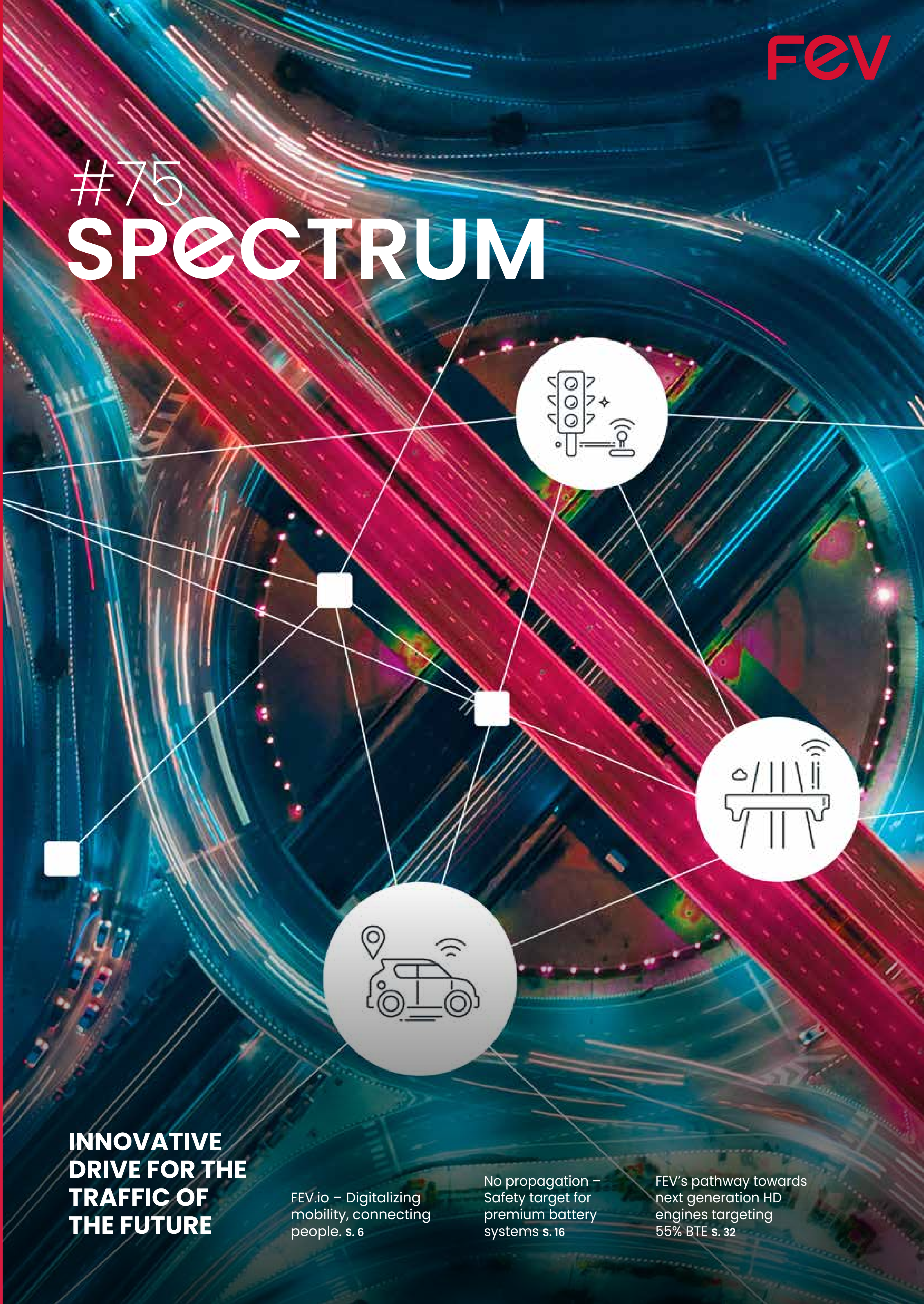

FEV

#75

SPECTRUM

INNOVATIVE DRIVE FOR THE TRAFFIC OF THE FUTURE

Dear Readers,

Intelligent, safe, and sustainable technologies are now an indispensable part of contemporary mobility. We are only at the beginning of the possibilities that will one day be accessible to everyone and change life for all. There are still a number of hurdles to be cleared for widespread implementation: Level 3 systems must be secured for all relevant scenarios; and the networking of infrastructure, people, and vehicles requires common standards. In addition, platforms are needed to enable continuous software updates. With the new global brand, FEV.io, we at FEV are addressing these and many other challenges associated with developing and connecting complex transport ecosystems. In this issue, we are very pleased to introduce you to FEV.io and to provide insights into the competencies of our colleagues who are working in this exciting field.

In this issue, we also present FEV development solutions for individual battery systems. Depending on the drive type and design goals, as well as other aspects such as BMS and integration, different development challenges arise for low and high voltages; for which we pursue different, reliable approaches. In another article, we address battery safety, which is critically important due to the increased energy and packing densities of battery systems being developed for next-generation vehicles with electrified powertrains. In this context, we illustrate how the close integration of development and testing leads to effective solutions.

To achieve climate targets, openness of technology, as well as to a diverse range of solutions, is essential in the mobility sector. Promising approaches in this area are provided by H_2 applications such as the fuel cell as well as the hydrogen combustion engine, with the most common application being based on the spark-ignition Otto combustion principle. In the following pages, we highlight potential for optimizing the powertrain to maximize the benefits of such an engine. Commercial vehicle fleets are also subject to strict targets to reduce CO_2 emissions by 30 percent by 2030 compared with the 2019 fleet average. This requires further improvements to the powertrain of medium and heavy commercial vehicles. SInce the combustion engine will continue to play an important role in commercial vehicles for the foreseeable future, the aim must be to continuously optimize and increase efficiency. And in this issue, we present a possible path to increase engine efficiency to a level of 55 percent.

I wish you an exciting read. You can find news and further information about FEV on our online channels, such as **www.fev.com**, or by reaching out to our highly qualified staff at any time.

Professor Stefan Pischinger
President and CEO of the FEV Group

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No propagation – Safety target for premium battery systems

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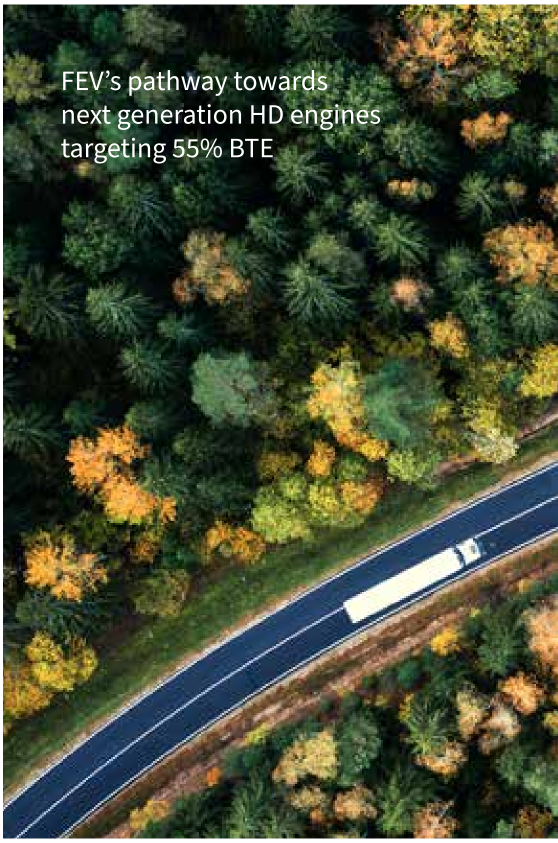


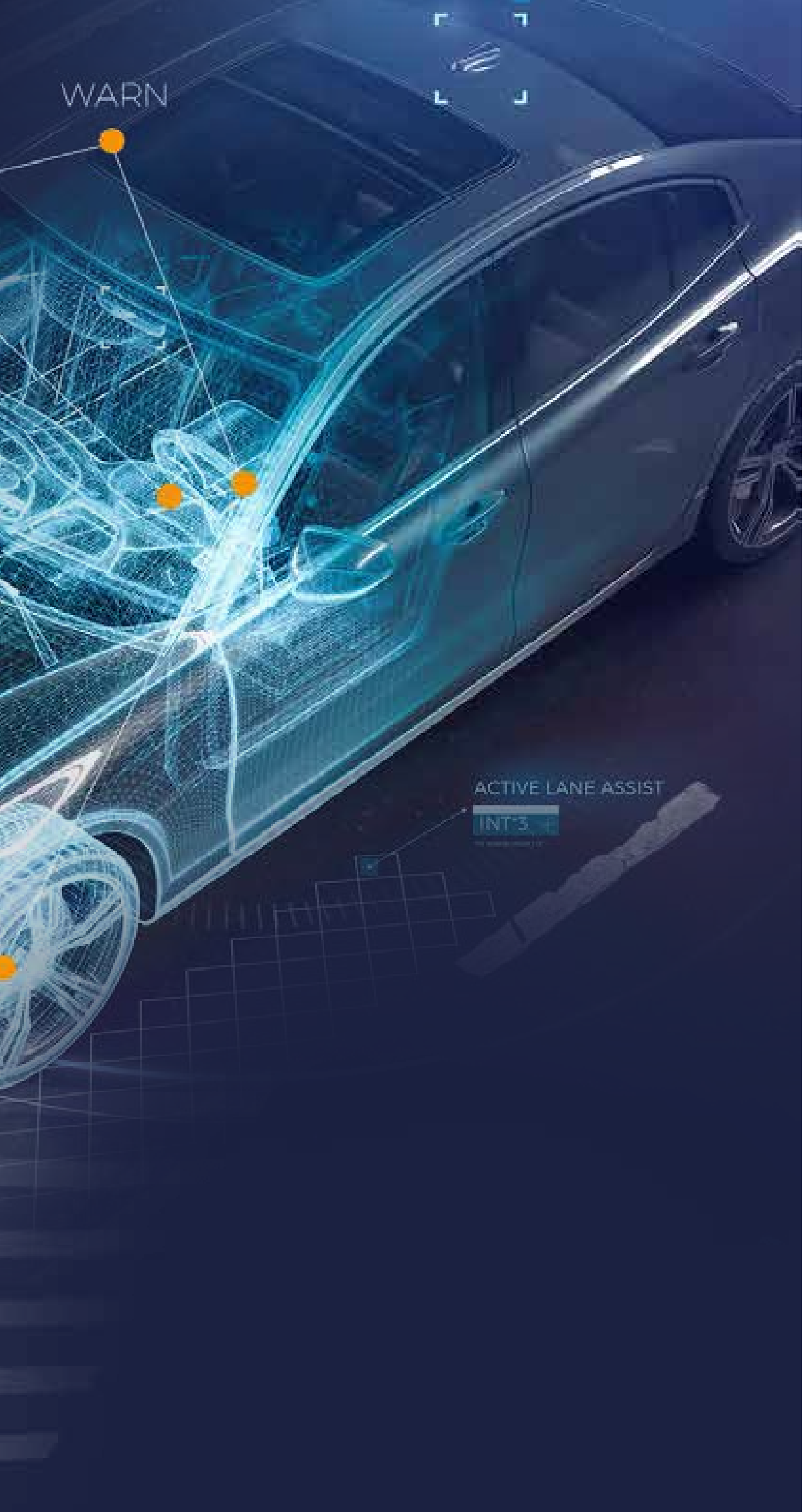
FEV's pathway towards next generation HD engines targeting 55% BTE

FROM RESEARCH AND DEVELOPMENT

NEWS

SOFTWARE & ELECTRONICS

FEV.io – DIGITALIZING MOBILITY, CONNECTING PEOPLE



Smart vehicles and mobility concepts are on everyone's mind. The whole world is talking about autonomous cars, buses that transport people on their own, and the linking of infrastructure – people and vehicles – to enable mobility for everyone. However, there are still many hurdles to overcome for widespread implementation: Level 3 systems must be secured for all relevant scenarios, and connectivity requires common standards. In addition, robust platforms are needed to enable continuous software updates. With its new global brand, FEV.io, FEV is addressing these and many other challenges to make intelligent, safe, and sustainable mobility a reality for all.

FEV.io is characterized by a deep understanding of software and electronics, combined with detailed expertise in all vehicle domains required for the development of intelligent mobility solutions. This is complemented by an understanding of data flows between vehicles and cloud servers that spans the entire ecosystem. This unique technological expertise enables the development and connection of complex transportation environments. Two performance examples provide a practical insight into FEV.io's business perspective.

Cost-efficient ADS solutions

The introduction of Level 3 Automated Driving Systems (ADS) is currently experiencing significant delays. A major reason for this is the challenge of defining and constructing the vast amounts of specific spaces and scenarios required for robust simulation. Since it is neither practical nor cost-effective to validate autonomous functions exclusively through the use of in-field testing, virtualization plays a crucial role in system validation. High-quality scenario data sets must describe specific driving situations, such as changing lanes on a three-lane highway, while accounting for all potential environmental influences, such as a sun that is low on the horizon, or rain-soaked reflective roads. This data is essential for the development of autonomous vehicles. And through intelligent data management, in combination with a scenario-based systems engineering approach, FEV.io ensures that the scenario data recorded by vehicles is of sufficient quality to support the various validation phases of an autonomous driving system.

FEV.io offers this solution after working together with a market-leading automotive manufacturer on a system that enables the qualitative evaluation of unprecedented amounts of scenario data. In addition to establishing requirements, FEV.io has created a performance catalog for various data sources and defined the standards for automated data transfer from these sources to the cloud. In the near future, this will enable customers to select the most suitable data sources as part of their overall strategy – ensuring the highest level of quality, safety, and effective cost control.

The union of information, entertainment, productivity, and connectivity.

Another example of challenges associated with intelligent mobility systems is the interface between man and machine, or HMI (human-machine interface). In the future, automated buses and taxis are expected to play a key role in public transport and offer a unique mobility experience. For many people, this will also be the first time they hand over control to a machine, which implies a maximum level of trust. The HMI system must therefore play a key role in building that trust and satisfaction among passengers.

In the case of an automated, self-driving minibus, FEV.io has developed an intuitive client based on the requirements of our society. For this purpose, visually- and acoustically-optimized systems were combined to guarantee a safe, engaging, and comfortable travel experience. This was supported by employing natural language assistants such as Amazon's Alexa, which create a high level of trust through a human-like communication experience. Smart displays provide essential route information, points-of-interest, and safety tips.

To successfully develop and implement this system, data had to be input, interpreted, translated, and output from various areas such as the powertrain, chassis, and areas in the immediate vicinity of the vehicle. By successfully modeling the entire system architecture, including all necessary interfaces, FEV.io created the basis for simplified and efficient collaboration between all development partners.

The FEV.io service portfolio

These two examples are only an excerpt from FEV.io's solution portfolio, which is divided into seven areas that solve the central challenges of intelligent mobility:

- System Engineering
- Functional Safety & Cyber Security
- Connected Mobility
- ADAS/AD
- Infotainment
- SW & EE Platforms
- SW & EE Integration

Thanks to its overall systems expertise, FEV.io can provide industry-leading know-how along the entire development cycle of mobility solutions, and, as part of the FEV Group, offer customers the entire spectrum of vehicle development support – from conception to start of production.

Contact
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INTERVIEW WITH JOHANNES RICHENHAGEN, MANAGING DIRECTOR OF FEV.io IN GERMANY

On the occasion of the founding of FEV.io, we spoke with Dr. Johannes Richenhagen, who together with Dr. Johannes Scharf will lead as managing directors of FEV.io in Germany.

Learn more about intelligent vehicles and mobility concepts
www.fev.io

What does the ".io" in the company name actually stand for?

Dr. Johannes Richenhagen: ".io" stands for input-output. With this name, we want to not only emphasize our digital origins, but also convey the message that we are a reliable and attentive partner who takes in our customers' input, transforms it in a customer-oriented way, and delivers valuable output from it. In doing so, we demonstrate true collaboration and design interfaces between partners and technology areas transparently and clearly.

Why did FEV decide to spin off its in-house intelligent mobility unit and establish a new brand in this segment at this particular time?

Dr. Johannes Richenhagen: In the FEV Group, we recognized the importance of software and electronics in the automotive sector and the value of software-defined mobility early on. Vehicles are already frequently defined more by software functions and less by their other characteristics. That is why we decided in 2019 to bundle all activities in this area into a separate business unit. This strategic decision set the course for the highly successful software and electronics or "digital" business at FEV.

