FEV CUSTOMER MAGAZINE Issue 72

FEV

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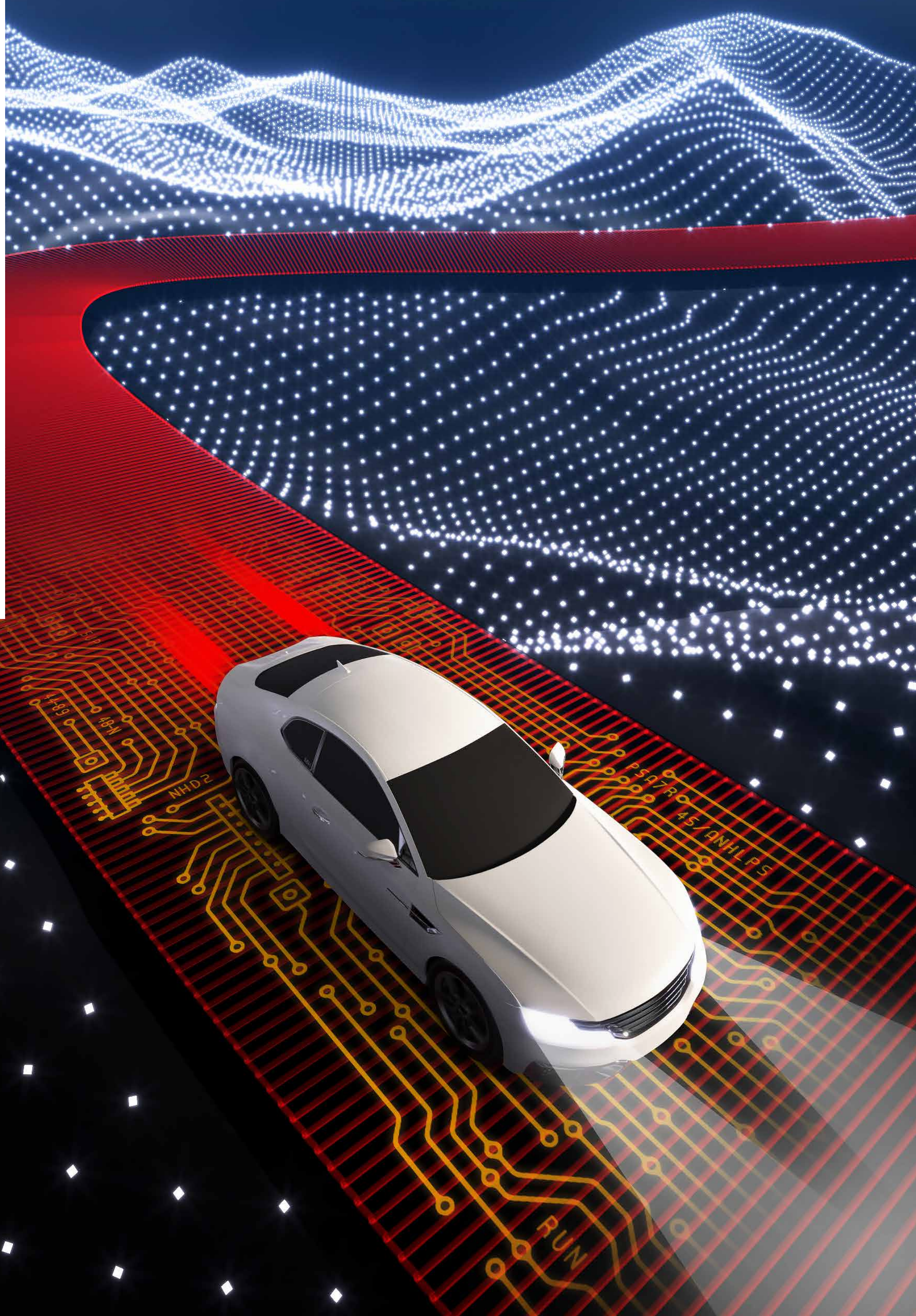
SPECTRUM

ANSWERS ON FUTURE MOBILITY QUESTIONS



Dear Readers,

With our SPECTRUM magazine, FEV would like to provide its customers with regular insights into a wide range of current mobility topics.

