torque at the rear axle. The operating strategy of the hybrid powertrain is illustrated using the example of the Nürburgring race track (Figure 12). During braking and before a curve, the energy is recuperated. The acceleration out of a curve is supported by boosting with the EDU (EM2) at the front axle. All engines drive the vehicle on straight sections at full power demand.

Thermal management

The cooling concept used here in the overall vehicle and the breakdown of the heat flows for a system power of 710 kW. The high temperature circuit (HT) of the engine-cooling system needs to dissipate 232 kW. For this purpose, it uses two radiators integrated in the side pods. The transmission oil cooler transfers an additional 18 kW to the environment. The cooler for the low temperature circuit of the electric motor EM1 is located in the left rear wheel housing. The heat of the battery is transferred to a cooling circuit via an intermediate water circuit. The cooling circuit transfers the heat (6 kW) to the environment. A second condenser provides for the cooling need of the passenger cabin cooling. The heat of the cooling water of the air-water charge air cooler is transferred to the environment (in total 80 kW) through a second cooler.

Emission control concept for Euro 7

The tightening of global emission legislations promotes the aim of low emissions operation under all driving conditions:

1. The restriction of the permissible particle number emission to a limit of 1011 PN/km x CF under RDE conditions, which was introduced with Euro 6d-TEMP.
2. The auxiliary emission strategies which receive less and less acceptance, and the discussion about the introduction of conformity for the pollutant CO under RDE conditions.
3. The significant reduction of the emission limits for gaseous pollutant to ~ 50 percent of the currently applicable Euro 6d-TEMP limits with the simultaneous restriction of CF = 1 expected with Euro 7, and the stricter focus on shorter driving distances after a cold start (< 10 km).

Figure 14 shows the exhaust gas aftertreatment system. The illustrated system is designed for one bank, and is mirrored for the second bank. The exhaust gas aftertreatment is equipped with one adsorber catalyst with a volume of 1.5 L per bank.
EMISSION REDUCTION

CYLINDER DEACTIVATION STRATEGIES FOR DIESEL ENGINES

The cylinder deactivation on a diesel engine has shown potentials on the one hand side to further reduced pollutant emissions, while on the other hand to gain some fuel economy in parallel. This has been demonstrated by several investigations in the past. Nevertheless, a static deactivation of half of the cylinders is limited by their operation range. An additional dynamic deactivation of several cylinders delivers further degrees of freedom that could provide an extension of the cylinder deactivation operation range.

The authors have used different simulation tools such as 1D steady-state engine process model and transient could provide an extension of the cylinder deactivation operation range. An additional dynamic deactivation of several cylinders delivers further degrees of freedom that could provide an extension of the cylinder deactivation operation range. Standard PID-controllers have been used to control components like EGR rates or boost pressure un- through steady-state maps which dependent on engine speed and load. The ap- proach describes the standard at FEV and has been used in the past. To obtain an accurate result, the 1D model has been validated to surrogate data. The accuracy of boost pressure showed a deviational maximum 1 percent. The calibration level of the emis- sions models were more challenging and provided a maximum deviation of 5 percent.

Map calibration for considered heating strategies

To investigate the exhaust heating poten- tials of the different exhaust heating strat- egies within the mean value powertrain model (MVPM), the baseline engine-out maps have to be adjusted, based on the results of the 1D model simulations. For this purpose, differential and factorized maps have been generated and added into the base engine maps.

A state-of-the-art diesel engine for passenger cars (PC) and medium duty (MD) truck applications have been used for the investigation program.

For the PC applications a 2.0 l 4-cylinder diesel engine with a single stage boosting system and a compression ratio (CR) of 15.5 has been considered. Further engine applications have been an advanced exhaust gas recirculation (EGR) system (uncooled high and cooled low pressure EGR path) and a 2000 bar fuel injection system (FIS). It has been decided to investigate two different vehicles, a C segment vehicle, as well as a compact SUV. Those have been equipped with a 7- and 6-speed dual clutch transmission (DCT). The exhaust aftertreatment system has installed a closed-coupled DOC, SDPF as well as a passive underfloor SCR. All EATS components have been used as aged system. The cyclic investigations have considered the standard WLTC and a RDE operation.

The MD truck has been powered by a 7.7 l 6-cylinder diesel engine. The air path has a standard wastegate turbine (WG) boosting system together with a cooled HP-EGR system installed. The combustion system has considered a 2400 bar FIS and a CR of 15.5. A state-of-the art EATS based on closed-coupled DOC, DPF and SCR has been installed. For the MD truck appli- cation, the WHTC has been considered.

1D engine process simulation model

The commercial 1D engine process simulation software GT-SUITE has been used to investigate the thermodynamic reactions of the different exhaust gas heating strategies. The 1D engine model has considered the entire engine con- figuration, such as the boosting system, the air and exhaust path, the EGR path (high pressure and low pressure) and combustion chambers. The burn rate of fuel combustion has been implemented through profile ar- rays from several engine operation points of the entire engine operation range. Those have been generated by a standard 0D ap- proach of cylinder pressure analysis of steady-state experi- mental engine measurements. The en- tire EGR control of the model has been modified from a mass flow control to an oxygen concentration control. The fuel injection pattern and rail pressure as well as boost pressure set points have been kept constant.

This 1D model can operate in the entire map range, and allows simulation throughout the entire engine operation range. Standard PID-controllers have been used to control components like EGR valves or turbocharges in order to regulate EGR rates or boost pressure un- der steady-state investigations. Finally, a sub model for engine-out emission predic- tions has been added to the engine model. This uses the physical correla- tion approach of in-cylinder O2-concen- tration to predict engine-out NOx and soot emissions. Thus, transient effects on emission production have been con- sidered, which usually occur during the engine operation. In addition, HC and CO emissions have been implemented by steady state maps which dependent on engine speed and load. The ap- proach describes the standard at FEV and has been used in the past. To obtain an accurate result, the 1D model has been validated to surrogate data. The accuracy of boost pressure showed a deviational maximum 1 percent. The calibration level of the emis- sions models were more challenging and provided a maximum deviation of 5 percent.

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CO2

NOx

THE INCREASED INNER LOAD HAS PROVIDED A HIGHER EXHAUST TEMPERATURE AT A HIGHER ENGINE EFFICIENCY

Fig. 1: Dynamic Skip Firing operation
Together with the differential and factorized maps, a new engine calibration with a specified exhaust heating strategy has been considered.