Since customer needs and the pace of development in this digital segment require a very specific setup in terms of processes, working environment, and corporate culture, we needed an agile and rapidly adapting structure, and the autonomy to appropriately nuture it. With the establishment of FEV.io, we will now ensure this, while at the same time retaining our ability to leverage FEV Group's energy and mobility system development expertise, including vehicle and powertrain development – and vice-versa. This will ensure that the unique "from a single source" value proposition of FEV Group remains intact for all customers.

Does FEV.io work with partners?

Dr. Johannes Richenhagen: In order to offer our customers the best mobility solutions, we seamlessly complement the competencies of our own experts with the special skills and capacities of our partners as needed. In this way, we ensure efficient and maximum output in the interests of the customer. With Wipro, for example, a leading global IT provider, we offer joint solutions in consumer electronics and cloud services. We also have close partnerships with Ibeo, a pioneer in automotive lidar applications, and LiangDao, known for world-class testing and data management solutions. In this way, we create a cutting-edge trust of technological know-how for the development of automated driving systems.

That sounds like the place to be when it comes to software and EE development. Are there opportunities for aspiring team members to join?

Absolutely! Despite being well-equipped, we are always looking globally for eager pioneers and bright minds from all domains. We encourage interested parties to visit the career section of the FEV.com website. Alternatively, we welcome proactive applications to inquire at career@fev.com and use the keyword "FEV.io".

Thank you very much for the interview.

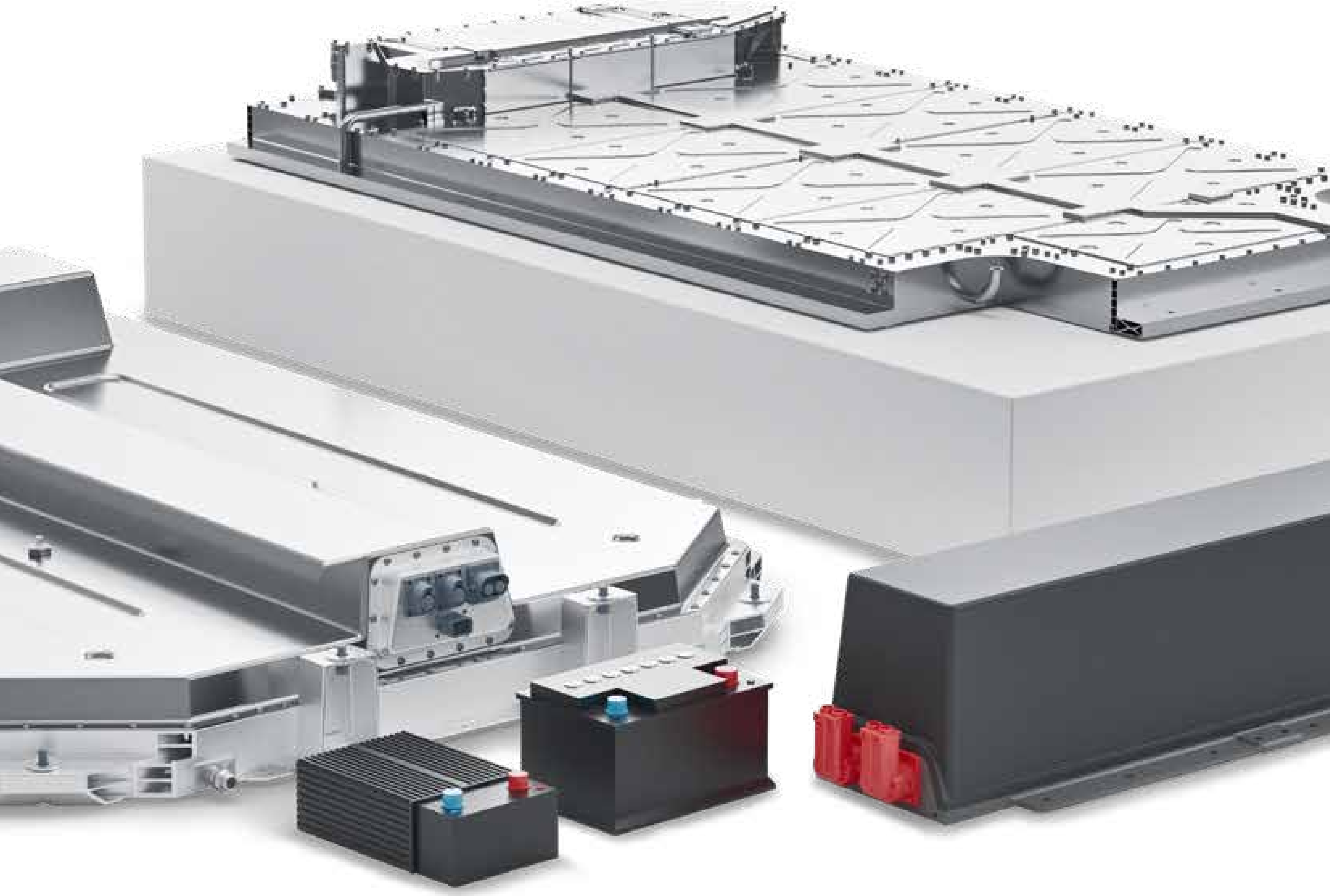
BATTERY DEVELOPMENT

TAILORED BATTERY SYSTEMS FOR ENTRY-LEVEL UP TO HIGH-PERFORMANCE APPLICATIONS

Today, approximately one quarter of global CO_2 emissions comes from the transportation sector, and road travel accounts for three-quarters of transport emissions. This statement highlights the importance of reducing the fuel consumption of on-road vehicles, and underscores the need to electrify all powertrains. The European Union has set clear targets to reduce CO_2 emissions from on-road vehicles, leading to a powertrain mix that will require electrification in the coming years.

As requirements in terms of use, market demands, legislation, and regulations will differ depending on the vehicles and geographical zones considered, FEV expects that while battery electric vehicles sales will increase tremendously for the next ten years and fuel cell vehicles will also be deployed, several forms of hybridization will also develop; leading to an eclectic offering of propulsion solutions. This offering will impact the requirements for the different batteries inherent to these systems, as each vehicle will be equipped with at least one electric energy storage system, at a low and/or high voltage, and will have different technical requirements.

From a low-voltage system (i.e., 12V or 48V battery to support SLI or a mild-hybridization respectively) to a high-voltage system (like those of a HEV, PHEV, BEV, or FCEV), requirements on the battery differ strongly due to the differences in the use of the vehicle both regarding high-level (e.g., power, capacity, packaging, etc.) and low-level (e.g., BMS, integration, etc.) requirements. These differences lead to upcoming development challenges that are equally complex. For example, if the use of lead becomes forbidden, 12V batteries will have to be based on different technology

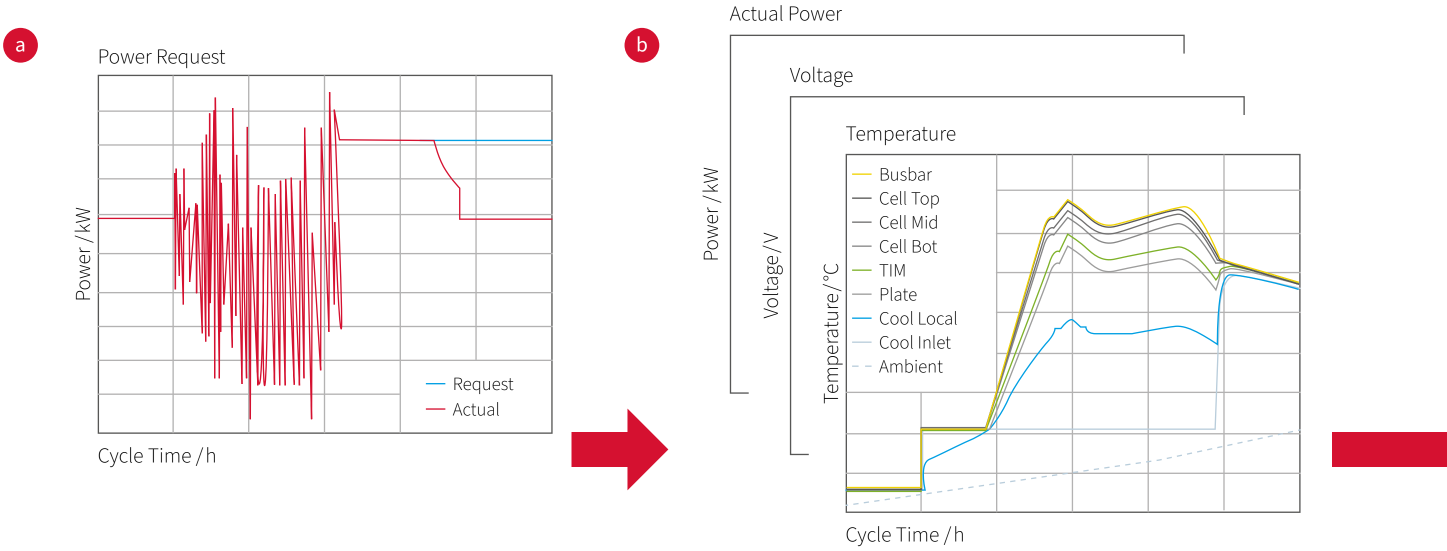


while maintaining the same operational performances at constrained costs. Similarly, high voltage for batteries will have to increase their power and energy densities to cope with stronger expectations both in terms of use and performance to enable BEV market penetration. In the following, FEV activities are presented that are aimed at ensuring that the battery systems to be developed, reliably meet their individual requirements in the diverse areas of application.

LV – 48V battery market and special features of 12V applications

Mild Hybrid vehicles are especially expected to grow significantly in the coming years. The voltage level remains lower than 60V, enabling easier cost mitigation due to relaxed constraints compared with higher voltage levels. Nevertheless, the power is limited and 48V systems allow a maximum of 30 kW at peak, for a limited full-electric drive in specific configurations. Despite the 48V introduction that just occurred approximately five years ago, electric power requirements do not cease to increase, and the new possibilities brought by 48V systems lead OEMs to install more and more auxiliaries in the 48V system; adding more requirements to the 48V battery—namely the availability of components in key-off conditions. Additionally, expected strengthening of pollutant emission standards (e.g. Euro7) will lead to the installation of high power electric components, such as electrically heated catalyst; relying totally on the 48V battery to operate and further constraining the batteries.

In the application field of 12V systems, significant differences arise compared to the other domains, as the aim is generally not a distributed architecture but a fully integrated one—ideally on one board. The



① *Schematic representation of the lifetime estimation. The requested battery power (a) is used as initial input. An electrothermal model calculates the actual cell loads (b) at each SoH step. Those loads are analyzed by the aging model (c) to deduce the*

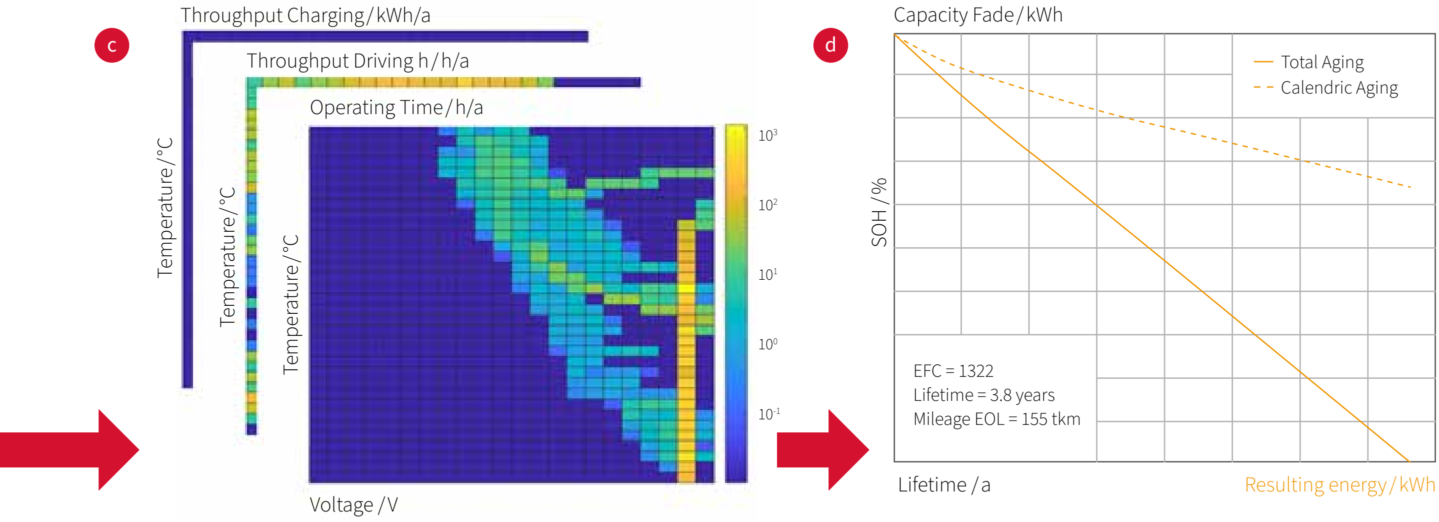
BMS components are typically supplied from their own cell stack, and thus require self-current measurement. Since standby loads must be continuously supplied, the isolators are permanently closed, even during sleep mode. The wide range of currents encountered, including high rates for motor starting, constitutes a challenging target for measurement accuracy. If a supply for (partially) autonomous driving is desired, functional safety requirements also arise and the battery must be secured according to ISO 26262 for a safe power supply. Due to the direct competition with lead-acid batteries including for intelligent battery sensors, the cost pressure is very high. The BMS hardware must also meet significantly lower requirements in terms of insulation.

Lifetime simulation for HEV/PHEV supporting system layout and design

PHEV and HEV battery systems must meet power requirements similar to BEV systems, but with a much smaller battery capacity. Consequently, single cells have to electrically withstand higher continuous and peak power loads. Based on extensive vehicle simulations, decisive parameters such as the usable energy quantity and the energy throughput over the service life, must be derived to identify a suitable battery cell. The increased heat losses resulting from high relative cell currents further call for an elaborate investigation of the thermal behavior to avoid overheating and cell degradation.

Besides the instant electric performance, a crucial factor in battery development is the service life target, which is given by the total mileage before reaching a minimum residual capacity. In this regard, the overall use of the vehicle must be considered. Respective scenarios ideally cover entire days with different use cases of the vehicle including standstill times. This way, the delicate dependence of cyclic and calendric aging on cell temperature, voltage, charging and discharging currents, as well as SoC and DoD, can be accounted for. For aging calculations, FEV has developed a tool for fast estimation of the battery lifetime (see Figure 1). Starting from power requirements and available charging power (Figure 1, a), cell states and loads are calculated via an electrothermal model, shown here exemplarily for temperature development throughout an adapted WLTC and charging cycle (Figure 1, b). For each scenario and each state of aging, distinct histograms of key aging parameters are obtained (Figure 1, c), which in turn result in a current aging rate. Integrated over time, these rates yield the expected lifetime (Figure 1, d).

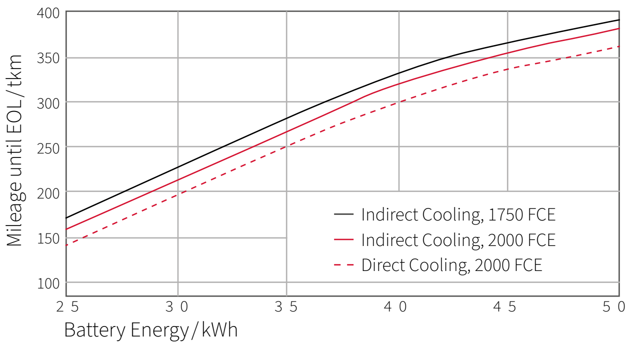
In an exemplary case, the question is raised whether a high-range PHEV battery pack can be realized using NMC 811 cells. To this end, the expected lifetime is calculated in dependence of the energy content (Figure 2). Initially, NMC cells (Lithium nickel manganese cobalt oxides) with an approximate cyclic stability of 2,000 FCE (first cycle efficiency) at reference conditions are investigated. Indirect cooling via a bottom cooling plate is assumed (solid red line). As expected, the lifetime increases with rising battery capacity due to reducing electrical and thermal loads. Towards higher energy contents the curve flattens, indicating the increasing relevance of calendric aging during standstill. A mileage of 250,000 km is reached at about 33.1 kWh, suggesting a target energy of 34.6 kWh for technical reasons.



current aging rate and calculate the expected battery lifetime (d).