In this edition, we present FEV's holistic methodologies in the context of automated driving and the associated increasing complexity of vehicle systems, which ensure the overview and functionality of the entire system within the development process. The data exchange of vehicles with the outside world also expands the diversity of the spectrum of requirements for the corresponding competencies in software development. Over time, FEV has built up a global network of Software Engineering Centers, which we would like to present to you with its advantages and competencies.

If we look at the development of security relevant software, the aim is often to increase efficiency and reduce time to market. In this issue, we present our two-part approach to achieving this without compromising on quality requirements.

In another article, we highlight how FEV coordinates the complexity of the tasks involved across different disciplines as part of the overall vehicle development process, and how the available expert know-how is optimally incorporated for the customer at all levels and from a single source.

We will also be looking at innovative powertrain solutions that can help to achieve the ambitious emission reduction targets – such as a novel type of exhaust aftertreatment system for heavy-duty vehicles, the synthetic fuel methanol or an optimized hydrogen engine.

I wish you an exciting read. By the way, you can find news and further information on our fields of activity on our online channels, for example www.fev.com.

Professor Stefan Pischinger
President and CEO of the FEV Group

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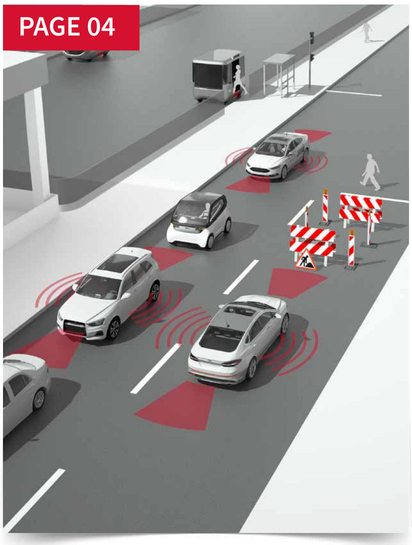

Developing Highly Automated Driving Functions at SAE Level 3 and Higher

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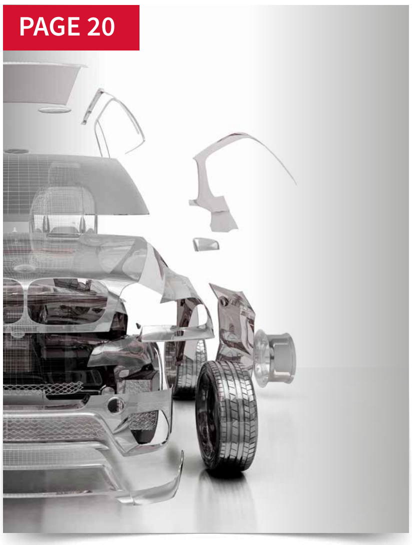

Aggregated Engineering Expertise Under One Umbrella

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Improved Transient Engine Performance of HD Hydrogen Engines While Maintaining Lowest NO_x Emissions