**Mean value powertrain model**

The FEV Complete Powertrain Simulation Platform, a precursor of FEV’s advanced VCAP calibration platform was utilized in this study. The powertrain model has integrated five main sub-models for boundary/ambient conditions, vehicle settings, transmission, engine and the aftertreatment system. The boundary/ambient condition sub-model described the different road conditions, emission test cycles and different driver behaviors. Inside the vehicle model the rolling resistance as well as road influence, aerodynamics and gravity were considered to model vehicle longitudinal dynamics. The main transmission and driveline components were modelled with ideal torsional systems, subjected to a distinct efficiency at different oil temperatures. Based on those sub-models, the main objective was to calculate the required inputs for the engine, mainly actual engine speed and load request. The engine model provided than on the specific operation point the corresponding engine out conditions, which were described by calibration maps at different coolant temperature.

**Selective cylinder deactivation by Dynamic Skip Firing**

Dynamic Skip Firing (DSF) is an advanced cylinder deactivation technology. A DSF-equipped engine has the ability to selectively deactivate cylinders on a cylinder event-by-event basis in order to match the torque demand at optimum fuel efficiency while maintaining acceptable noise, vibration and harshness (NVH). To illustrate this concept, Figure 1 shows an example of DSF operation in a four cylinder engine. A varying torque request is shown in green, which results in cylinders being fired (red) or skipped (grey). The combined firing pulse train for all four cylinders is in blue. As torque demand increases, the density of firing cylinders also increases. When torque demand is zero or negative, no cylinders fire. This is termed DCCO, or deceleration cylinder cutoff.

**Evaluation of simulation results**

The evaluation process has been substituted into two tasks. The first task has dealt with the steady state simulation investigations of the different heating strategies by means of 1D engine process models. Whereas the second task has focused on transient cycle investigation.

**Analysis of steady state 1D engine process simulation results**

The 1D steady-state investigation have been obtained for partly loaded operation. Those investigations have been done under four different fire density (FD) levels, where 1 indicates full cylinder operation. A FD of 0.25 is equal to a single cylinder operation out of this 4-cylinder engine. The steps in between are defined as 0.75 and 0.5.

The engine operation at a FD below 1 has led to an anomalous turbocharger operation due to the changed exhaust gas dynamics. Therefore, reduced boost pressure levels have been achieved and resulted in a limitation of the maximum engine load operation. Figure 2 shows a schematic of maximum engine operation loads that can be achieved at different FD levels.

![Fig. 2: Schematic representation of Dynamic Skip Fire at firing densities equivalent to individual cylinder deactivation](image)

Since the deactivation of one or more cylinders, the load at the remaining fired cylinders have been increased to hold a constant engine power output. The increased inner load has provided a higher exhaust temperature at a higher engine efficiency. Figure 3 summarizes the relative simulation results at a FD = 0.5 of engine efficiency improvement by BSFC and absolute exhaust temperature increase in the lower part load area. It can be seen, that FD of 0.5 has provided a fuel consumption benefit of 15 percent in average in the shown operation area. At the same time an exhaust temperature increase of almost 130 K at 3 bar of BMEP has been achieved in comparison to a 4-cylinder operation.

Additionally to the mentioned advantages other effects have occurred by a steady-state cylinder deactivation. On the one hand a reduction of the exhaust mass flow rate has obtained by deactivating cylinders. Hence, also a lower emission engine out mass flow rate has been achieved. While this has delivered, on the other some degrees of freedom to lower the steady-state EGR calibration to keep the same NOx engine-out mass flow rate compared to a 4-cylinder operation.

**Fig. 3: Steady-state simulation results of FC potential and exhaust temperature increase with FD 0.5**

![Delta BSFC (% (FD 0.5 – FD 1)/FD 1 BMEP/1)](image)

**Fig. 4: Simulation results showing firing density, SDPF inlet temperature and cumulated TP NOx emissions over WLTC cycle for C segment and compact SUV**

**THE CYLINDER DEACTIVATION HAS POSITIVE EFFECTS, SUCH AS REDUCING POLLUTANT EMISSIONS**
The results of compact SUV have showed a lower NOx reduction potential by DSF operation. This heavier vehicle application has led to a higher engine operation with an increase exhaust temperature level. Furthermore, the DSF operation has been reduced based on the higher load request. Thus, only a slightly exhaust temperature increase has entered the SDPF. Nevertheless, an improvement in CO2 emission by around 1 percent has been obtained.

Figure 5 summarizes the simulation results of WL TC and RDE. The results under RDE have provided than additional improvements at the trade off between NOx and CO2 emissions.

Figure 6 shows the simulation results of the MD truck application under cold stared WHTC. It can be seen, that the activation of DSF has increased the exhaust temperature upstream SCR by 10–30 K in a wide range of the cycle. Thus, an improved NOx conversion has occurred and provided a tailpipe reduction by 15 percent compared to base configuration. Also fuel consumption benefit has achieved of around 1.6 percent due to the dynamic cylinder deactivation.

Figure 7 shows the summary results of MD truck in weighted WHTC. The investigations have shown a tailpipe BSNOx improvement of around 30 percent in parallel to BSFC benefit of 1.6 percent.

To determine the impact of DSF on relevant cycles, the WLTC and RDE were simulated for the PC application, and the WHTC was simulated for the MD application. Figure 4 shows transient results of C segment and compact SUV application over WLTC. It depicts the fire density, exhaust temperature upstream SDPF as well as the cumulated tail-pipe (TP) NOx emission.

The WLTC begins at an ambient temperature of 23 °C. A minimum coolant temperature limit of 60 °C is imposed to represent hardware constraints, and effectively eliminates DSF operation until 140 seconds. The exhaust temperature traces upstream SDPF have showed only slightly increase after cold start and warm-up phase, due to the thermal mass of the DOC. Afterwards, an exhaust temperature increase by around 20 K has been achieved under DSF operation at segment C vehicle. That increased exhaust temperature has improved the NOx conversion of SDPF and dropped the TP NOx emission down to 43 mg/km. It represents a reduction by 4.4 percent compared to the 4-cylinder operation of segment C. Additionally, these improved results have been achieved with a benefit in CO2 emission by 1.5 percent.