Despite the promising results, the more extreme use cases suggest the need for advanced cooling techniques to avoid thermal degradation. Therefore, a thermal design using immersion cooling is investigated (solid black line). Again, a cycle stability of 2,000 FCE is assumed. Comparing both cooling approaches the limited effect on battery lifetime becomes obvious: The benefit amounts to only 10,000 km of mileage until reaching 80% state of health (SOH).

Consequently, a PHEV battery can be realized using chosen NMC cells and indirect cooling. Service life targets of 250,000 km are met with a capacity of 34.6 kWh.



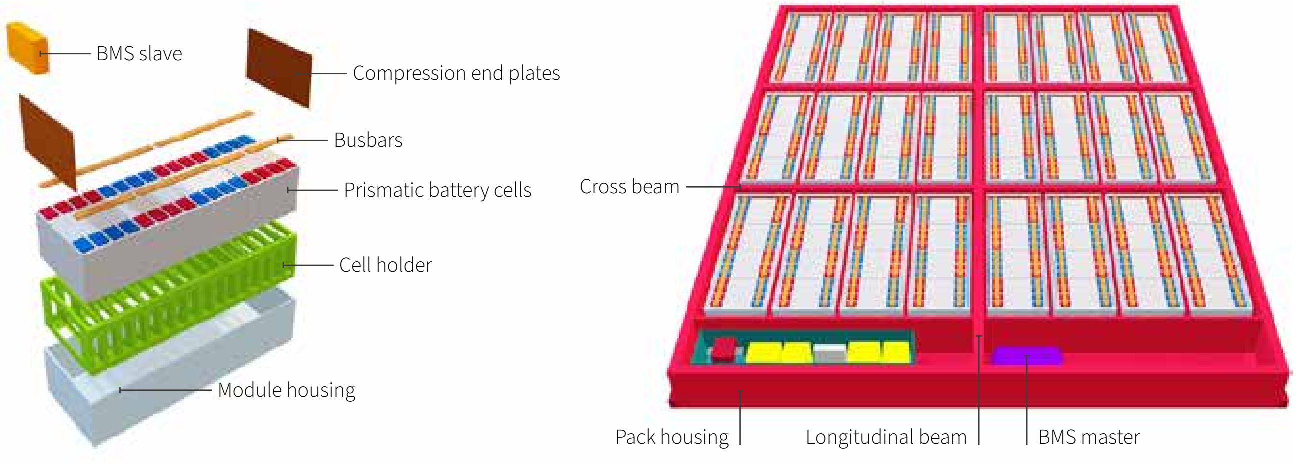
② *Expected lifetime (mileage until EOL) of a PHEV battery utilizing NMC cells in dependence of the battery size for different cooling approaches*

Concept study on highly integrated BEV battery packaging

Since high energy density on system level is particularly significant for purely battery electric vehicles to achieve a long driving range, highly integrated design approaches such as cell-to-pack are crucial, in addition to the energy density of the cells. To investigate geometric potentials of design approaches with different degrees of integration, battery concepts were generated and evaluated with FEV's battery concept tool. Various design parameters for wall thicknesses, air gaps and component dimensions are considered and configured according to experience gained over many years to ensure feasible battery concepts. The focus is on comparing battery systems based on NMC cells to LFP (lithium iron phosphate).

A conventional modular battery pack is based on subunits containing a specific number of cells, which are then assembled into a pack. To further increase the energy density of the battery system, cell-to-pack approaches aim to skip the intermediate step of modules and integrate battery cells directly into a pack.

The basic concept represents a 400V BEV battery with 70 kWh energy from an FEV development. The battery contains state of the art prismatic CATL 50Ah cells in standard VDA PHEV2 format with NMC cathode, interconnected in 4P96S and divided into 24 modules. To contribute a high structural rigidity to the vehicle frame and to guarantee sufficient safety in case of lateral impact, the pack has a robust housing plus one longitu-



③ *Three-dimensional graphic of battery module in exploded view and battery system concept*

dinal and two cross beams in addition. The necessary E/E components such as contactors, fuses, shunts, and the rest; as well as the BMS master, are placed in the front area of the battery. Shielding plates are placed between the battery modules as an avoidance measure for thermal propagation (TP). Figure 3 depicts the battery components modeled in the tool and, on the right, the basic concept in the conventional module-to-pack design.

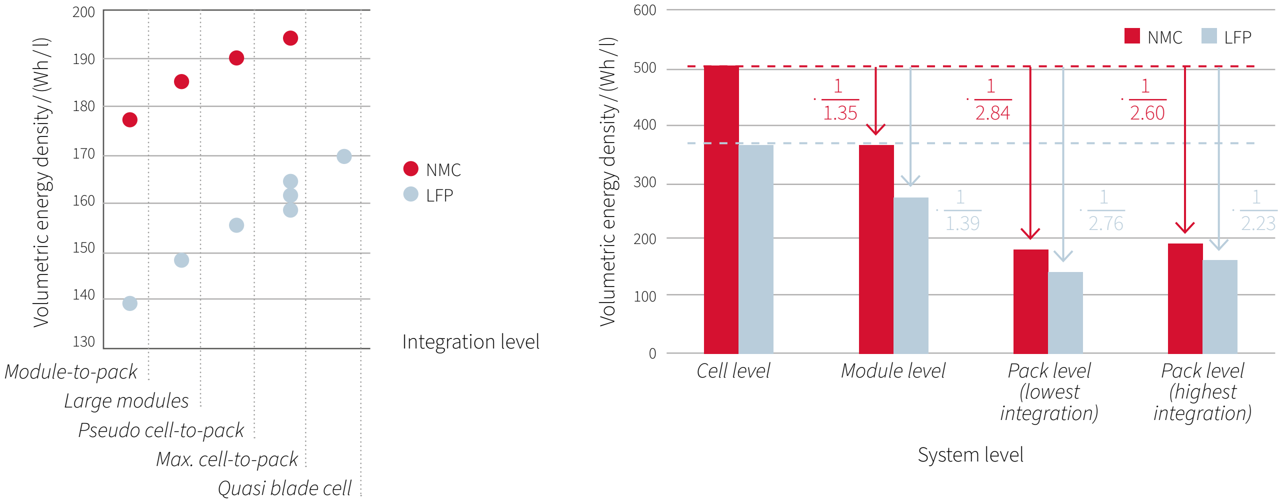
To evaluate the energy densities at different integration levels, a pack with identical external dimensions, layout in terms of cell geometry, module arrangement, housing, cross and longitudinal beams and more is designed from cells with LFP cathode for comparison. At the module level, there is now a 3P5S interconnection to best compensate for the lower nominal voltage of the LFP cells for the module and still remain close to the cell count 16 in the original concept with a total of 15 cells here. The reference is a prismatic CATL LFP 110Ah cell, whose capacity is rescaled to a custom cell format in order to match the exact external dimensions of the battery pack with NMC cells, which results in a capacity of 49.07 Ah. The proportionality factor here is the volume of the electrode stack. Due to the lower cell energy density, this leads to a total pack energy of 56.5 kWh.

In the following, it is assumed that the LFP cell intrinsically provides a higher safety level than the NMC cell since it does not contain oxygen at the cathode. Studies demonstrate that LFP cells show a lower tendency to TR and, even in the case of a thermal event, burn only at about 400 degrees Celsius compared to about 1,000 degrees Celsius for NMC cells. They also develop less venting gas volume by a factor of approximately five. In addition, there is less energy introduced in the overall system due to the lower energy density of the LFP cells. Based on these assumptions, denser packaging than in the analogous NMC concept is implemented in the following concepts that incorporate LFP cells. On the way to an increasingly integrated pack design, the design parameters are adapted step-by-step, or components are omitted. In general, various strategies and combinations of measures are possible for cell-to-pack designs. In this study, the housings and the cross-members are left unchanged, since structural stiffness is an essential criterion and is independent of the cell chemistry used.

The feasible degree of implementation for a particular application strongly depends on its requirements and the boundary conditions for vehicle integration.

Large modules: In the first adjustment step, the number of cells per module is doubled and the number of modules is

④ *Concept layout visualizations of designs in increasing integration levels*



⑤ *Energy density in different integration levels and on different system levels in comparison*

halved accordingly. Due to fewer gaps between the modules and the reduced module housing material, a slightly higher packaging density is achieved.

Pseudo cell-to-pack: Subsequently, the module housings are omitted, but a subdivision into cell groups according to the original modules remains.

Maximum cell-to-pack: Thereafter, the spacing between the cell arrays is reduced for the NMC battery, which still allows some design measures against TP between the cell arrays. For the LFP cell, a stepwise study is performed for the inter-cell clearances to investigate the geometric potentials and parameter sensitivity assuming a cell featuring an extremely low TR tendency.

Quasi blade cell: At last, an LFP battery with the same external dimension is designed with a rescaled extremely large cell in 1P interconnection. The cell extends over almost half the battery width and is inspired by the LFP blade cells developed by BYD.

Some LFP concept layouts of the different integration levels are visualized in Figure 4

The study shows that by increasing the integration level, the energy density of the NMC battery can be increased from 177.4 Wh/l in the baseline design to as high as 194.2 Wh/l. Similarly, the energy density of the LFP battery increases from an initial 139.3 Wh/l to up to 164.4 Wh/l and even 169.2 Wh/l with the use of very large cells. It is particularly noteworthy that the energy density of the NMC example at the cell level with 504.6 Wh/l is a factor of 1.36 above the LFP cell with 371.4 Wh/l, but at the pack level in the highest integration design, there is only a factor of 1.15 in between. This higher packaging density is expressed by the volume factor between the total system volume and the pure cell volume of a battery. Figure 5 summarizes the resulting energy densities of the NMC and LFP batteries from cell to system level for the different integration levels and also indicates packaging density volume factors.

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The content of this article was first published at this year's International Vienna Motor Symposium.

In conclusion, the study confirms the geometric potential that, assuming a very high level of cell safety, an LFP battery can be significantly closer to the energy density of an NMC system at the pack level than the difference at the cell-level initially suggests due to the possibility of denser packing.

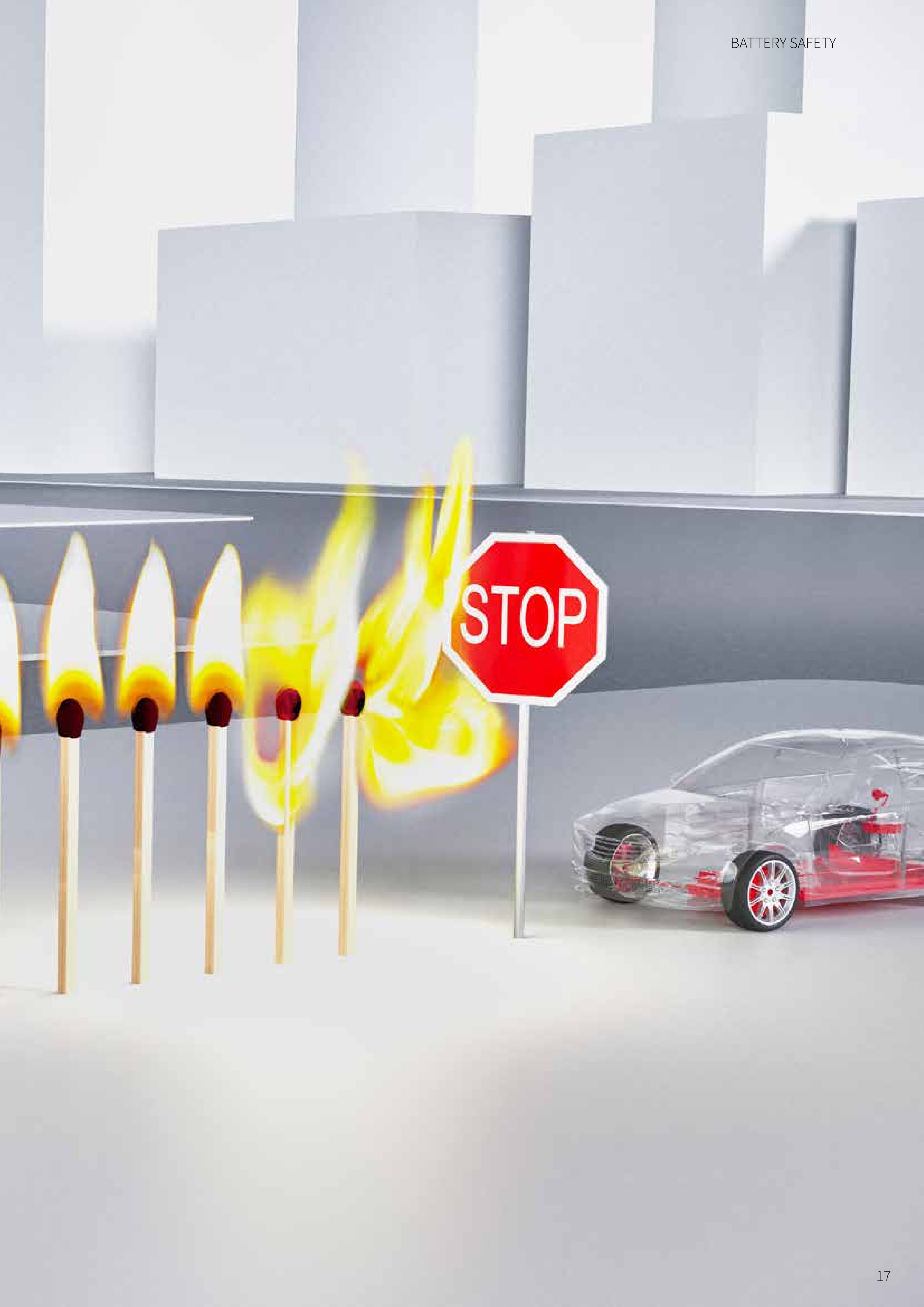
Nevertheless, it is important to emphasize that the densest maximum cell-to-pack integration level for LFP in particular is considered as a theoretical maximum. Also, the very large quasi-blade cells will have to prove their maturity and reliability over a long period of time.

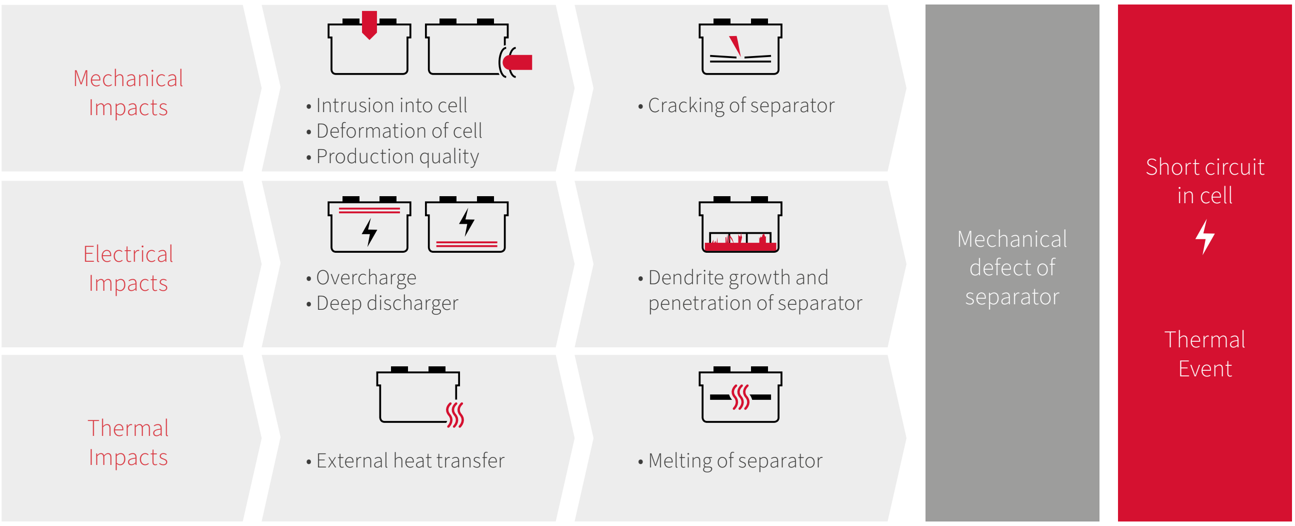
BATTERY SAFETY

NO PROPAGATION – SAFETY TARGET FOR PREMIUM BATTERY SYSTEMS

Battery systems for vehicles with electrified powertrains must achieve ever higher energy densities while maximizing safety and reducing costs to offer customers the highest driving ranges at affordable prices. Higher energy densities at the system level are achieved by new battery cells and higher packing densities with, for example, cell-to-pack or cell-to-chassis approaches. But higher energy densities also lead to significantly more reactive cell chemistries and larger cell formats. This increases the risk of battery fires occurring as a result of manufacturing defects in the cell or operating faults. The severity of a so-called “Thermal Runaway” increases as the reactivity of the cell increases. At the same time, the requirements for passive safety up to "Stop Propagation" or even "No Propagation" are continuously increasing. To achieve these goals, close integration of development and testing is required.