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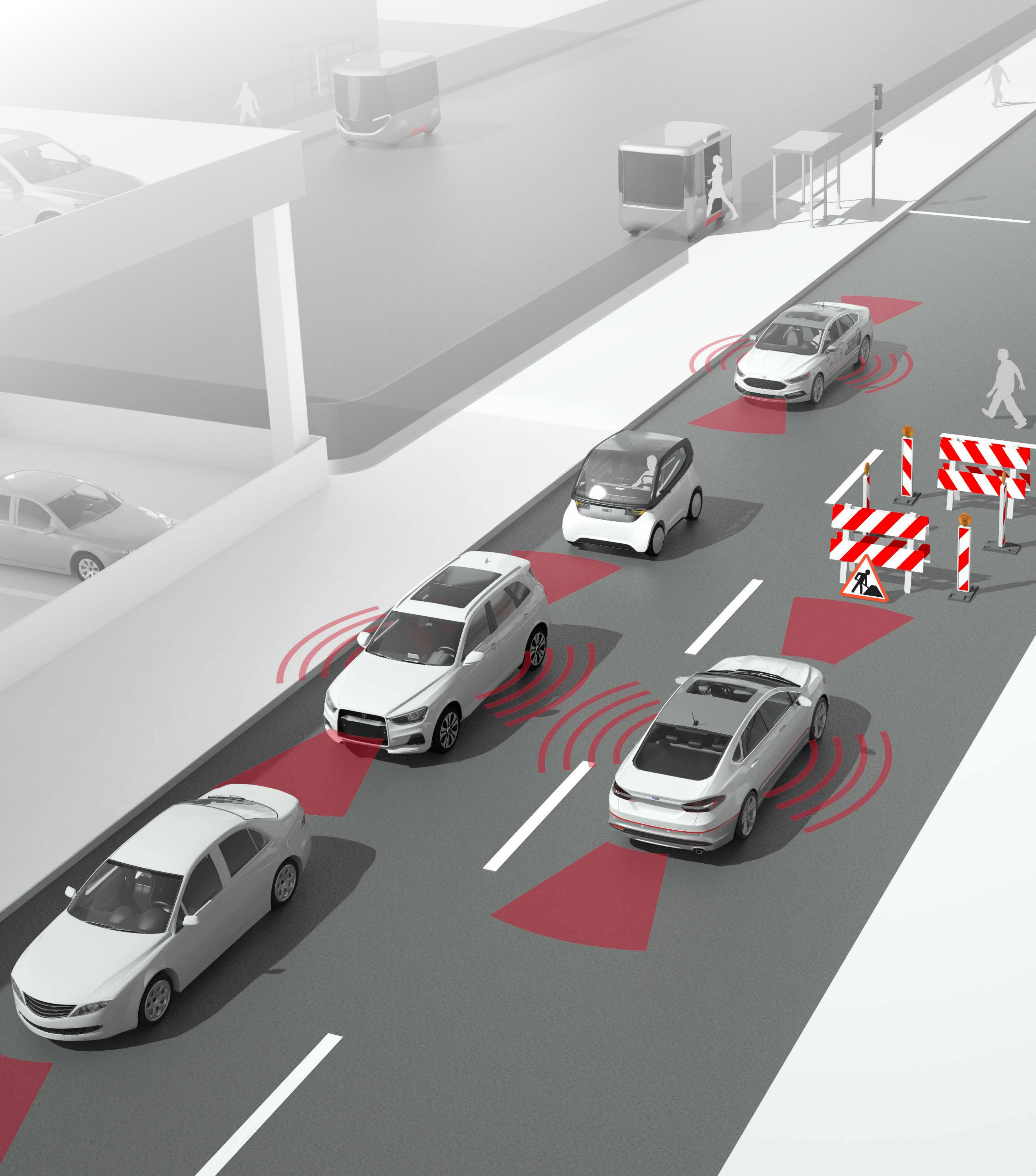