**Evaluation and assessment of transient MVPM simulation results**

**Fire Density / 1**

**Temperature before SCR / °C**

**Cumulated TP NOx mass / g**

**BMEP / bar**

**AN IMPROVED NOx CONVERSION HAS OCCURRED AND PROVIDED A TAILPIPE REDUCTION BY 15 PERCENT COMPARED TO BASE CONFIGURATION**

**Fig. 5: Summary results of C segment and compact SUV application benefits of DSF in WLTC and RDE**

**Fig. 6: Simulation results showing firing density, SCR inlet temperature and cumulated TP NOx emissions over cold stared WHTC for MD truck**

**Fig. 7: Summary results of MD truck application benefits of DSF in weighted WHTC (cold and warm started)**
OBJECTIFIED EVALUATION AT ENGINE-IN-THE-LOOP TEST BENCH

The increasing number of passenger car variants and derivatives in all global markets with regionally specific legislative requirements (e.g. Real Driving Emissions in Europe), different market specific driver behaviors and customer expectations together with the vehicle manufacturers’ efforts to achieve global market and brand specific drivability characteristics as unique selling propositions, require an objectified evaluation and classification approach for the drivability capabilities of modern cars. The utilization of systems, which allow the customer to adjust the product-specific drivability capabilities additionally in a multistep way by different drive modes, is a major driver in this context. To streamline the vehicle development process, and to reduce manpower and prototype hardware resources an objectified drivability evaluation and classification approach, which is based on physical criteria, is developed at the RWTH Aachen University in cooperation with FEV.

For the demonstration of the reliability and maturity of this approach, results of sensitivity tests, which are based on ECU calibration changes with regard to the longitudinal vehicle drivability behavior and carried out with a real vehicle on a proving ground, are examined. Additionally, by reproducing this automated drivability measurement program with the same internal combustion engine (ICE) on a modern and highly dynamic Engine-in-the-Loop (EiL) test bench, the transferability of the holistic method is demonstrated. Hence, as introduction, the derived physical based criteria for the objectification of positive longitudinal drivability load change maneuvers are presented.

1. Time to reaction
2. Duration of acceleration build-up phase
3. Duration of load reversal
4. Stumble
5. Jolt
6. Backlash
7. Surging

Drivability results on the road and at the engine in the loop test bench

For the analysis of the transferability of engine related longitudinal drivability development and evaluation tasks from the real prototype vehicle to the EiL test bench, both, the vehicle and the EiL setup, were equipped with the same ICE and ECU version (incl. the same market related data set version). At the EiL test bench, the whole vehicle, with the exception of the real ICE, was simulated in the real-time co-simulation platform.

Initially, three different ECU longitudinal drivability calibration data sets, one sportive, one comfortable and one in between (medium), were calibrated in the real prototype vehicle.

The boost pressure build up at the EiL test bench is slower, because the corresponding ECUs is missing some information. Firstly, the alternator is running unloaded at the test bench, and does not deliver any electrical power. Therefore, no additional torque is requested from the ICE (by the ECU). In the real vehicle, even though all electric loads are switched off, the alternator requires about 3 Nm of torque from the ICE to supply electricity to the board net of the real vehicle. Further, torque losses in the transmission and the other drivetrain components are indeed simulated in the real-time capable models at the EiL test bench, but the data is not communicated to the ECU, since they are generally compensated by the driver model during the execution of emission cycles. The ECU in the real vehicle receives the required information, and it tries to compensate these losses by requesting more boost pressure to deliver the same drive torque as would occur without these losses. Additionally, due to safety reasons, the ambient pres-
For the sportive, as well as the comfortable drivability calibration, the reaction of the engine on the test bench is in good agreement with the reaction of the engine in the test vehicle. Even the small hock in the course of the throttle valve position in the comfortable calibration can be observed in both test setups. In principal, the courses of the throttle valve position for both drivability calibration data sets are significantly different. With the sportive drivability calibration, the throttle valve opens almost immediately (0.2 s after tip-in start), while in the comfortable calibration the throttle valve is used to shape and slow down the drive torque build-up and thus to reduce the build-up of the vehicle longitudinal acceleration. Further, the differences between the two ECU calibrations are clearly visible in the longitudinal acceleration signals for both test scenarios. The build-up of the longitudinal acceleration for the sportive ECU calibration is distinctly faster than for the comfortable ECU calibration, while the comfortable ECU calibration produces smaller load change oscillations (less backlash and surging).

In Figure 5, the longitudinal acceleration measured in the real vehicle is compared to the simulated longitudinal acceleration of the virtual vehicle at the EiL test bench for the sportive and comfortable ECU calibrations. For both test scenarios, the differences between the two ECU calibrations is clearly visible, but there are a few differences between the simulated and the measured acceleration values. As an initial load change reaction, the acceleration of the virtual vehicle at the EiL test bench is slightly faster because any of the mechanical play in the drive train components is not simulated with the models. As the drivability maneuver progresses, the simulated longitudinal acceleration of the virtual vehicle rises slower than the corresponding acceleration of the real vehicle. The reason is the already mentioned slower boost pressure build up at the EiL test bench. Due to the simulation of the elasticities of the drivetrain components, similar oscillations can be observed in the longitudinal acceleration signals for both test scenarios. Considering the clear differences in the longitudinal acceleration signals between both ECU calibrations at the EiL test bench, it is expected that the objective and physically criteria are good measures to analyze the longitudinal drivability in virtual and real test scenarios. For the analysis with regard to reproducibility, 50 of the same positive load change maneuvers (2nd gear, 2500 RPM, 0 percent to 50 percent pedal) have been performed for each ECU calibration in the two test scenarios. For all these measurements, the drivability attributes were calculated. In Figure 6 and Figure 7, the attribute “jolt” is compared to the “time to reaction”, and the attribute “backlash” is compared to the “duration of acceleration build-up phase”. The influence of the different longitudinal drivability calibration data sets on the results of the EiL test bench are shown in Figure 5, and subsequently the data of the corresponding vehicle tests are presented in Figure 7.

As expected, it becomes clear for both test scenarios that the sportive ECU drivability calibration data set leads to an increase of the attribute “jolt”. Also, the “duration of acceleration build-up phase” is reduced by the sportive ECU calibration. The “time to reaction” is not affected by the prepared different ECU drivability calibration data sets, because the comfortable ECU calibration does not delay the initial reaction of the ICE to changes in the accelerator pedal position (it only shapes the torque build-up). The “backlash” of a comfortable ECU drivability calibration is supposed to be lower compared to a sporty one. However, the ECU drivability functionalities of the chosen vehicle were not able to depict this correlation for the attribute “backlash”. Nevertheless, this behavior is determined in both test scenarios. The sensitivity of the ICE towards changes in the ECU drivability calibration at the EiL test bench is nearly identical to the sensitivity of the ICE in the real vehicle. The attribute “time to reaction” is shorter at the EiL test bench due to the missing play in the virtual powertrain components in comparison to the real vehicle. Overall, the influences of the different ECU drivability calibrations on both the longitudinal drivability attributes are clearly visible in the same way and on the same level for the EiL test bench and for the real vehicle.