On this topic, FEV has developed and combined multiphysics and fluid dynamic models that help to reduce the development time of lithium-ion battery systems and define a safe system as early as possible in the process. Initial cell tests generate the necessary input data for the simulation models. Subsequently, various measures for optimizing the thermal propagation behavior can be tested virtually. The accuracy of the models can be further optimized by cascaded test series with different cells, materials, and venting systems; and can be applied at cell level, in the cell compound, in the module, in the module compound, or in the overall system. The chosen approach ensures the validation of the thermal propagation homologation test at the earliest possible stage of development. In this way, it is possible to develop an effective solution methodology for "Stop Propagation".


STOP



① *Thermal runaway trigger mechanisms*

Thermal Runaway and Propagation

Thermal runaway (TR) is the most severe failure mode in lithium-ion batteries (LIBs). It describes a self-accelerating exothermic chain reaction within the cell that can lead to high temperature, explosion, fire, and release of toxic and flammable gases and particles, thereby posing a serious risk to vehicle occupants. TR can be triggered by different mechanisms, shown in Figure 1.

Without sufficient countermeasures heat from the triggered cell is transferred to the neighboring cells in a battery module or pack, which can then themselves go into TR. This event is called thermal propagation (TP).

Design Measures Towards No Propagation

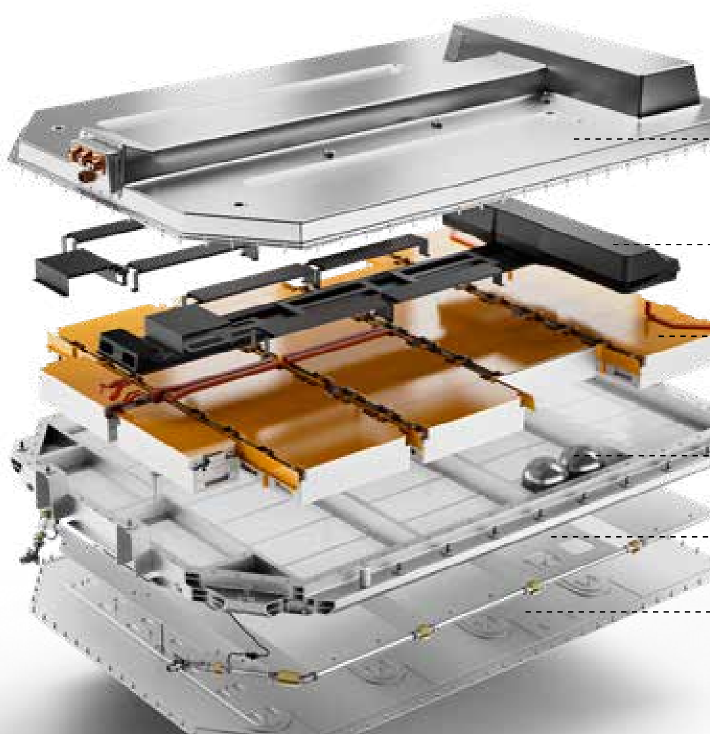
FEV uses a variety of design measures to increase the safety of battery packs and stop TP. These measures can be divided in different categories based on their targeted effect.

To mitigate cell-to-cell heat conduction, usage of thermal insulation materials is a well-established method. Special thermal barriers, that fit the requirements regarding low thermal conductivity, stability at elevated temperatures, and mechanical flexibility to compensate for cell swelling, are commonly used.

The battery pack needs to be designed with a redundant venting valve layout to reliably release the vent gas from the system and avoid significant overpressure. Short path lengths from the event cells to the valves minimize heat impact on other pack components. To ensure passenger safety, ignition of the gas/air mixture outside the battery housing must be prevented. Therefore, smoldering particles in the exhaust gas above a certain size must be filtered out. The corresponding filter system (e.g., metal meshes) must be able to endure high exhaust gas temperatures of over 1,000 °C, as well as retain large quantities of particles in a short period of time without losing its filtration function or becoming clogged.

Figure 2 shows a high-voltage battery pack with design features for TP prevention. Mica sheets are used for thermal and electrical insulation of the modules and other critical components. Pressure relief valves serve to equalize the pressure during regular operation and during a TR event. The metal mesh filters are shaped as hemispheres to allow particles to slide off.

② *Exploded view of a high-voltage battery pack with design features to prevent TP*



The potential of electric arc formation is minimized by reducing the voltage differences and increasing the clearances between components with different potentials. This can be achieved by designing module-to-module busbars as meltdown fuses and using busbar terminal covers and temperature resistant busbar insulation.

Utilization of the battery cooling system during TP homologation test is not explicitly prohibited. Apart from the risk of cooling system failure in a real-world vehicle crash scenario, an optimized cooling strategy in case of TP can remove a significant amount of heat from the battery pack, thus mitigating TP. To ensure cooling system functionality in case of TR, it needs to be properly protected from mechanical impacts and requires a separate energy source for the cooling pump.

Thermal Propagation Testing

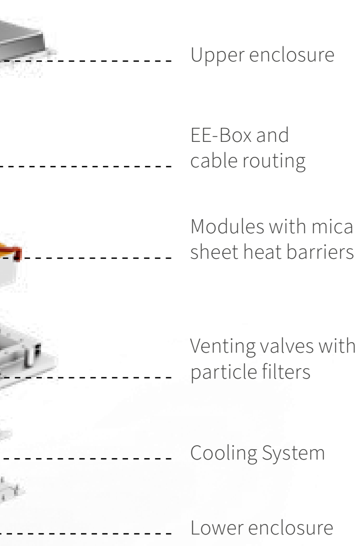
Testing plays a significant role in every phase of high voltage battery development. At FEV's eDLP, a cascaded testing approach for TR and TP mitigation is successfully used. This method provides necessary measurement results for the initial parameterization, adaptation, and validation of simulation models. Figure 3 shows the cascaded test procedure from single cell to full pack testing.

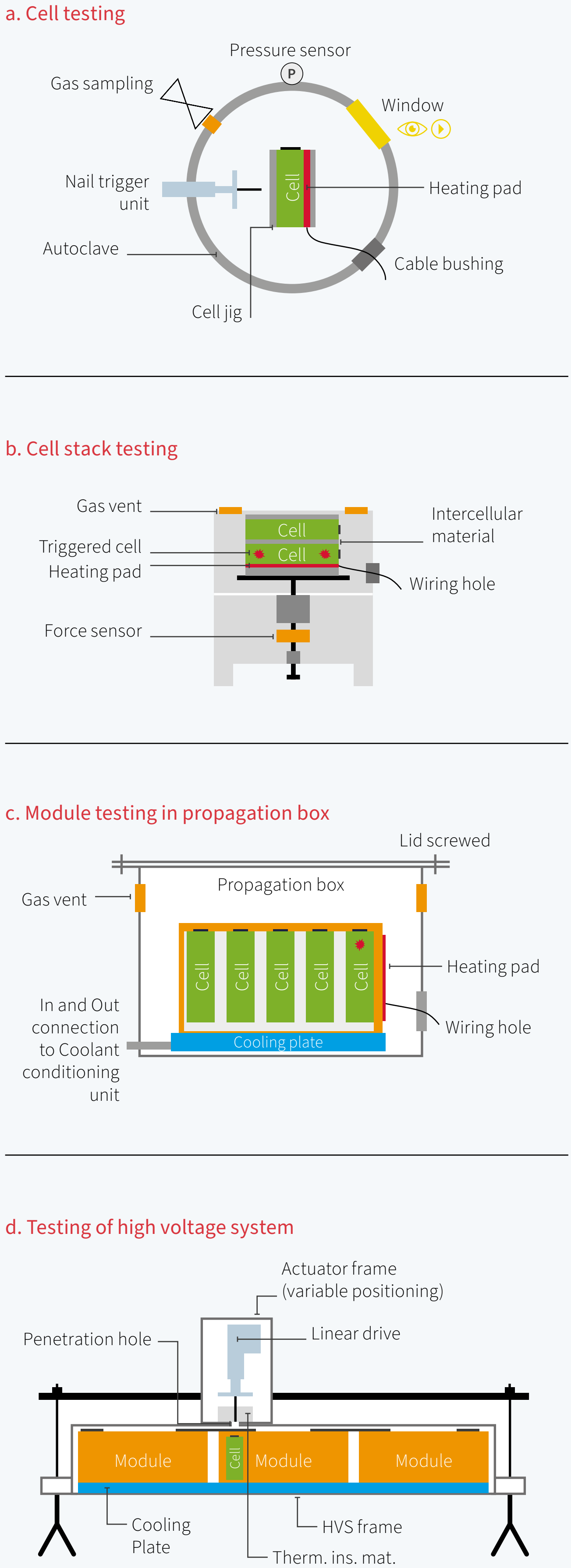
Single cell tests are necessary to identify the cell-specific TR characteristics. These tests are typically conducted in an (adiabatic) autoclave. The setup provides a confined environment to the device under test and allows to measure relevant data like vent gas amount and composition or onset temperature of TR.

Cell composite tests offer a convenient way to investigate intercellular and thermal insulating materials for their propagation behavior. The focus here is to prevent thermal infection of the neighboring cell. Furthermore, geometric solutions can be used to investigate fire suppression measures.

The propagation box offers the possibility to investigate different cooling strategies or active extinguishing concepts for individual modules or module groups to prevent TP. One of the major advantages is the variable positioning of the trigger and sufficient space for the required additional measurement equipment.

In addition, FEV offers tests for entire high voltage systems necessary for homologation, with a subsequent disassembly and detailed analysis. This allows direct evaluation of the separation of the high voltage lines, the condition of the insulating materials, and the occurrence of electric arcs.





③ *Schematics of the cascaded test approach from single cell to full pack testing*

Simulation Methodology

To support design decisions and minimize testing effort, FEV has developed a TR/TP simulation methodology. The methodology consists of two separate numerical models. In COMSOL Multiphysics a detailed thermal model and in StarCCM+ a computational fluid dynamics (CFD) model of the vent gas flow has been developed.

The multiphysics model can resolve the heat generation during TR inside of the cell locally and time dependent. It can accommodate for different cell triggering methods and the reaction kinetics during TR are modeled by Arrhenius correlations. TP is simulated considering conductive and radiative heat transfer in and between solid components with detailed material properties. Thus, the model allows evaluation of the temperature distribution and propagation times from cell to cell and module to module. Different design choices to stop TP can be investigated. Figure 4a exemplarily shows a successful TP stop by utilizing thermal barriers between modules.

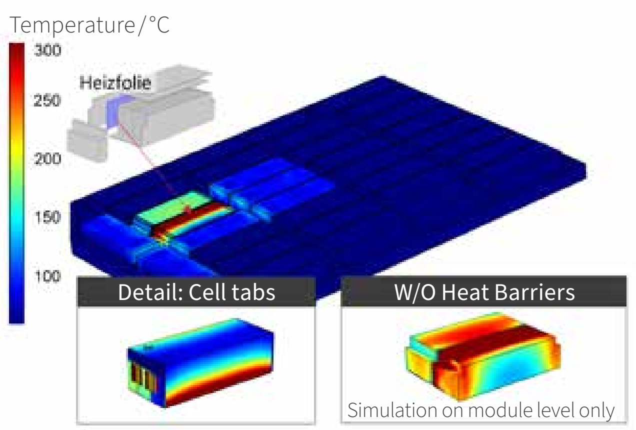
The CFD model gives insides into the flow behavior of the vent gas from the triggered cell or module to the vent valves installed in the pack housing. Detailed degassing characteristics of the valves are considered. Thus, the time dependent overpressure inside the pack can be evaluated, which can further be used in structural simulations of the pack housing. Furthermore, dedicated venting paths can be developed to quickly guide the hot vent gas away from critical components. Convective heat transfer to neighboring modules and other temperature-critical parts such as busbars can be simulated and then used as an additional boundary heat source in the multiphysics thermal model. An example of the vent gas distribution inside of a battery pack is shown in Figure 4b.

Coupling the CFD model with a Lagrangian particle model allows to simulate the transport of small ash particles and other unburnt cell material ejected from the event cell. The cumulation of the particles in certain areas of the pack and the likelihood of particles containing significant energy leaving the pack through the vent valves can be investigated. Moreover, qualitative feedback on the abrasive potential in critical areas can be given. An example of the diameter-dependent particle distribution is given in Figure 5a.

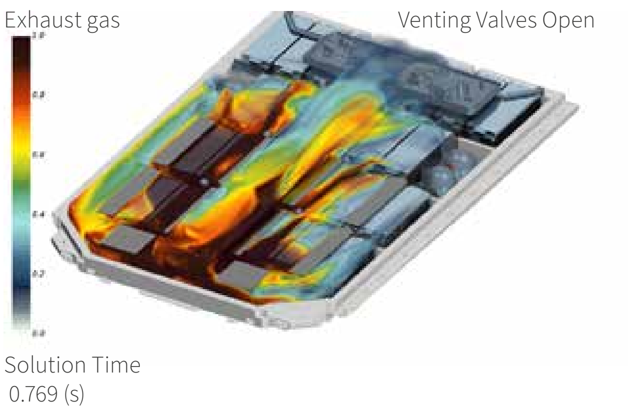
Furthermore, using a simplified combustion approach, additional harms like increased housing loads due to increased pack pressure and higher thermal loads because of higher gas temperatures can be considered. An example of the flame front simulation is shown in Figure 5b.

With the current simulation methodology, many development requirements can be met. However, one major remaining risk for TP homologation test failure is the formation of electric arcs during TR and TP. Although the clearances and creepage distances in the pack are designed to reliably prevent arcing during normal operation, the arcing behavior during TR and TP is virtually unknown. To address this issue, research is being conducted to model the potential of arc formation. Particles in the vent gas flow and ions in the flame front are identified as the major factors influencing the breakdown voltage of the gas. Therefore, previously discussed particle and combustion modeling techniques need to be coupled and further refined. Based on experiments, the existing breakdown voltage formulations will be adapted to the TR conditions in the battery pack and implemented in the model. This will lead to a better physical understanding of the electric arc formation and appropriate countermeasures can be developed.