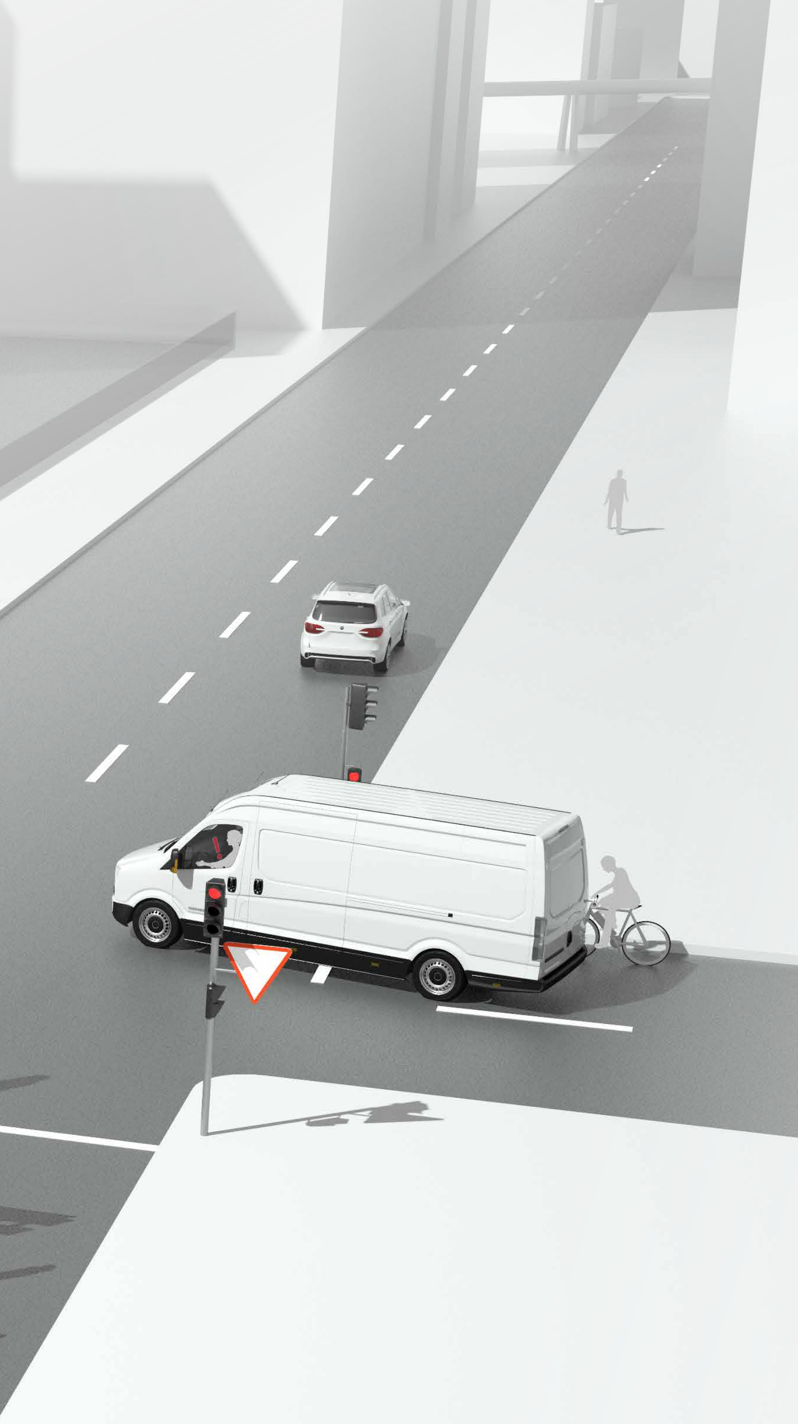
02 TECHNICAL DEVELOPMENT MADE BY FEV