As a major advantage for the EiL test bench application, it can be stated that the reproducibility of the individual load change drive maneuvers is distinctly better in real vehicle tests where there is typically a larger dispersion of the drivability attributes (Figure 5 and Figure 6). The reason is that various environmental influences the real vehicle is exposed to, such as wind, road conditions and temperature changes, which are not present, if not explicitly required and simulated, at the EiL test bench.

**Conclusion**

The basic comparability between the operation of a real vehicle and the automated drivability testing and evaluation approach via an EiL test bench could be demonstrated with an analysis of relevant engine operating data (throttle valve position, intake manifold pressure, engine speed etc.) for the same load change maneuvers. Also, different ECU drivability calibrations regarding e.g. a very sporty or more comfortable throttle response can be reproduced very well with the EiL method in comparison to the real vehicle test. Exactly the same statement can be made based on the results of the physical based and objectified drivability evaluation approach for the sensitivity of the reaction of the internal combustion engine to changes in drivability calibration at the EiL test in comparison to the real vehicle. As a major advantage for the EiL test bench application, it can be stated that the reproducibility of the individual load change drive maneuvers is distinctly better in real vehicle tests, where there is typically a larger dispersion of the drivability attribute results. Thus, the reliability, maturity, validity and transferability of the holistic method to different fully, partially or neither virtual testing scenarios is demonstrated.
ELECTRIC DRIVE CONCEPT

HIGH PERFORMANCE THROUGH INNOVATIVE TWO-SPEED GEARBOX

The trend towards battery electric vehicles will continue and likely even accelerate in the future. These vehicles will make a significant contribution to meet future targets for fleet fuel consumption and emissions. To be commercially successful, these new vehicles require modern and intelligent solutions for their powertrain, including battery and drive unit.

The optimal drive unit concept has to be developed based on an evaluation of performance, efficiency and cost on a system level, including all powertrain components, such as battery, inverter, electric motor and transmission. This is what FEV and YASA have done with a high performance D-class passenger car application in mind. The result is a drive unit concept with an exceptionally high power density and efficiency based on YASA’s unique axial flux motor technology and an innovative 2-speed transmission concept by FEV.

The 2-speed functionality is realized based on a Ravigneaux planetary gearset. Figure 4 explains the topology of the transmission. The planetary gearset is arranged coaxially to the electric motor. The small sun (SS) does serve as the input, and the ring (R) serves as the output to the intermediate shaft and differential. Two brakes B1 and B2 are used to realize two speeds. Brake B1 is connected to the carrier and paired with a one-way clutch (OWC), B2 is connected to the large sun gear (SL). Despite being mechanically more complex than architectures in a simple planetary gearset, this architecture has a number of technical benefits. As shown in the table “Clutch relative speed matrix”, the delta speed at open brakes is always below the input speed at the small sun, an important quality for minimum drag losses. At the same time, the torque reaction at the brakes is favorable as shown in the table “Clutch torque matrix”. Brake B2 only has to react less than half of the input torque. Brake B1 has to react 1.5 times the input torque, but is supported by the one-way clutch.

 brake avoid the use of rotary joints or engagement bearings to actuate the gearshift. In addition, the thermal capacity of brakes can be scaled via the thickness of their stationary steel lamellae without negatively affecting rotary mass moments of inertia. The exclusive use of brakes was therefore an important criterion in the selection of the concept. Both brakes are actuated via an existing series-production, on-demand actuator from LuK. The unit, also known as HCA (Hydrostatic clutch actuator), operates with a brushless electric motor for each gearshift element, which opposed to clutches, brakes.

Fig. 1: Compact 2-speed EDU for high performance cars

**Motor and inverter concept**
- E-motor and inverter integrated in a co-axial fashion for minimum package space
- Different power variants possible using common package (e.g. 300 kW / 300 Nm and 220 kW / 380 Nm)
- Mass of machine plus inverter in only 25 kg (10 kW kg)
- Motor and inverter share the same cooling circuit
- Motor maximum speed in 10,000 rpm, a perfect match to the FEV 2-speed transmission

Fig. 2: YASA motor and inverter

**Integration benefits**
- Reduced volume, mass and interconnection complexity
- Reduced cooling circuit

**System weight (total, dry)**
- < 85 kg

**Power**
- 300 kW peak / 150 kW cont.

**Maximum axle torque**
- 6,000 Nm

**Maximum EM torque**
- 500 Nm

**Vehicle top speed capability**
- > 200 km/h

**System weight (total, dry)**
- < 85 kg

**Performance**
- High performance with neutral function
- Axial flux electric motor with e-coaxial, integrated inverter for highest power density
- Maximum EM torque: 500 Nm
- Maximum axle torque: 6,000 Nm
- Power: 300 kW peak / 150 kW cont.
- Vehicle top speed capability: > 200 km/h
- System weight (total, dry) < 85 kg

**Mature LuK on-demand shift actuator clutch**

**Park-by-wire system (optional)**
- Join on-demand cooling/lubrication circuit for inverter, motor and transmission w/ integrated oil reservoir
- Easily scalable to lower power levels by attaching different motor/inverter unit

**Applications**
- E-scooter (e.g. BMW C evolution)
- E-bike
- E-scooter
- E-moped
- E-truck
- E-ATV
- E-Airplane
- E-Boat
- E-Ship
- E-Bus
- E-Tram
- E-Hybrids
- E-Taxis
- E-Cars
- E-Commercial vehicles
In the VASA motor, oil coolant is in direct contact with the copper windings, providing very efficient and even cooling over each winding cooling circuit. Using a dedicated EDU oil which fulfills the requirements of both the electrical and mechanical components, also allows for the transmission to be integrated into that cooling circuit. As of today, such a fluid is not yet readily available, however several oil suppliers have confirmed that it can be successfully developed within a standard series development of 3 years duration. The obvious advantage of such a highly integrated cooling and lubrication circuit is less complex and more cost effective, as only one pump, one cooler and almost no external housing would be required. In addition, the interfaces to the vehicle would be simplified considerably. Alternatively, separate oil circuits can be used for the electric motor/inverter and transmission; in this case, oils are readily available and can be tailored even better for the requirements of each circuit. The development risk will be reduced, but complexity and cost of the overall system will be increased.