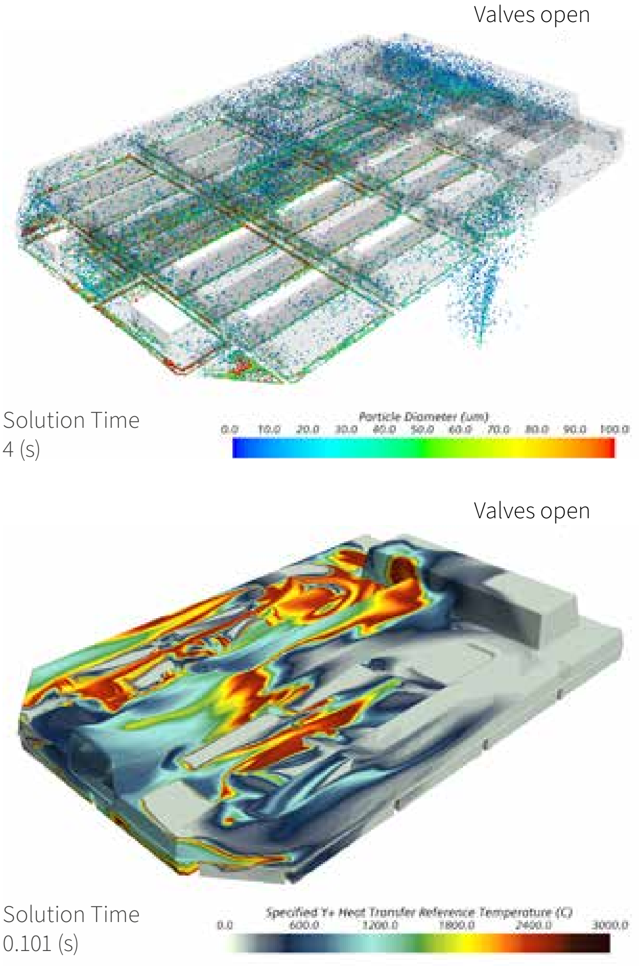
a



b



④ *a: TR and TP simulation in COMSOL Multiphysics: effect of heat barriers, B: CFD simulation in StarCCM+: vent gas distribution*



⑤ *a: diameter dependent particle distribution in particle flow simulation, b: near wall temperature distribution in flame front simulation*

Summary and Outlook

Legislative requirements for passenger safety significantly increase the development efforts to achieve TR/TP prevention goals. The presented tool and methodology chain considers advanced simulation tools to prove the potential of design measures and a cascaded testing approach to parametrize and improve the simulation models. It offers major advantages in battery development, as well as increased safety of the vehicle in customer use.

A variety of design measures can be used to mitigate TP and increase battery safety. These include the effective use of thermal barriers, dedicated venting paths with minimized impact on critical components, the use of redundant venting valves and pre-filters, coverage of temperature or arcing critical components with additional insulation such as Mica sheets, and a dedicated cooling strategy in case of TR.

Improved combined multiphysics and fluid dynamic simulation models help to reduce costs and accelerate the development time of thermal propagation resistant battery packs by significantly reducing the testing efforts. Moreover, important topics such as simulation of arc formation in the case of TR/TP are currently under development and will further improve the benefits of virtual testing.

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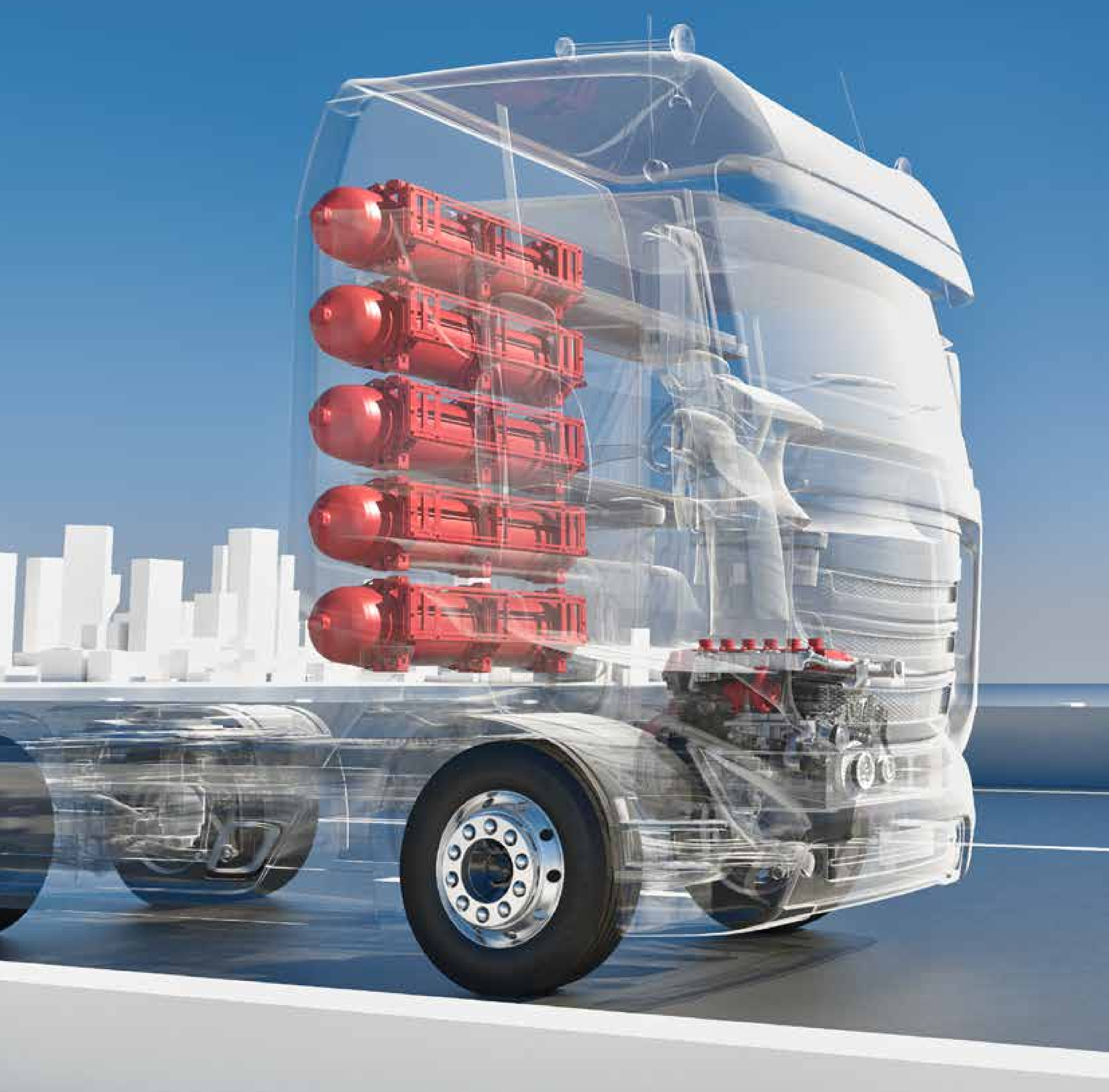
H2 ICE

POWERTRAIN OPTIMIZATION FOR THE H2 INTERNAL COMBUSTION ENGINE



Several different combustion system options exist for H2 ICEs. Suitability varies by application and depends also on availability of enabling technologies. The mainstream application uses a spark ignited "Otto" combustion principle. Such engines, powered by H_2 alone, will be considered further in this paper.

Combustion systems

Port fuel injection system (PFI)

With PFI, hydrogen is injected into the intake manifold at low-pressure levels (~10 bar). The long time for mixture preparation and the turbulence created at the intake valve ensure a high level of mixture homogeneity. The occurrence of rich air/fuel areas is limited, which reduces the NOx formation and the knock tendency.

On the other hand, the external mixture formation reduces the cylinder filling. At a typical lambda value of 2, the cylinder air charge is reduced by ~20 percent. Both fresh air and hydrogen must be pushed into the cylinder. Consequently, the boost pressure demand strongly increases.

Thermodynamic investigations have been carried out on a 7.7L engine, modified for H_2 operation. Diesel- and CNG-like BMEP levels have been reached thanks to an upgrade of the boosting system (two-stage TC replacing original single TC) and optimized piston design. Eventually, a maximum BMEP of 19.6bar was demonstrated. Also, achieving the CNG engine power level of 220 kW was possible.

A PFI system is easy to integrate in an existing engine. Injectors are already available on the market. Hence, a PFI configuration represents an attractive solution for retrofitting lower power applications. On the top of that, the risk of failure is low since well-proven technology is used.

Safety risks must be mitigated because of backfire. Valve timing adaptation is recommended. Intake and exhaust valves must not overlap as ideally no hot gases should be pushed back to the intake side.

	External mixture preparation	Space requirement cylinder head		
	Low pressure PFI	**Low pressure DI**	**Mid pressure DI**	**High pressure DI**
Fuel Injection	Port fuel injection ~ 5 – 10 bar	Direct injection ~ 15 – 30 bar	Direct injection ~ 40 – 60 bar	Direct injection ~ 300 bar
Specific Power (HD) enigne	< 25 kW/l	> 25 kW/l	> 25 kW/l	~ 30 kW/l
Peak BMEP (HD) engine	< 20 bar	> 20 bar	> 20 bar	> 25 bar
Combustion	Stoich/Lean Spark ignited	Lean Spark ignited	Lean Spark ignited	Lean, Spark ignited -- Diffusive
Knock tendency	↓	0	0	↑ **(SI)** -- Not existing (Dif.[1])
Boost pressure demand	↑↑	0	0	0
Transient load response	↓↓	0	0	↑
Main benefit	· Easy to integrate · Hardware available · Low failure risk	· Robust against back-fire · Power density · Trainsient response	· Same as LP DI · Smaller packaging compared to low pressure · Potentially better mixture preparation	· Same as MP DI · Diffusive combustion possible
Main challenges	· Boosting · Safety (Backfire)	· Integration DI Injector · Uniform mixture preparation	· Integration DI Injector · Range	· Integration DI Injector · High pressure generation · For Diffusive combustion high NOx raw emissions

① *Injection systems for heavy duty engine (13l) with single stage turbocharging.*

1: Diffusive combustion

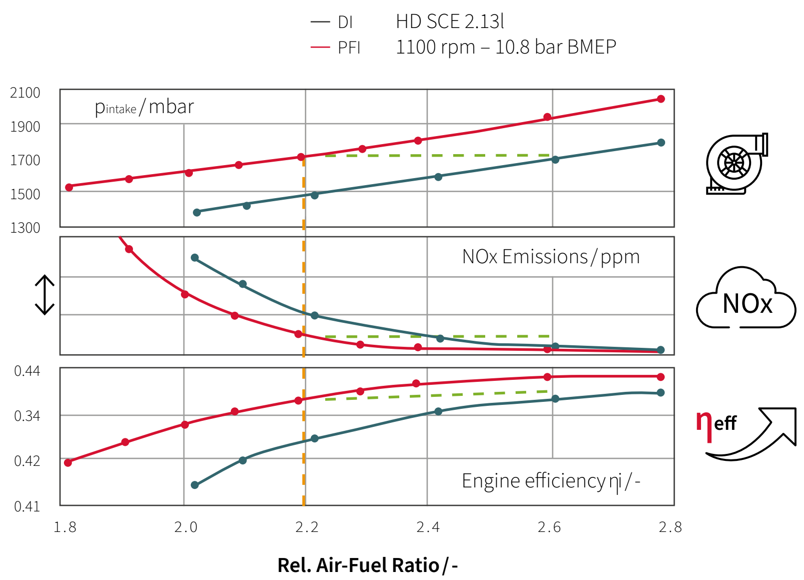
Nevertheless, load response remains a drawback with a PFI layout. A mild hybrid support with a 48V system can be a good lever to significantly improve the transient behavior. Choosing a DI system is another possible option.

Direct injection system (DI

Low pressure direct injection (LP-DI) requires an injection pressure ranging from 15 to 30bar. With medium pressure direct injection (MP-DI), the fuel is injected at 40 to 60bar, which reduces the injection duration. Thanks to the higher fuel pressure, a possible benefit exists in mixture formation, as a higher air/fuel ratio can be utilized.

The results of experimental investigations shown in Figure 2 were carried out with a heavy-duty single-cylinder engine. When comparing at constant BMEP level and constant lambda, the DI configuration has disadvantages in NOx emissions and engine efficiency. However, for a realistic evaluation, a comparison at the same boost pressure is more meaningful. Here, DI offers an advantage in NOx emissions at the same engine efficiency level.

With its shortened time for mixture preparation, a major challenge for DI systems is to provide PFI-like mixture homogeneity. Further improvement is being researched with the aid of simulation tools, which may lead to higher benefits from the DI solution.



② *Comparison of NOx emissions, engine efficiency and boost pressure between PFI and DI as a function of relative air/fuel ratio*

For high pressure direct injection (HP-DI), a pressure level of around 300bar is required. The standard hydrogen tank pressure is either 350bar or 700bar. It means that HP-DI can only be realized if on-board high-pressure generation is possible. A major advantage of HP-DI is the possible diffusive combustion, which eliminates the need for a spark plug, offers knock-free combustion and potentially higher power density.

The integration of a DI system into the cylinder head is a challenge. Due to the very low density of gaseous hydrogen, the injector is very voluminous. With higher pressure, the packaging is easier, as the injectors can be made slimmer for the same mass flow rate.

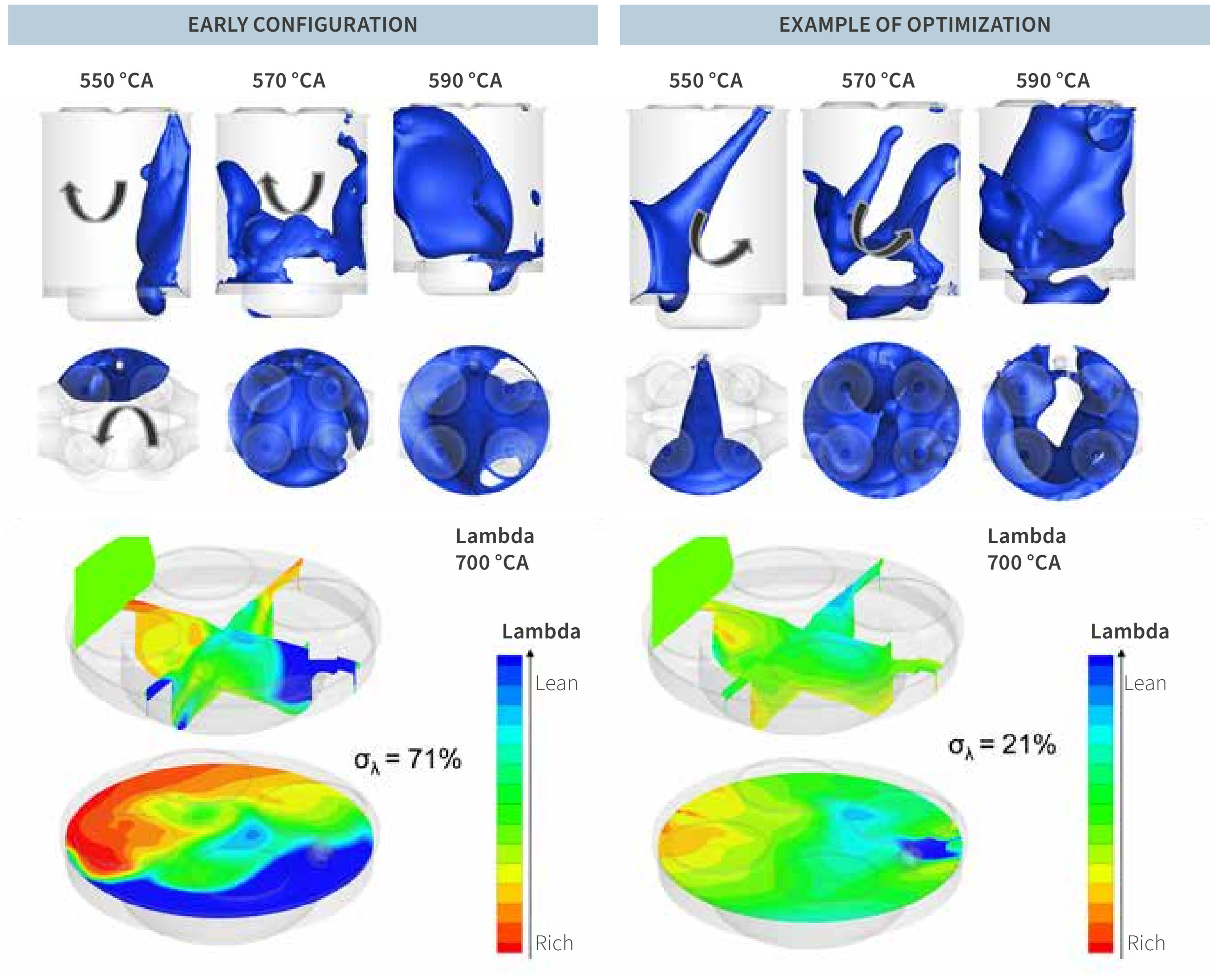
Having the hydrogen delivered directly into the combustion chamber reduces the risk of backfire. It does not impact the volumetric efficiency, improves the engine efficiency and transient response.

Simulation tools

Mixture formation optimization of DI system with 3D-CFD simulation

The mixture formation is key to enhancing engine efficiency while keeping the NOx raw emissions low. The interaction between fuel injection and charge motion determines the homogeneity of the mixture.