03 NEWS

AUTOMATED DRIVING

DEVELOPING HIGHLY AUTOMATED DRIVING FUNCTIONS AT SAE LEVEL 3 AND HIGHER





Driver assistance systems, such as automatic distance and lane-keeping features, are already augmenting safety, driving comfort, and even energy efficiency. During long drives, or in stop-and-go traffic, every driver probably wishes for an autopilot to completely take over control of the vehicle, enabling the driver to focus on tasks not associated with driving. Highly automated driver functions at SAE Level 3 and higher make that possible. They relieve drivers from the task of constantly monitoring the driving system and their environment in certain situations.

These “L3” driving systems are causing systems to become significantly more complex overall. Switching the responsibility of driving from the driver to the vehicle is associated with increasing demands on the performance of the sensors, the sophistication of the control features, and the necessary computing power. Comprehensive validation of these systems for different weather and light conditions must be completed for all relevant traffic situations to ensure functional safety. To accomplish that during development, alternative integrated environments for the R&D process need to be taken into account in order to maintain an overview of the entire system’s behavior.

When engineering these systems, a major challenge is found in studying and validating the vehicle’s behavior within the complicated system as a whole and as defined by the various driving situations. To address these issues, FEV has developed methods specially tailored to this challenge as part of its holistic development process. They encompass the areas of systems engineering and data