Figure 6 explains the variant with one common cooling and lubrication circuit. An electric oil pump draws oil out of the transmission sump and feeds it via an oil/water heat exchanger to the inverter. From there, the oil flows through the electric motor and subsequently back into the transmission, where the volumetric flow is divided. One part is fed into the main shaft of the planetary gear set, from where it not only lubricates the gears and bearings, but also cools the brakes as required. The remainder is drained into the sump, but buffered in a storage tank where it not only lubricates the gears and bearings, but also cools the brakes as required. The remainder is drained into the sump, but buffered in a storage tank. From here, further components are lubricated via various channels, including the gear meshes and the bearings of the intermediate shaft.

An intelligent oil pump control strategy allows to vary the level of the storage tank and thus the oil level in the transmission, which makes a large contribution to a reduction in churning losses and thus an increase in efficiency. Figure 7 shows two internal views of the transmission including the integrated oil reservoir. A park lock system is arranged on the intermediate shaft and can be actuated by a stand-alone, electro-mechanical park-by-wire actuator.

**Summary**

The presented 2-speed drive unit does use a high powered, dense yet modular combination of an axial flux electric motor and a coaxially arranged inverter. The transmission is based on a Ravigneaux planetary geared with two brakes as the shift elements. Together, with a one-way clutch, this arrangement is both favorable in terms of drag losses, as well as controllability and shift comfort. The brakes are actuated on-demand for minimum energy consumption. The electric motor, inverter and transmission do optionally share a single, common cooling and lubrication circuit which reduces complexity and simplifies the interfaces of the drive unit to the vehicle. With a peak power of 300 kW and a weight of less than 85 kg, the drive unit provides an outstanding power density of 3.5 kW/kg on system level. The maximum axle torque of 6,000 Nm even exceeds typical wheel slip limits for both front- and rear wheel drive applications and ensures superior acceleration performance on vehicle level.

**Final remark**

The drive unit concept presented in this article has been jointly developed by VASA and FEV. The motor and inverter technology described in this paper is owned by VASA Limited, a UK-based developer and manufacturer of electric motors and inverters. The 2-speed transmission concept described in this paper is owned by FEV, an independent provider of powertrain and vehicle engineering services.
The comparison with high-voltage hybrid systems in Figure 1 demonstrates that the operating range of 48V mild hybrid systems is clearly moving toward the system limits. The growing number of 48V components additionally increases the dynamics of torque requirements and the variances in terms of operating strategy. This comes with interactions, dynamic framework conditions, and a high system complexity that stretch rule-based operating strategies to their limits. The use of predictive energy management is very promising, since the available electrical energy and power is ideally distributed within the 48V onboard circuit, allowing for ideal operation of 48V systems designed to save costs and resources.

**Concept vehicle**

In cooperation with RWTH Aachen University, FEV has developed a 48V mild hybrid concept vehicle. The vehicle is based on a Mercedes-Benz AMG A45 equipped with all-wheel drive and a seven-speed dual clutch transmission. The series vehicle is equipped with a turbocharged 2.0 l gasoline engine that has a specific output of 133 kW/l. This impressive output is achieved through the use of a large exhaust turbocharger (ETC) that, despite twin-scroll technology, significantly limits the maximum torque in the lower engine speed range and results in a noticeably delayed response. In this context, electrified charging and/or electric torque support can significantly improve elasticity, especially in the economical, lower speed range. The 48V mild hybrid powertrain is schematically represented in Figure 2. The central element is the belt starter generator (BSG) in the belt drive of the combustion engine (CE). The P0 topology enables a variety of hybrid functions such as regeneration, load point shifting, and electric torque support. Since the maximum power that can be transmitted with the belt is limited and there is a permanent connection to the combustion engine, the system is not intended solely for electric driving.

There is also an electric compressor (EC) positioned in the charge air path, upstream of the intercooler. The EC reaches a maximum pressure ratio of 1.45 and can significantly increase the charge pressure, and thus the response behavior, in operating ranges with low exhaust enthalpy, regardless of the operating condition of the BSG. The concept vehicle is operated using a rapid control prototyping (RCP) development control device.

**Rule-based operating strategy**

A driving performance-oriented, rule-based operating strategy with priority-based power distribution controls the electric charging, as well as the electric torque support of the BSG (Figure 3). The operating strategy is made up of the torque-supporting functions in drive management and the overarching power distribution in electric power management. The electric charging is controlled through the pressure ratio between the desired and the current charge pressure in the intake manifold. As long as the waste gate (WG) regulated ETC does not provide the desired charge pressure, the pressure is additionally increased in the air path through the EC. The required rotational speed is calculated using the compressor diagram of the EC and then limited in accordance with the available electric power.

In contrast to electric charging, during which the drive power results from the additional air and fuel mass, the BSG directly converts electric energy into mechanical drive power that supports the combustion engine (Figure 2). The torque required by the BSG results from the difference between the current torque of the combustion engine and the driver’s needs. When the accelerator pedal is pushed, this difference is positive, so that the BSG temporarily replenishes the torque deficit. The BSG torque is then limited in accordance with the available electric power.

The electric power limits of the various individual 48V components are prescribed by the electric energy management. During an acceleration, the 48V battery must also power the cooling agent pump and the 12V system via the DC/DC converter, in addition to the EC and the BSG. It is therefore necessary to carry out a situation-based prioritization of the 48V components. The available battery discharge capacity is, in this context, prescribed by the battery management system (BMS). The available electric discharge capacity for the respective 48V components is then calculated depending on their priority and the actual power consumption of elements with a higher priority. In order to ensure reliable driving operation, the engine cooling and the 12V...
The remaining power is made available for the EC and the BSG in consideration of a calibratable power ratio.

Even though such rule-based approaches can be improved through further dependencies, there are principle-based disadvantages. For instance, the operating strategy merely reacts to the current system status and adjusts the parameters regardless of the expected load status. Since, however, the temporal behavior of torque build-up and the efficiency heavily depend on the load status, the selected operating strategy of the electrified drive (ICE with ETC, EC, and BSG), and the electric system limits, this control is usually suboptimal.