The location of the injector (central or side) is the dominant parameter. Spray forming caps can also be used to guide the flow of the hydrogen jet. The injection pressure along with the valve lift dictates the flow rate of the injector. Higher flow rates are desirable for realizing a short injection duration. The opening and closing ramps of the injection profile significantly affect the jet momentum, as slower ramps do not push the rich mixture away from the injector.



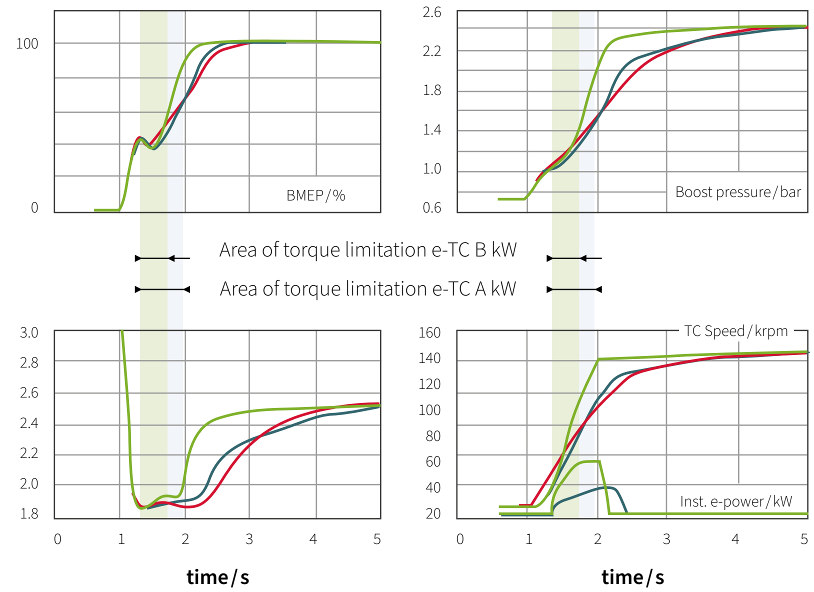
③ *Example of mixture formation optimization with 3D CFD*

Tumble and swirl constitute the charge motions for pent-roof and flat-head cylinder designs. The swirl motion may lock the hydrogen in the center or close to the cylinder liner, depending on the injection location and direction. The tumble motion, on the other hand, is typically realized with a pent-roof concept to realize a homogeneous mixture formation.

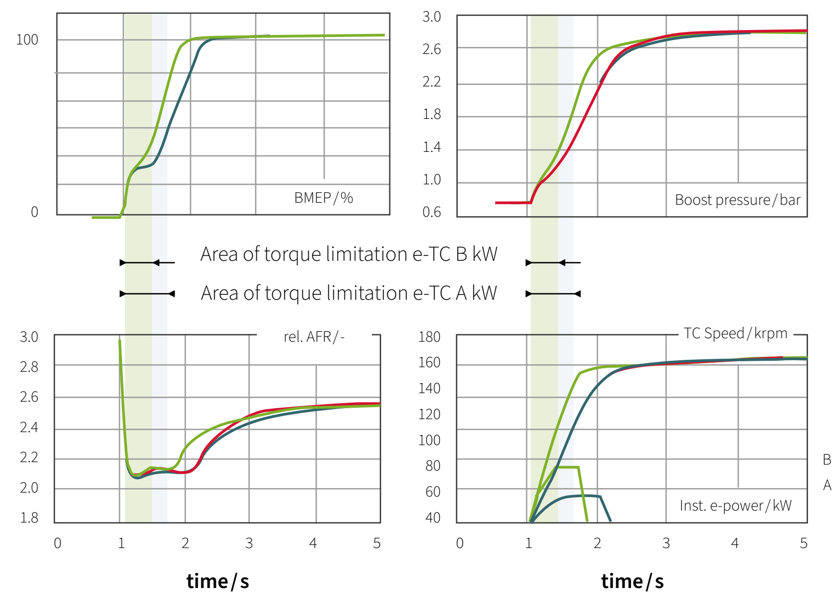
The hydrogen injection also interacts with the charge motion and turbulence through its momentum and shear at the jet boundary.

To optimize the above parameters, FEV applies its tailored H_2 simulation tool chain. To further develop the simulation tools, experimental data from test engine and low-pressure optical chamber investigations are continuously being validated against simulation results.

An example of mixture formation is shown in Figure 3. A variation of the charge motion coming from the intake ports, the design of the spray cap, the injection pressure and the injection timing was performed. The target homogeneity for DI hydrogen engines, represented by the standard deviation of the air/-fuel ratio, was set according to correlated performance to the engine with external mixture formation.



④ *a: Load jump simulations at 1,000rpm*



④ *b: Load jump simulations at 1,500rpm*

In Figure 3, iso-surface of 1-percent H_2 by mass fraction is represented. For the early configuration, the hydrogen is trapped near the cylinder liner due to the base swirl inside the cylinder. The tumble motion generated by the injection is not strong enough to bring hydrogen towards the center of the cylinder. As a result, poor homogeneity is observed. As part of the optimization, the swirl from the ports was reduced to almost zero. The cap design was readjusted to produce more conventional tumble. The combination of these changes was sufficient to significantly improve the mixture homogeneity.

To achieve optimal results, a comprehensive H_2 simulation tool chain must be applied within the confines of each engine.

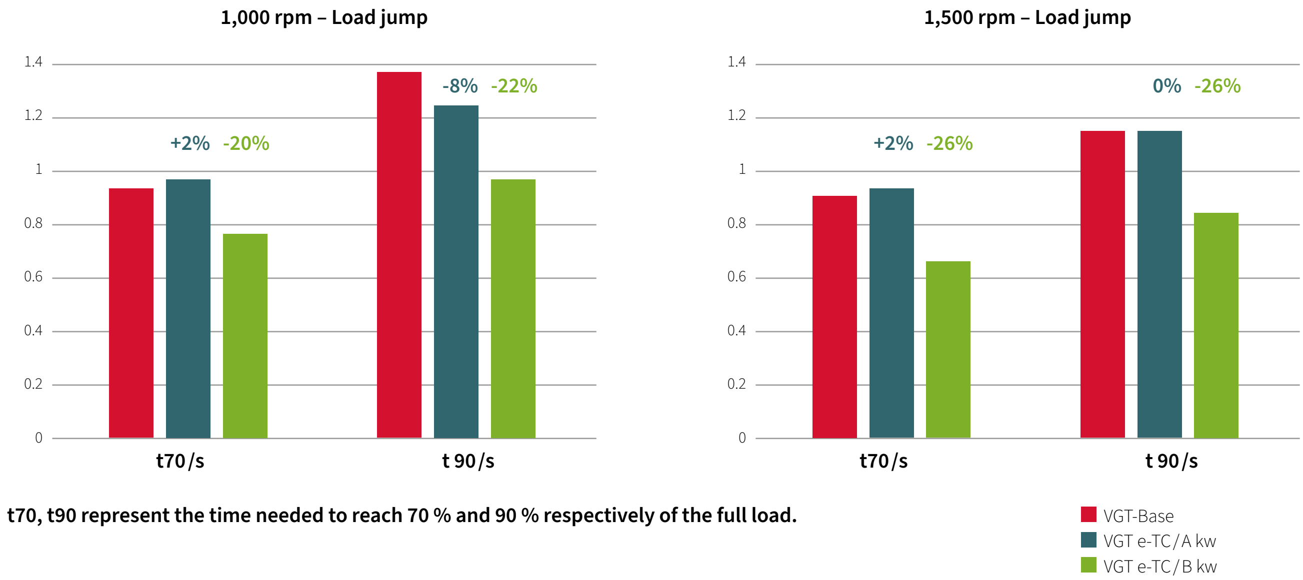
Transient performance evaluation of different turbocharger technologies with 1D simulation

As said before, the boost pressure requirements for H_2-ICE are high. 1D simulations have been performed to evaluate how an e-turbo can improve the transient response.

Load jumps at constant engine speed (1,000rpm and 1,500rpm) have been investigated for three different cases – conventional VTG TC, and two different e-TCs featuring A kW and B kW of e-power respectively. The base VGT was carried over from the Diesel variant of the engine. The simulation models have been matched with test bench data.

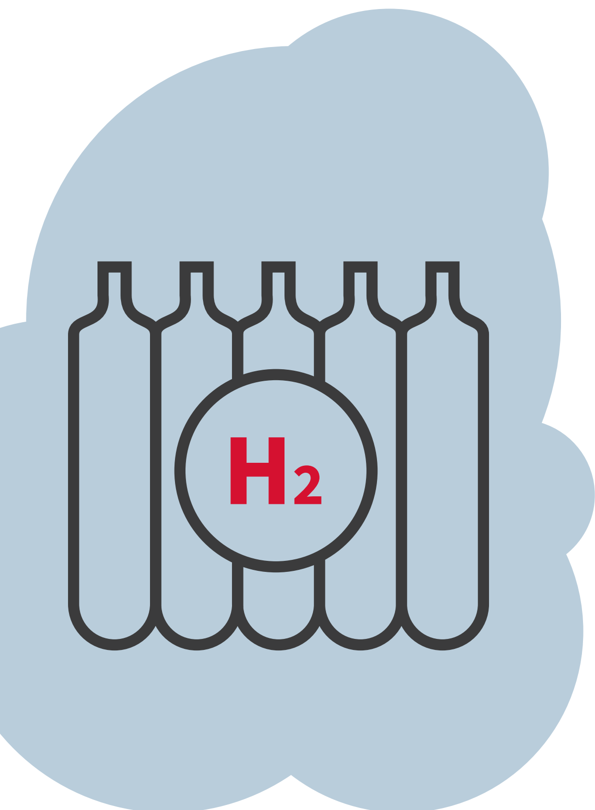
The focus is on the low engine speeds, where getting sufficient low-end torque in short time is a challenge. As depicted in Figure 4, lambda limitation (1.8 at 1,000rpm and 2.1 at 1,500rpm) is applied to avoid issues with knocking combustion and to minimize NOx overshoot.

Figure 5 displays improved response time when using an e-turbo. With a A kW electrical support, the transient performance is close to the base turbocharger layout. The moment of inertia of e-turbos



t70, t90 represent the time needed to reach 70 % and 90 % respectively of the full load.

⑤ *Load jump evaluation*



is higher. It appears that an assistance, greater than A kW would be more beneficial to counteract the added inertia and provide shorter response time. This is confirmed when looking at the B kW curve of the VGT e-TC, which offers better performance overall.

This case study shows that a certain e-support level, higher than a minimum threshold (here A kW) could be considered for e-TC turbo layout, aiming for higher power rating and better transient performance.

Engine control strategy

The NOx raw emissions depend mainly on the relative air/fuel ratio and the position of the center of combustion.

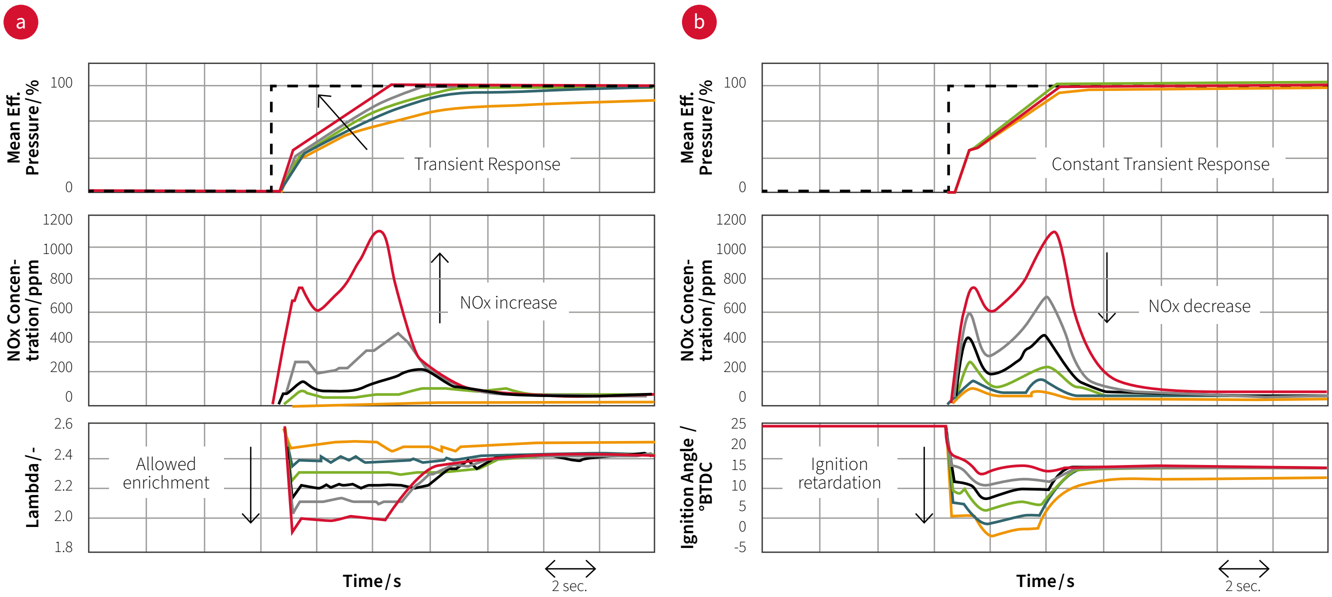
As illustrated in Figure 6a, enrichment of the air/fuel ratio supports a rapid load build up. It can also be seen that with the shorter response time, supported by the richer mixture, the NOx emissions increase to a large extent.

Figure 6b) shows that NOx emissions can be reduced while maintaining the same response time via ignition retardation. However, a drawback in engine efficiency is expected. Figure 6b) shows that NOx emissions can be reduced while maintaining the same response time via ignition retardation. However, a drawback in engine efficiency is expected.

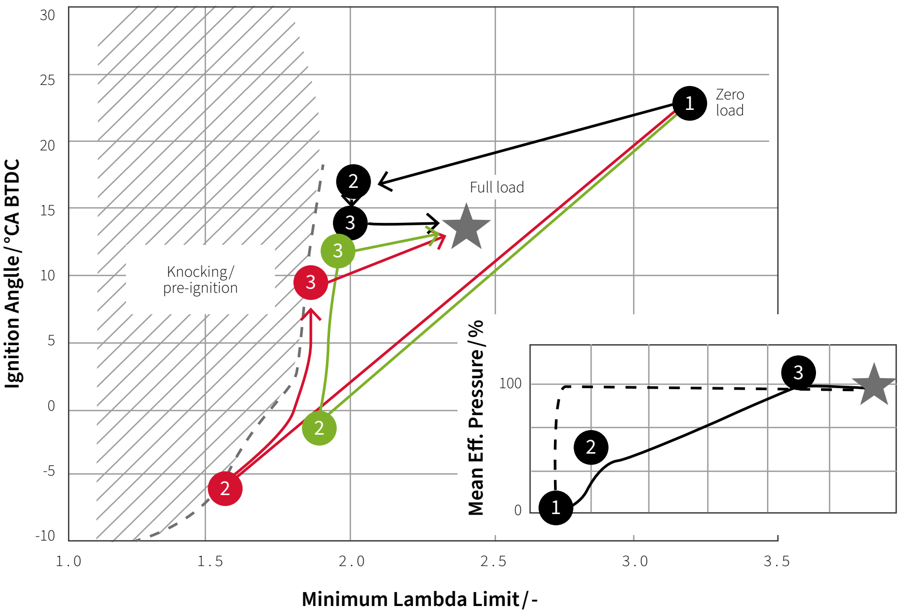
Thanks to FEV H_2-ICE software, a flexible control of load steps can be applied to maintain a balance between engine efficiency and NOx emissions.

In Figure 7, the black curve depicts a basic control that aims for a lambda value of 2 and a center of combustion of 8 °CA ATDC during a load step. The strategy aiming at the best transient response at minimum lambda value is shown in red. It allows the maximum enrichment during the load step. Richer lambda leads to NOx peaks as seen before. The minimum lambda value is restricted by the knock limit. Shown in green is the strategy that targets the best transient response under a maximum NOx limit condition. It also allows limited enrichment to balance the transient response and the NOx emission.

In most cases, the strategy shown in green would be preferred. When raw NOx peaks can be adequately post-treated by an efficient exhaust gas aftertreatment system, maximum enrichment might be preferred if transient response is a key performance feature.