management, in addition to function, system, and vehicle testing; and have already been used successfully in projects with vehicle manufacturers and suppliers. As part of the European L3Pilot research project, automated driving features are being tested to determine their viability for public roads. The consortium includes, among others, 13 vehicle manufacturers with the target to establish a very broad baseline of applications and experience. FEV is taking part in this project with its own test vehicle and uses the experience to further improve its own development and testing methods, as well as networked data loggers and data management.

Scenario and Model-Based Systems Engineering for Development of Highly Automated Driver Assistance Systems

The concept for systems engineering on the basis of scenarios and models brings significant advantages in this context; namely how it can help overcome system complexity and control the huge and steadily increasing effort and expense of verification and validation of automated driving features.

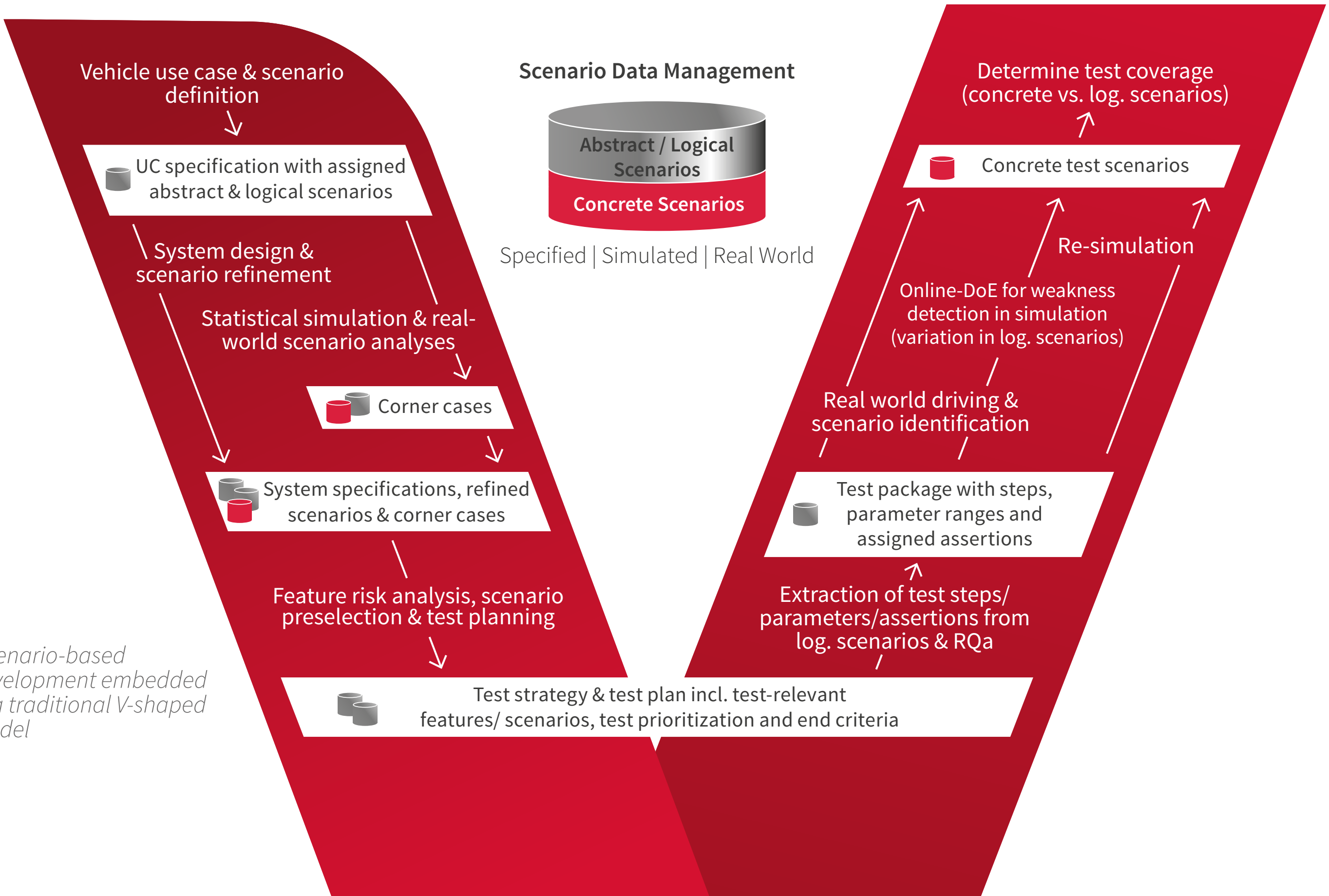
As part of Project Pegasus[1] for the German Aerospace Center, funded by the Federal Ministry for Economy and Energy, the foundation was laid last year for validating automated driving features. That research project focused mainly on answering the question of, “How good is good enough?” In other words, how can reasonable exit criteria for the testing of automated driver assistance features be devised that also foster social acceptance of this new form of mobility? To that end, the project devoted time to monitoring what was called a “highway chauffeur”, for which model scenarios were created to enable validation during development.