Optimized Energy Management

Predictive optimization-based energy management strategies use dynamic route information from the electronic horizon for the long-term optimization of route guidance and the speed trajectory. Based on this information and adequate vehicle sensor systems for surroundings detection, hybrid management considers the electric power limits and load prediction to determine ideal trajectories for gear selection, drive torque, and charge strategies for a medium-term horizon. The predicted system values also enable the derivation of an expectable charge condition evolution of the electric energy accumulator, which adapts an energy weighting factor. This factor represents the importance of electric energy in the energy balance sheet and directly influences the accumulator, which adapts an energy condition evolution of the electric energy and subsequently save electric energy.

In order to reduce charge change losses. In contrast to this, at $\xi=0$, the NMPC only briefly provides support through the BSG in order to utilize the rapid dynamics of the electric machine and subsequently save electric energy.

The operating strategy, in such an acceleration scenario, is always a compromise between response behavior and energy efficiency. The response behavior is described through the acceleration time and the energy savings through the inverse of the effective drive efficiency. With a variation of the electric power limitation, the framework conditions are changed.

Additionally, for each of these power trajectories, the prioritization of the rule-based strategy and the weighting ratio of the NMPC optimization were varied. It becomes clear that increasing energy savings are at the expense of the response behavior. However, the NMPC resolves the conflict of objectives significantly better and can describe both the energy consumption and the energy savings through the inverse of the effective drive efficiency. With a variation of the electric power limitation, the framework conditions are changed. The stronger the electric power limitation and the smaller the focus on the response behavior, the more the potential of the NMPC develops.

Results

The NMPC was more closely examined during a validated co-simulation of a B-segment 48V mild hybrid with turbocharged gasoline, electric compression, and P0 BSG. Figure 4 shows a comparison of the NMPC and the rule-based approach for a full-load run-up for various energy weighting factors $\xi$. An energy weighting factor of four is equivalent to an overall changing efficiency factor of 25 percent, while the electric energy in the limit case of zero, e.g. due to a high battery state of charge and an upcoming downhill drive, is free of charge. Due to the lack of forecasting, the rule-based operating strategy reacts identically in both cases, while the NMPC adjusts the parameters for the WG, the EC, and the BSG based on the situation in order to achieve a desired drive torque. Beyond that, the variation of the optimization parameters shows that the NMPC reduces the drive torque with increasing weighting of energy ($\xi$) and can reduce energy consumption. If the electric energy is free of charge ($\xi=0$), the drive torque is shifted to the BSG, while the EC builds up charge pressure with the WG open, in order to reduce charge change losses. In contrast to this, at $\xi=4$, the NMPC only briefly provides support through the BSG in order to utilize the rapid dynamics of the electric machine and subsequently save electric energy.

The NMPC will calculate the ideal parameter evolution for the WG and the EC, which influence the combustion engine torque through the air path, as well as the torque of the BSG, which can obtained through the addition of the belt drive. This way, both the differences in the temporal behavior of the charge air path and of the BSG torque and their impact on the overall efficiency of the electrified powertrain are taken into account in the optimization.
The list of challenges is long. First, and most importantly, are battery tests. Today’s lithium ion batteries provide an energy density 20 to 30 times inferior to gasoline, and to achieve cost parity with a petrol-driven vehicles, we have to cut their costs four-fold. This cannot be done overnight, but the calibration of the BMS (Battery Management System) must be optimized immediately, which requires precise means of optimization on the test bench. For battery test benches, a highly automated and staff-saving process is required. It must be able to react and supervise all the test benches in real time. File formats must be identical, irrespective of their source. In some centers, each device has a different file format, which affects the center’s productivity. In addition, safety is a prime concern with batteries. Great attention must be paid to extreme conditions, in which the internal chemistry in the battery can go out of control. Severe battery tests are necessary, including fire tests, overvoltage tests, crash tests or tests in which the battery goes completely discharged. While the battery is the most sensitive element to be tested, testing electric motors also presents technological issues. Upcoming motors can reach up to 25,000 rpm. In some phases, the temperature suddenly rises, to the detriment of the motor’s longevity. In this case too, the optimization of the global Energy Management System (EMS) will allow critical cases to be managed, increasing the life span of the e-motor.

FEV summarizes the keys to e-mobility test center and system development by highlighting three points: the automated management and global supervision of the processes and the test benches, using the FEVFLEX™ and MORPHEE® software suites. The standardisation of test bench solutions, or Test Cell Products. And, the calibration of the controllers and the optimization of energy management, which demands the extended use of simulation. This vision is the result of more than ten years of experience, with two test centers in Munich and Saint Quenien-Yvelines (France), equipped with 22 test benches to test batteries, and numerous e-motor and e-axle cells.

ELECTRIFICATION – SOFTWARE AND TESTING SOLUTIONS

Within the next ten years, electric vehicles are expected to account for 90 percent of the market, including full-electric vehicles and various versions of hybrid vehicles. Many new test benches for e-mobility and batteries are being built. So what are the key points we need to understand for this new type of bench? How can we find our way around this new world of tests for electric or hybrid vehicles?

T he list of challenges is long. First, and most importantly, are battery tests. Today’s lithium ion batteries provide an energy density 20 to 30 times inferior to gasoline, and to achieve cost parity with a petrol-driven vehicles, we have to cut their costs four-fold. This cannot be done overnight, but the calibration of the BMS (Battery Management System) must be optimized immediately, which requires precise means of optimization on the test bench. For battery test benches, a highly automated and staff-saving process is required. It must be able to react and supervise all the test benches in real time. File formats must be identical, irrespective of their source. In some centers, each device has a different file format, which affects the center’s productivity. In addition, safety is a prime concern with batteries. Great attention must be paid to extreme conditions, in which the internal chemistry in the battery can go out of control. Severe battery tests are necessary, including fire tests, overvoltage tests, crash tests or tests in which the battery goes completely discharged. While the battery is the most sensitive element to be tested, testing electric motors also presents technological issues. Upcoming motors can reach up to 25,000 rpm. In some phases, the temperature suddenly rises, to the detriment of the motor’s longevity. In this case too, the optimization of the global Energy Management System (EMS) will allow critical cases to be managed, increasing the life span of the e-motor.