⑥ *a: Load step with allowed enrichment*
b: Load step at constant air fuel ratio (AFR=2)



Load step from 0 – 100% BMEP at 1400 rpm
- Load step strategy at lambda limit 2 and CoC 8 °CA ATDC
- Load step strategy at min. lambda limit
- Load step strategy at max. NOx limit

⑦ *Load step strategies with hydrogen combustion engine*

Further development is underway. Investigations already performed on a full scale 6-cylinder hydrogen engine demonstrate attractive NOx raw emission levels, with specific values of 0.51 g/kWh for a warm World Harmonized Transient Cycle (WHTC). Combined with a Diesel-like exhaust gas aftertreatment system consisting of an oxidation catalyst and an SCR, NOx tail pipe emissions could be reduced to 0.050 g/kWh. The results already achieved without full optimization demonstrate the great potential of an H_2-ICE.

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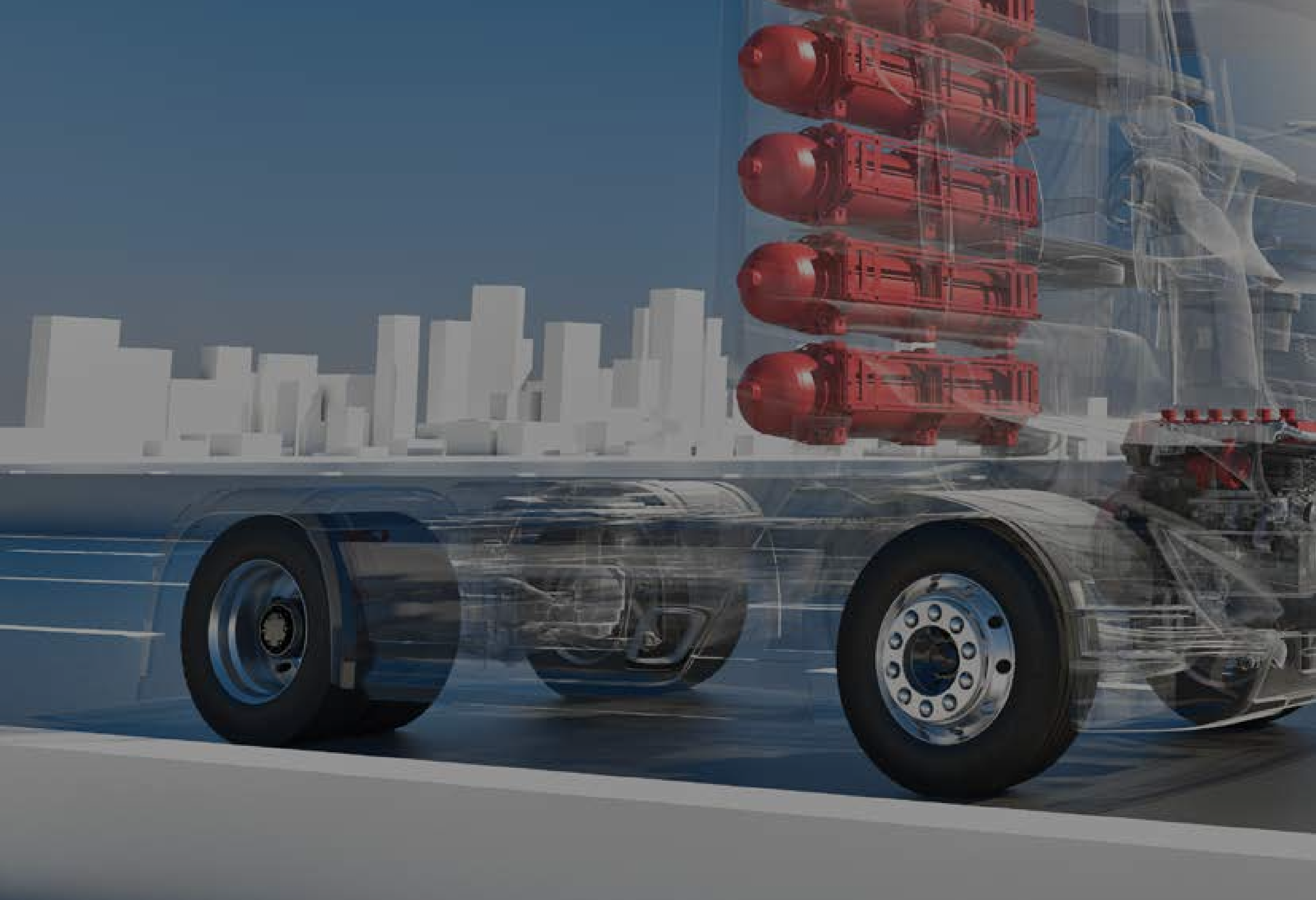
Summary and outlook

Hydrogen combustion engine offers the chance for very low engine output emissions combined with attractive engine efficiencies.

PFI brings benefits regarding fast market introduction, maturity of the hardware and relatively easy integration. However, PFI comes with certain limits in terms of operational safety, power density and transient response.

DI has great potential to address the backfire issue and improve the transient response. Lean full-load and ultra-lean part load operation allow high engine efficiency and low NOx raw emissions at the same time. For higher power densities and better transient response, a combination of DI with an e-turbo is an attractive solution.

Smart engine control can unlock even further performance potential. Adapted software in conjunction with a suitable exhaust gas aftertreatment system can be successfully developed towards a zero-impact emission powertrain.



MANAGING THE COMPLEXITY *OF ADAS/AD SYSTEMS*

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WARN
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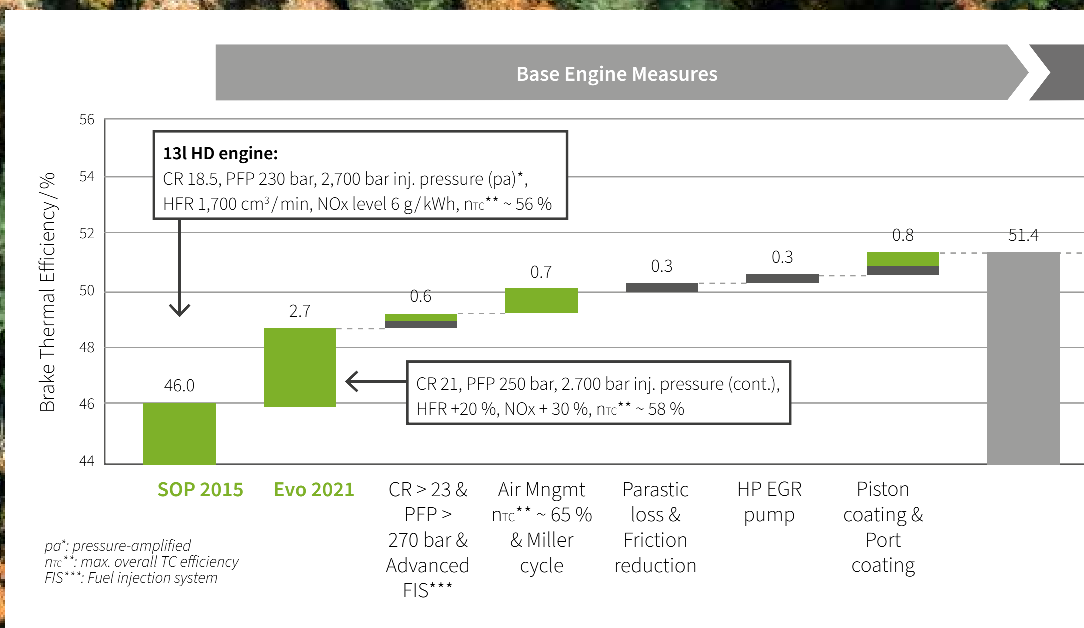
THERMAL EFFICIENCY

FEV'S PATHWAY TOWARDS NEXT GENERATION HD ENGINES TARGETING 55% BTE



The significant increase in CO_2 emissions over the last decades has had a negative impact on the climate in terms of global warming. In order to prevent further irreversible damage, regulators have been prompted to set stringent CO_2 targets for the next decade, particularly for the heavy-duty transport sector, which contributes a significant portion of the anthropogenic CO_2 emissions. In order to achieve the ambitious target of 30% CO_2 reduction of new truck fleets by 2030 (compared to the 2019/2020 reference period), it is required to optimize every aspect of vehicle technology. The powertrain is part of this technology, in which the engine is a key element. Engine efficiency improvements can be achieved in three main improvement areas. First, combustion, including all measures which have their effects within the combustion chamber. Second, air management, which encompasses all intake and exhaust components together with the boosting system. And third, all the parasitic losses of the engine components, including pumping losses and mechanical friction. This paper will describe a possible pathway to increasing engine efficiency to a 55%-level.

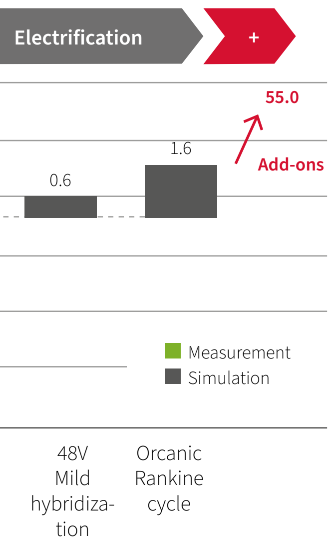
Emission standards 2025+

In April 2021, the EU commission published its first guidelines for the upcoming Euro 7 pollutant emission legislations. The Euro 7 regulations will ensure that future vehicles powered by an internal combustion engine will emit the lowest pollutant emissions under all driving conditions over the complete vehicle lifetime. This includes the following boundary conditions:

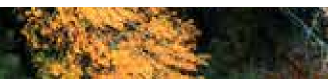
- Emissions fulfillment for all driving situations under very wide ambient conditions,
- Limits for new specifications such as PN10 and N2O,
- Lowest power-specific emissions during warm exhaust gas aftertreatment operation (e.g., NO_x app. lower than EU VI regulations by a factor of eight),
- Full accounting of cold start emissions with very challenging emission limit (e.g., 100-150 mg/kWh of NO_x after an engine works comparable to three times the WHTC in any operation profile),
- Full compliance with emission standards up to 1.2 Million km operating time and 15 years truck lifetime (>16 to vehicles),
- Introduction of an On-Board Emission Monitoring (OBM) system to ensure that the vehicle fulfills the emission limits anytime.

To meet these requirements, even EU VI trucks that comply with today's legislations must achieve a significant improvement in cold start emissions performance and a moderate improvement of emissions performance under warm catalyst conditions. In addition, sophisticated control and monitoring concepts are required to ensure lowest emissions under all driving conditions.

The new emission standards will lead to innovative exhaust aftertreatment systems (EATS).



① *FEV's engine technology roadmap for future heavy-duty applications*



Fleet CO_2 emissions and customer TCO as drivers for engine efficiency improvements

As of 2019, fleet CO_2 emissions are strictly reduced for all new registered heavy-duty trucks in categories 4, 5, 9 and 10. The reduction targets are 15% from 2025 onwards and 30% from 2030 onwards, compared to EU CO_2 fleet average reference (period 07/2019 till 07/2020).
The level of the penalties is set to 4,250 euros per gCO_2/ 1,000 km in 2025 and 6,800 euro per gCO_2/ 1,000 km in 2030 in cases of non-compliance. Because of these fines, improving current trucks to comply with the CO_2 regulations is of the utmost importance. However, the challenge is to achieve this in a cost-effective way, since for the truck end customer, the TCO (total cost of ownership), including the purchase price of the truck, must still result in a sustainable continuation of their business.

From a product cost perspective, FEV's internal assessment is that it is most efficient to implement engine-related efficiency improvements first. The additional product costs required to optimize these more conventional areas, such as combustion, air management and friction reduction, are very favorable at around 400 euro per %-point of CO_2 reduction.
This is more affordable, and thus, more favorable to owners than newer technologies such as powertrain hybridization, waste heat recovery and alternative energy carrier adaptation such as fuel cell technology.

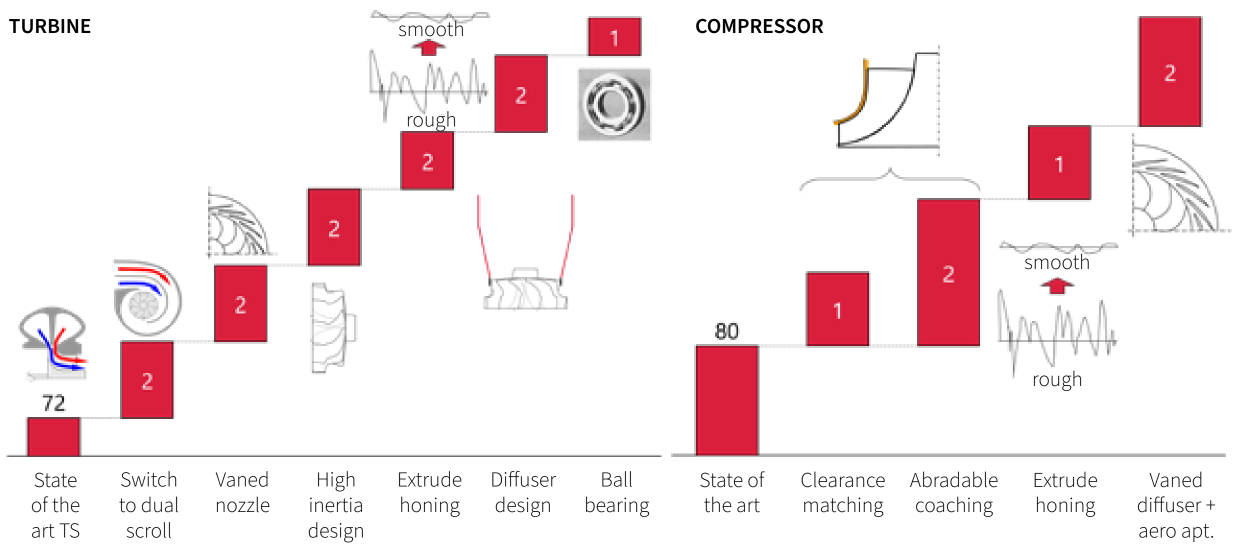
Pathway towards highly efficient heavy-duty powertrains

Figure 1 shows FEV's technology roadmap for future HD engine developments. This roadmap combines the most promising internal and external engine measures to focus on, such as the combustion system, air management, and energy recuperation to illustrate an efficient pathway towards a BTE (brake thermal efficiency) of 55%.

Effective energy recuperation is mainly provided by a 48V electric waste heat recovery system (WHR). That additional electric energy requires engine technology intended for a mild-hybridization approach. The following sections give an overview of FEV's research activities on future HD engine developments.

Mild hybrid technologies

With a 48V P1 mild-hybrid system featuring a peak power output of 16 kW, in addition to the fuel-saving potential from braking energy recuperation, electrification of the air compressor, and more efficient electric power generation, there is also an opportunity to improve the efficiency of the combustion engine. This is achieved by electrifying the coolant and the oil pumps, which are driven with electricity generated by the electric WHR. With this arrangement, the mechanical pump drives can be removed for friction reduction. The fully flexible pump speeds allow for a more efficient cooling and lubrication system at the optimum operating point to ensure maximum power operation. Overall, the electrification of the engine improves BTE by 0.6%. The P1 machine will efficiently integrate the residual electricity from the electric WHR into the engine.



② *FEV's turbocharger map peak efficiency walk for HD applications*

Combustion system optimization

Further development of the combustion process represents the most substantial improvement to thermal efficiency. Combined with an enhanced spray pattern from the injection nozzle, the shape of the piston bowl was optimized by means of 3D CFD simulation. This work resulted in a step-bowl shape with a compression ratio (CR) of 21. Experimental investigations on an HD single-cylinder engine (SCE) confirmed a significant BTE increase of 48.7%.

In addition, other hardware changes have been incorporated. A new direct pressurized fuel injection system (FIS) with a maximum rail pressure of 2,700 bar is installed together with a fast-acting injector. Another adaptation refers to a more efficient turbocharger hardware, representing a 2021 best-in-class configuration. This results in slightly reduced gas exchange losses. Finally, the overall combustion efficiency analysis is performed at an increased NO_x raw emission level of 8 g/kWh.