Based on the approaches taken in Project Pegasus, FEV conducted its own project for developing driving features for a “traffic jam chauffeur” and chose a model-based systems engineering (MBSE) approach as the basis for making the complexity of the requirement placed on project development more manageable through engineering expertise.

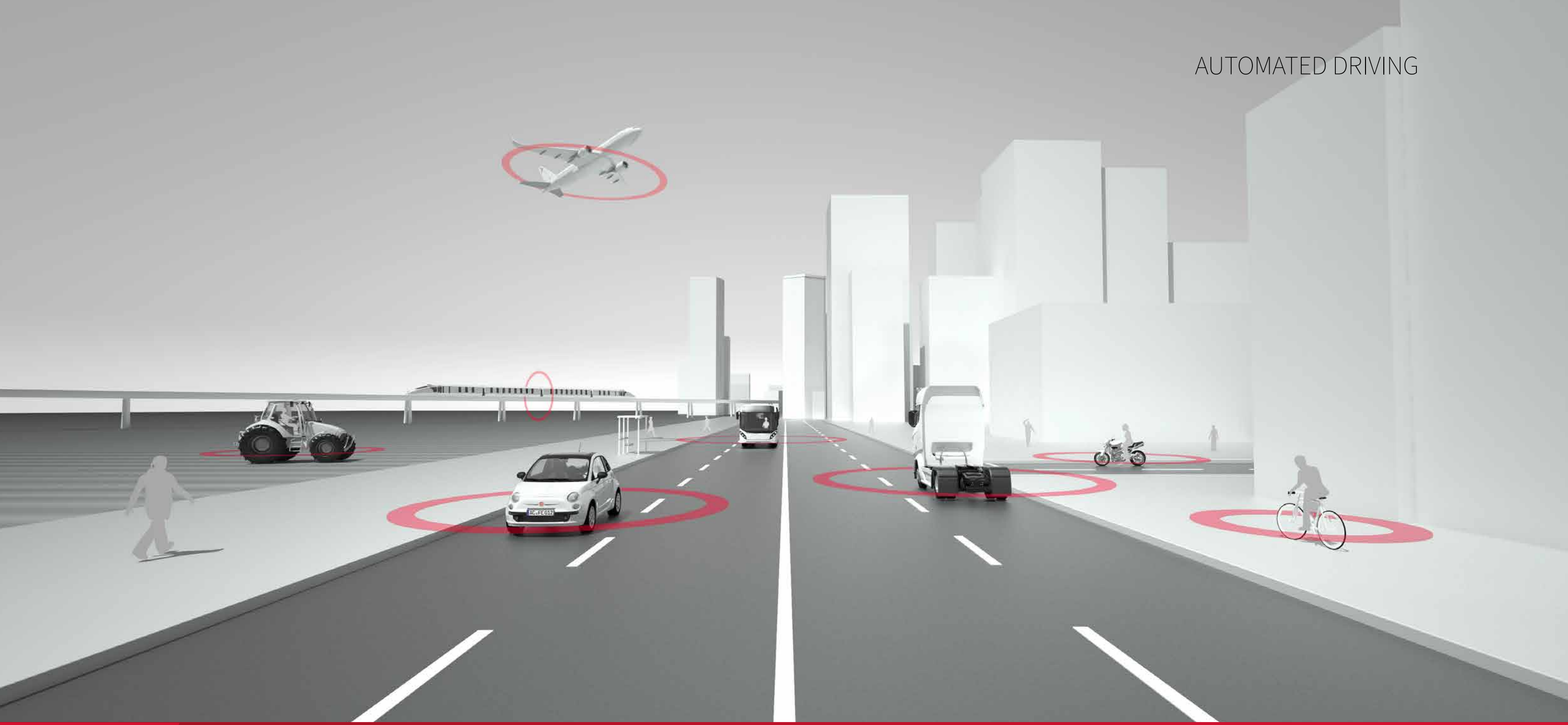
At FEV, development of automated driving features is guided by current standards such as ISO 21448. That goes especially for SAE Levels 3–5 at their current state of research. Key technologies outlined there are being refined and made ready for serial production.