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Fully automated process
A fully automated process is a key factor in any modern test center, but it is particularly important in battery test centers. This is done through software, such as FEVFLEX™ and MORPHEE®. FEVFLEX™ is a modular software suite dedicated to manage and monitor the entire test field. (For more information on using FEVFLEX™ in an e-mobility and battery test center, see article “Expertise and capacity for e-testing projects,” pages 40). All the information sent to FEVFLEX™ is produced by MORPHEE®, FEV’s automation system. The electric revolution is only just starting. Batteries, electric motors and general vehicle architectures are set to evolve even further. In this respect, FEVFLEX™ and MORPHEE®’s upgradeability and applicability makes it a complete must. These open tools can be easily configured by the user, at no additional development cost. MORPHEE can be connected to all types of devices using the same programming interface. It produces and synchronises result files in an identical format, irrespective of the equipment used.

Test cell products: standard solutions
2019 will be a very special year for FEV Software and Testing Solutions, with the launch of the test cell products and standard test bench solutions. Over the years, many benches have been built, both on FEV’s own sites and on customer sites in Europe, Asia and America, ranging from
complete engineering projects, to simple automation. FEV has built on this experience to develop standard test bench solutions, or test cell products, that use FEV’s products and products from approved suppliers. Thanks to this standardization, FEV can control costs and propose shorter deployment cycles. This offer covers all the necessary dimensions of the field of electric vehicles, and the safety-related aspects in particular.

FEV proposes battery test benches covering every test case: cell benches with up to 24 cells per climate-controlled chamber, module benches with up to six modules and integrated pack benches, either in walk-in chambers, or in king-sized climate-controlled chambers.

FEV also proposes standard e-motor test benches that can be used to characterise electric motors. The key aspect of this type of test bench is its ability to test at very high speeds and in a highly-dynamic process where vibrations are taken into consideration. FEV produces state-of-the-art e-motor test benches, including dynamometers. It offers e-motor test bench solutions enabling rotational speeds of 35,000. The MORPHEE® solution used to control the bench replaces the bench controller, offering very easy connectivity with the calculators. The e-powertrain is optimized by taking several use cases (motorways, urban environments or rural areas) and several factors (voltage and current signals, frequency versus angular position and speed, transient torque management etc.) into consideration. In this case, FEV’s OSIRIS® Powermeter serves to analyse the efficiency of the e-powertrain system by measuring the power before and after the inverter and before and after the e-motor.

FEV offers unique solutions facilitating not only the optimization, but also the validation of the complete driveline. Durability tests simulating mechanical cycles (vibrations, reducer, differential) and thermal shocks (cooling, rotor thermal management) must also be conducted. In this configuration, a good solution is to test not only the e-motor, but also the complete drive chain. On the so-called e-axle test bench it is possible to test the entire system in the downstream steps of the development process and involves using both MORPHEE® and OSIRIS®, as well as FEV dynamometers and conditioning units for fluid cooling – the so-called eCoolCon™.

Energy Management System optimization

The final key factor of success of an e-mobility test center is its capacity to optimize the calibration of the various calculators and the EMS (Energy Management System) of the drivetrain. This was already one of FEV’s strengths in the field of conventional engines, and it is still the case with electric or hybrid motors. FEV has achieved this by developing tools with two characteristic features: a very high level of performance and complete compatibility with one another. In the initial development phases, xMOD™, a virtual experimentation and co-simulation platform, creates a system that was complex to develop by co-simulating the different models that describe it: the electric motor, battery, driver, complete vehicle, etc. Consequently, virtual experiments can be made on the same platform in order to prevalidate the control laws. In the following step, the bench controlled by MORPHEE® – in this case the battery and BMS bench or the e-powertrain bench – is used to integrate the previously validated models by replacing the battery or e-motor model by the physical parts, and by keeping all the other parts to produce the most accurate representation possible of the drivetrain in its environment. Since xMOD™ and MORPHEE® share the same DNA, the interfaces, tests and models all follow the same process, from the beginning to the end, in what FEV calls the Collaborative Framework. It should also be noted, that the exceptional simulation performances of these tools, which are 10 to 40 times faster than any other solution on the market, enable highly complex models to run on the test bench in real time.
In the coming year, FEV plans to open two new battery test centers – one in Germany and the other one in France. Additionally, new e-motor and e-axle test benches have been integrated into FEV’s test centers and on customer sites. Based upon long-term planning and construction experience with FEV’s own test cells and test centers, as well as in numerous customer projects, FEV provides an effective methodology for specification development, concept layout and planning for e-mobility test benches, test cells and test centers, this methodology covers hardware (test equipment, technical infrastructure, building), software (data management, logistic and operation aspects)

Expertise and Capacity for E-Testing Projects

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The final goal is to develop a technical solution covering building construction aspects, concepts for the test cells and test benches, laboratories, workshops, the technical infrastructure including supply media and energy supply, furthermore operational and logistical issues. Due to long-term, global experience, FEV’s experts provide the right solutions. They have the in-depth knowledge and experience gained in the construction of their own test centers for the mobility of the future to support customers. They use specific calculation and simulation tools to simulate the different scenarios.

Boosting the Test Center Performance

In state-of-the-art test centers, the visible parts, such as the buildings, the building infrastructure and the test benches can no longer be separated from the invisible parts – the comprehensive information system with a high automation degree.

Let’s evaluate how this information system controls the workflow and use cases in a battery test center. When the battery pack, module or cells (sub-) components are received, a bar code is created that follows the Unit Under Test (UUT) throughout the entire workflow. The UUT is taken from a safe storage room and subsequently equipped with sensors and measuring devices in a preparation area. The availability and maintenance status of resources (equipment, test benches, employees) is documented in a database, thereby supporting an efficient and effective planning and assignment of UUT and resources. After the installation of the UUT at the test bench, the test programme is executed, followed by the post processing of the measurement data being acquired via the automation system and further measuring devices. The measurement data is checked regarding plausibility and finally documented in standardized test reports. The information system allows data on the UUT, the assigned resources, the test program and test results to be logically linked throughout the workflow. The above information system is based on the FEVFLEX™ software suite.

This modular, layer-based suite features dedicated modules for managing the main workflow of a test center, starting from the test demands up to the final test reports.

![Fig. 1: Questions to be asked at the beginning of a test center building project](image1.png)

![Fig. 2: Process managed by FEVFLEX™ in an e-mobility test center](image2.png)

At this layer, the FEVFLEX™ work orders are translated into the preparation of the automation system resulting in a base parametrization (including e.g. a measuring plan, channel limits, log list, integration of measuring devices, test program).

Furthermore, the flexible Lab supports the management of MOPHIE® configurations, including back-up and versioning. Launching the execution of test programs at the test bench is secured via communication between the FLEX Lab™ host system and the MOPHIE® automation system. Finally, FLEX Lab pushes the measurement data, which was acquired via the automation system to data evaluation tools, such as LinPit.