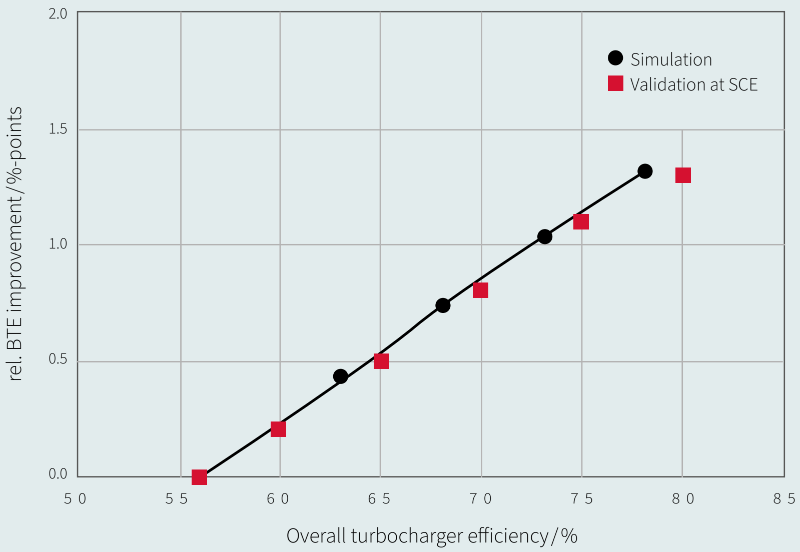
These investigations revealed the well-known relationship between peak firing pressure (PFP) capability and combustion efficiency. The potential of an increased compression ratio as a function of the max PFP is therefore analyzed below.

A further increase of the CR towards 23:1 yieldsan additional step in BTE of about 0.5% compared to CR 21:1. Again, a rise in PFP of more than 20 bar must be considered to achieve the greatest gain in efficiency.

Air management improvements

Three main contributors are applied to improve the air management. An improved dual scroll turbocharger (TC) increases peak efficiency up to 65%. An application of the Miller cycle through late intake valve closing and a high pressure EGR pump improves pumping losses. Combined with optimization performed by means of a 1D engine process simulation model based on a state-of-the-art 13-liters HD engine with the improved combustion system described above, a BTE of 48.7% may be realized. For each of the steps, DOE-based optimization of the TC matching, the valve timing, as well as the CR, and the engine control parameters such as beginning of the injection (BOI) and EGR rate are performed.

30percent
CO_2 reduction of new truck fleets by
2030
compared to the 2019/2020 reference period



③ *Impact of increased max. turbocharger system efficiency on BTE oserved by 1D simulation and validation measurements at a HD single cylinder engine.*

Figure 2 shows the influence of different technologies or design variants of the TC on the peak efficiency (stationary map measurements on a hot gas test bench). In the efficiency diagram, the measures on the turbine and the compressor side are considered separately, whereby the bearing friction losses are included in the turbine efficiency. With the use of all the technologies listed, an overall TC efficiency of more than 70% can be achieved. The following technologies are already fully developed, whereby their use in series production depends largely on the add-on costs vs. CO_2 savings:

Compressor stage

- Reduction of clearance losses
  - Clearance matching of housing and impeller.
  - Abradable coating.
- Extrude honing
  - Reduce the surface friction in the volute.
- Vaned diffuser
  - Shifts the peak efficiency towards lower mass flow.
- Aerodynamic optimization
  - Trade-off with inertia. Signification improvement possible if transient response is less important.

Turbine stage

- Switch to dual scroll
  - Reduces aero friction in the volute. Higher aerodynamic efficiency at equal admission. Better flow separation of both scrolls.
- Extrude honing
  - Reduce the surface friction in the volute.
- Reduction of clearance losses
  - Ball bearing tends to be stiffer and allows to run tighter clearances.
- Aerodynamic optimization
  - Trade-off with inertia. Signification improvement possible if transient response is less important.
  - Vaned nozzle to optimize for a sweet spot.
  - Long diffusor to increase pressure recovery downstream turbine wheel.

The application and rematching of a dual scroll TC with an overall peak efficiency of 65% achieves a benefit of around 0.4% points in BTE. The impact of a wide variation of TC efficiency with respect to BTE improvement assuming a perfect TC matching is displayed in Figure 3. As a rule of thumb, a 10% efficiency increase can result in a 0.5%-point improvement in BTE.

With increasing overall TC efficiency, the pressure gradient over the cylinder drops and reduces the possibility to drive EGR. To remain within a feasible engine-out NO_x level, an EGR pump is a suitable solution to allow TC selection towards the highest efficiencies and not cause any disadvantages in the TC matching process. At the same time, the combustion can be kept on a crank angle that ensures the best efficiency and injection timing does not need to be retarded to reduce the engine-out NO_x emissions. With the implementation of an EGR pump, the pumping losses could be reduced by slightly more than 0.4 bar, which corresponds to an around 5.3 kW

lower power requirement, while the EGR pump drive has a power consumption of 0.8 kW at 80% efficiency. The overall benefit of the EGR pump can therefore be quantified as up to 0.5% points.

Closing the gap up to 55% BTE

All measures described above and further mentioned in the roadmap add up to a BTE level of 53%. Closing the gap towards 55% is only possible when using more sophisticated or further optimized technologies, such as:

- Implementation of low-pressure EGR,
- Turbocharger technologies that realize overall efficiencies >70%,
- Further reduction of heat losses downstream of the turbocharger,
- Increasing the generator efficiency of the WHR system.

These measures require a considerable development effort and are not all part of research activities even today.

Summary and conclusion

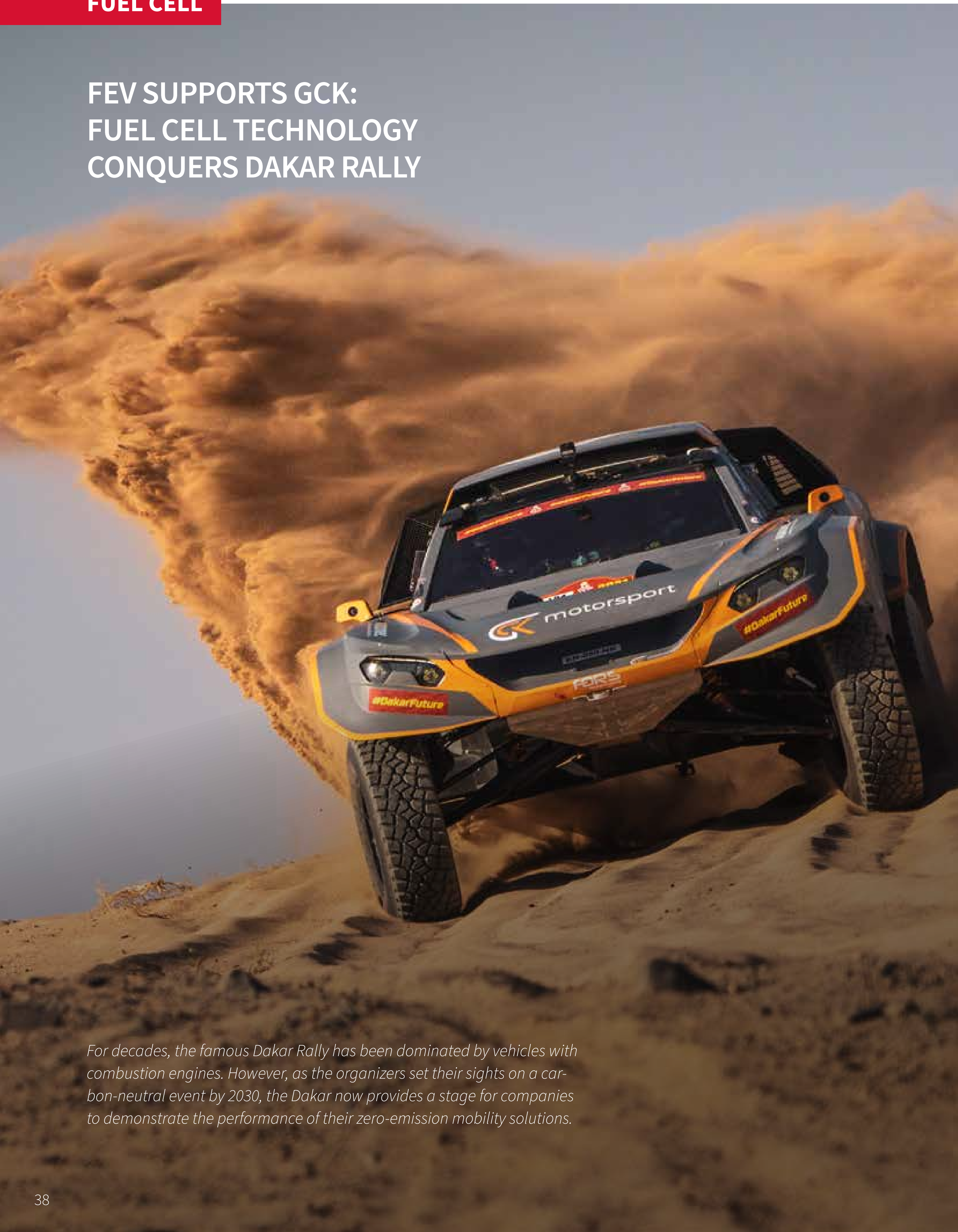
The requirements to reduce the CO_2 emissions of the commercial vehicle fleet by 30% by 2030 compared to the 2019 fleet average CO_2 emissions, require further improvements of the powertrains of heavy-duty vehicles. As the internal combustion engine will remain very important for HD vehicles in the coming decades, continuous optimization and efficiency improvements are being sought for it.

FEV has analyzed the BTE improvement potential of engine measures such as combustion optimization, air management improvements, friction and parasitic loss reduction, as well as waste energy recuperation. Also considered were powertrain hybridization technologies that enable brake energy recuperation. The following potentials were identified:

- Combustion: 3.9% BTE improvement
  - New combustion system using very high compression ratios
  - Updated FIS with 2,700 bar rail pressure
  - Thermal piston insulations to reduce in-cylinder heat rejection
- Air management: 1% BTE improvement
  - Turbocharger upgrade towards the highest overall efficiency of 65% to further reduce gas exchange losses
  - Implementation of an EGR pump to enable high pressure EGR rates at negative pressure differences between exhaust und intake side
- Friction and parasitic loss reduction: 1.1% BTE improvement
  - Utilizing electrified water and oil pumps to reduce overall engine friction level
  - Reducing heat transfer losses through thermal insulation of exhaust ports, exhaust manifold and turbocharger housing
- Waste heat energy recuperation: 1% BTE improvement
  - Harvesting of waste heat energy from the exhaust gas and the EGR cooler to power electrified auxiliaries and bringing back remain electric energy on the crankshaft

Overall, a BTE improvement of 7% point was demonstrated, resulting in a BTE value of 53%. Closing the gap to 55% BTE will require further measures such as low-pressure EGR, overall turbocharger efficiencies >70%, further reduction of heat losses downstream of the turbine, or high-efficiency electric generators. Most of these measures, however, will have an impact at the vehicle level, where the BTE improvements reported here have their effectiveness within the current engine package space.

FUEL CELL



FEV SUPPORTS GCK: FUEL CELL TECHNOLOGY CONQUERS DAKAR RALLY

For decades, the famous Dakar Rally has been dominated by vehicles with combustion engines. However, as the organizers set their sights on a carbon-neutral event by 2030, the Dakar now provides a stage for companies to demonstrate the performance of their zero-emission mobility solutions.

The fuel cell must withstand special requirements

Learn more about about the "e-Blast H2"
www.fev.com/GCK-video

In November 2020, GCK Motorsport published its plans to rely on sustainable fuel cell technology for the team's cross-country rally entries in the future. Following this ambitious strategy, GCK, with the support of FEV, will be the first team to participate in the Dakar with its fuel cell-powered vehicle. In January 2023, GCK will compete in selected stages of the Dakar with the "e-Blast H_2" before taking on the ultimate challenge the following year and participating in the entire event.

FEV is involved in GCK's Dakar commitment with its own 20+ years of expertise in design, software development and fuel cell integration. The "e-Blast H_2" features a fuel cell (FC) that stores 30 kg of hydrogen at a pressure of 700 bar in four R134-certified tanks. The system has an output of 200 kW - making it one of the most powerful FC systems currently available. In addition, the fuel cell is directly connected to a latest-generation lithium-ion battery that generates 50 kWh. The battery, in turn, drives GCK's new 2-speed electric motor, which produces 320 kW (435 hp) of power. This system enables the "e-Blast H_2" to complete a 250 km special stage entirely on green energy.

In the "e-Blast H_2", the system will be exposed to the harshest conditions in the desert. More than 8,000 kilometers will be covered over a total of 13 days. Ambient temperatures reach up to 50 °C, sudden weather changes in the form of storms, dust and constant vibrations with forces of more than 10 g due to the bumpy roads continuously affect the vehicle and the fuel cell system. It speaks for the high standards of GCK and FEV that they chose the Dakar Rally, one of the toughest rally raids in the world, as a challenge for the development of the high-performance fuel cell.

The fuel cell stacks are supplied by EKPO Fuel Cell Technologies, a joint venture between ElringKlinger and Plastic Omnium. FEV integrates these components into the FC system and also develops the software for controlling the fuel cell. To this end, 20 FEV engineers from Germany and France are continuously working on this project.

Currently, an extensive test program under real rally conditions is underway to further develop the powertrain on the company's special in-house test rigs. Environmental tests at system and vehicle level are also being carried out.

In summary, the system will offer a unique power and energy density, enabling integration even in the lightest vehicles. With cooling, compression and voltage conversion solutions adapted to this level of performance, the fuel cell system will meet the growing demand for hydrogen systems in all areas of the mobility market in the future, from trucks to buses and industrial plants.

BATTERY DEVELOPMENT

FEV AND PROLOGIUM TO DEVELOP SOLID-STATE BATTERY SYSTEMS

FEV and ProLogium Technology, a leading solid-state battery manufacturer, have signed a memorandum of understanding to collaborate on the development of solid-state battery systems. Both parties will use their expertise to jointly develop energy storage systems based on ProLogium's unique solid-state battery (SSB) technology. SSBs, whose properties and innovative internal structure require new battery concepts, are characterized by a number of advantages. Among other things, they are a suitable energy storage alternative with particularly high energy density for a wide range of applications, such as in the transportation sector.

The memorandum of understanding between FEV and ProLogium focuses on battery development for customers, sales activities and cell/module verification based on ProLogium's solid-state battery technology.

Promising battery technology

FEV, as a technology-open development service provider in the field of e-mobility, has been working on solid-state battery solutions for some time. With ProLogium, the company has now been able to gain a renowned cell manufacturer as a partner that is a leader in SSB technology and an ideal complement to its own 360-degree battery development. FEV, in turn, is able to meet all regulatory requirements and customer demands around the world in the development of cutting-edge technology thanks to its own unique development and testing capacities.

In general, the requirements for e-vehicle batteries are increasing in terms of safety, energy density, cost and service life. Solid-state batteries are among the most promising technologies that offer advantages over lithium-ion batteries with liquid electrolytes which are mostly used in e-mobility to date. Furthermore, SSBs provide an additional convincing mileage advantage due to their lower weight and smaller volume for the same capacity.

Founded in 2006, ProLogium Technology is an energy innovation company focused on solid-state battery research, development, and manufacturing, that provides next-generation battery solutions for electric vehicles in consumer markets and industrial applications. Through years of proven core technologies, ProLogium fulfills requirements for batteries including extreme safety, high energy density and low cost.

With its automated pilot production line, ProLogium has provided nearly 8,000 solid-state battery sample cells to global car manufacturers for testing and module development. ProLogium Technology is currently the world's only solid-state battery manufacturer that has reached mass production

To get the most out of this technology, core competencies lie in cell development and integration at pack level. Algorithms to control the technology are also critical to realize the benefits in terms of energy density, lifetime and safety.

Many years of experience

FEV has many years of experience in battery development. Customized design and integration of battery systems take into account the battery management system as well as the cells, modules and packs. Depending on the application, the company offers solutions with high specific power and energy density. With the eDLP near Leipzig, FEV also operates the world's largest independent battery development and test center for high-voltage batteries.

Through the cooperation of FEV and ProLogium, the automotive industry should now also be offered solutions in the field of SSBs to achieve innovative, clean and efficient energy consumption of electrified vehicles more quickly.

FEV

ProLogium

Meet more than 7,000 FEV experts in our international engineering and service centers

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