As a final conclusion, the workflow in FEVFLEX™ is supported by SCADA remote monitoring and run-time statistics:

- Remote monitoring supports immediate alerts and interventions in case of incidents.
- Run-time statistics support facility managers to repair weaknesses in their workflow sustainably.

With the help of this comprehensive information system based on the FEVFLEX™, an effective test bench usage of 96 percent was reached in FEV’s battery durability test center.

**FEVFLEX™ manages all the flows, processes and data of testing project. MOPHIE®, the FEV automation software, monitors all equipment and test beds of the test center.**

**Operation Flow**

1. Sensors/facility (sensors)
2. Equipment booking
3. Deliveries and UUT identify
4. UUT measurement, qualification and recording
5. UUT location
6. Loading UUT and required equipments connection
7. Running test cycles and test equipments in monitored and safe environment
8. Starting test cycles
9. Preparation of the testing project
10. Supervising of all running equipment and test process from one point
11. Report and analysis
12. Interfacing and controlling any testing equipment
13. Reliable and proven real-time interface
14. Test Field extension

**By:** Regis de Bonnaventure

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GENEVA MOTOR SHOW

FEV, SHARE2DRIVE AND NEW UNVEIL SVEN FOR THE FIRST TIME AT GENEVA MOTOR SHOW

The newly developed vehicle concept SVEN is optimized to meet the specific needs of carsharing. A combination of high customization, practicality, and economic efficiency appeals to an environmentally conscious and agile audience, and demonstrates FEV’s competence in turnkey vehicle development. The vehicle had its world premiere in March in Geneva and received consistently positive responses from visitors and the media.

### Technical data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>Q3 / 2021</td>
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<td>Doors</td>
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<td>Seats</td>
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<td>Dimensions (L/W/H)</td>
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<td>Turning radius</td>
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<td>Empty weight</td>
<td>850 kg</td>
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<tr>
<td>Drive type</td>
<td>Rear, fully electric</td>
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<tr>
<td>Loading capacity</td>
<td>210 l / 580 l (passenger seats flipped down)</td>
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<tr>
<td>Output</td>
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</tr>
<tr>
<td>Maximum speed</td>
<td>120 km/h</td>
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<tr>
<td>Battery capacity</td>
<td>20 kWh</td>
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<tr>
<td>Range</td>
<td>140 km (WLPT)</td>
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</tbody>
</table>

The vehicle and mobility concept is based on a research corporation with FH Aachen.

More information about SVEN sven-fev.com
FEV AND COVENTRY UNIVERSITY LAUNCH CENTRE FOR CLEAN MOBILITY DEVELOPMENT

The Centre for Advanced Low-Carbon Propulsion Systems (C-ALPS), a state-of-the-art facility for creating clean mobility solutions, has recently opened in Coventry (UK). C-ALPS, an innovative collaboration between global engineering specialist, FEV Group, and Coventry University, is looking to harness cutting-edge academic and commercial expertise to support the development of the next generation of electric, hybrid and combustion engines.

More than 30,000 sq ft of development space at the Technology Park of Coventry, near to the National Transport Design Center, will house some of the most advanced internal combustion and electrification test bed facilities currently available in the UK, creating a dedicated resource for testing current and future powertrain solutions quickly and efficiently. The capabilities will be available to OEMs, SMEs in the supply chain, and technology partners keen to accelerate the creation of new propulsion systems for use across automotive, aerospace, marine and rail sectors.

FEV is convinced that Coventry University is the ideal partner for the development of powertrain solutions in the UK due to its research focus and the conditions prevailing there. In addition, this move will enable FEV to be on-site with its UK customers and develop modern and clean powertrain solutions for them with C-ALPS and the most advanced capabilities.

Operating within Coventry University’s Future Transport & Cities Research Institute, C-ALPS has been designed and built to be the most advanced test facility of its type in the UK. FEV’s development test benches meet all the conditions with which current and future engines are confronted. It also houses test benches for powertrain components, including turbochargers, catalytic converters, battery systems and electric machines.

Three world class professors have also been recruited to lead the research team and they bring with them significant experience and knowledge in battery storage, power electronics and electric machines.

More than 100 people from the industry, science and politics attended the official opening of C-ALPS in March. In addition to speeches by representatives of FEV and Coventry University, Richard Harrington, Minister for Business and Industry, addressed the audience and praised C-ALPS’s commitment to research and development.
| MAY                  | 15.–17.05.2019 | 40th International Vienna Motor Symposium | Vienna, Austria  |
|                     | 19.–22.05.2019 | 32nd Electric Vehicle Symposium and Exhibition 2019 (EVS 32) | Chassieu, France  |
|                     | 21.–23.05.2019 | Automotive Testing Expo Europe 2019 | Stuttgart, Germany |
|                     | 21.–23.05.2019 | Autonomous Vehicle Interior Design & Technology Symposium Europe | Stuttgart, Germany |
|                     | 22.–24.05.2019 | JSAE Automotive Engineering Exposition Yokohama | Yokohama, Japan |
|                     | 23.05.2019  | FEV Day of Smart New Energy Vehicle 2019 | Chongqing, China |
| JUNE                | 04.–05.06.2019 | Automotive Engineering Expo 2019 | Nürnberg, Germany |
|                     | 10.–14.06.2019 | CIMAC Congress 2019 | Vancouver, Canada |
|                     | 12.–13.06.2019 | SIA Power Train & Electronics | Paris, France |
|                     | 25.–26.06.2019 | 23rd International Congress Automotive Electronics 2019 | Ludwigsburg, Germany |
| JULY                | 02.–03.07.2019 | FEV Konferenz – Diesel Powertrains 3.0 | Rouen, France |
|                     | 03.07.2019    | FEV Future Mobility Conference – Software & Testing Solutions | Shanghai, China |
|                     | 04.07.2019    | FEV Day of Future Mobility Solutions Korea | Seoul, Korea |
|                     | 17.07.2019    | FEV Future Mobility Conference – Engineering Solutions | Shanghai, China |
|                     | 17.–19.07.2019 | JSAE Automotive Engineering Exposition Nagoya | Nagoya, Japan |

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**DIESEL POWERTRAINS 3.0**
2–3 JULY 2019
Rouen, France

**ZERO CO2 MOBILITY**
7–8 NOVEMBER 2019
Aachen, Germany
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