Scenarios are an important method for describing depictions of complex traffic situations pertaining to the architecture and design of automated driving systems during the development of highly automated driving assistance features, as they supplement traditional use cases and requirements. First, scenarios or use cases are utilized to define the desired behavior of the feature, taking into consideration all relevant interactions with the environment, the driver, and other road users. Including scenarios in the MBSE approach allows for ensuring validation of the driving systems developed, in addition to better traceability from the left to right side of the procedural (V-shaped) model in software development. For example, exact testing scopes may be assigned for individual requirements and grouped in test scenarios for different testing platforms.

A scenario describes the temporal relationships between different situations. Situations, in turn, are snapshots of the environment, dynamic elements, actors, the observer’s own perception, and their interrelationships. This basically means that use cases relate scenarios to customer benefit and modeling of the system behavior, including the associated requirements. That makes them the strongest link in the chain of requirements-based development and the basis for devising test cases.



① *Scenario-based development embedded in a traditional V-shaped model*



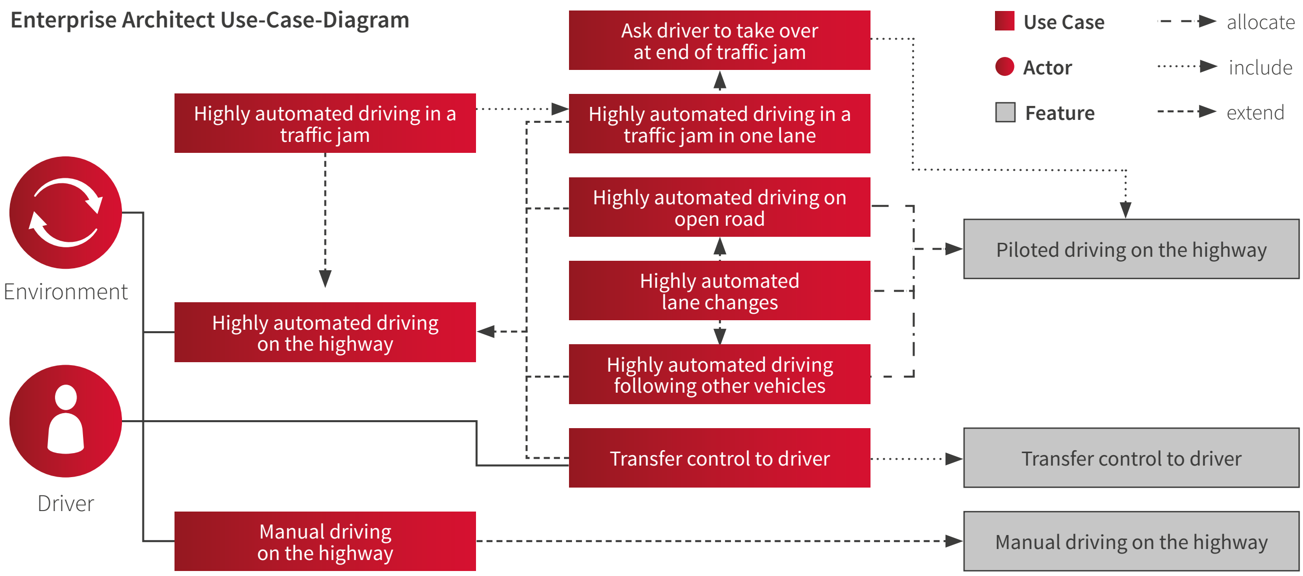
ENERGY EFFICIENCY SAFETY DRIVING COMFORT

Scenarios are incorporated as key elements of the development environment during the preparation of requirements within the MBSE approach.

A data collection toolchain developed by FEV assists with that. Using a connected logger, it collects measurement data from FEV's own autonomous vehicle during the test drive and can classify the data into scenarios during the test. With the aid of the collected data, scenarios can also be directly annotated and prepared in corresponding databases for simulation during the validation phase. It can be compared with the specified scenarios, thus closing the cycle of scenarios, creating an end-to-end development chain from system design to system testing and back. In the previously cited project example, the conditions for creating a "traffic jam chauffeur" were that it can be activated by the driver only on the highway and only when a traffic jam is detected, and that the task of driving is turned over to the driver again once the traffic jam ends. The conditions for activation are the recognition of a highway, a speed below 60 km/h, and the detection of a vehicle in front of one's own vehicle.

In contrast to the design of conventional systems, the definition of the use case for highly automated driving features is expanded to include a scenario specification as part of customer requirements at every level using FEV's proprietary MBSE method, and every functional requirement is linked to relevant scenarios. Clear and formal traceability between individual requirements and possible operating conditions creates high potential for automation; as well as database analyses and exporting test cases. In addition, individual test scopes are clear, and the criteria is optimized in comparison to an ODD approach at the functional level.

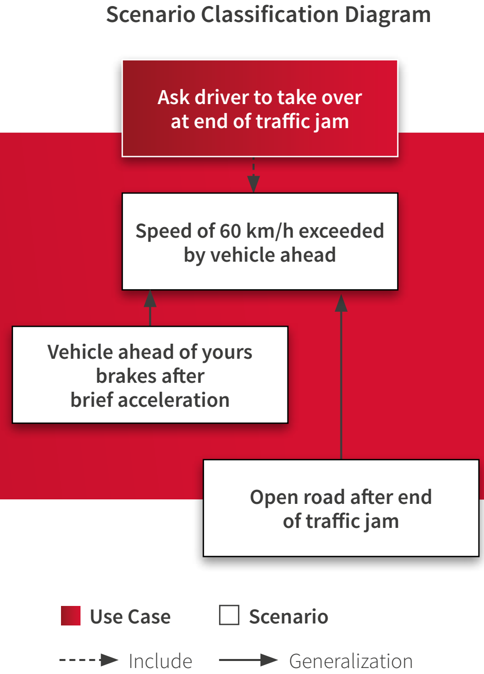
Further modeling involves possible use of the information contained (street, traffic infrastructure, temporary modifications such as construction site signs, movable objects, environmental variables such as weather, and information on data flow and communication). First, requirements such as performance needs can be transmitted to the sensors. Second, test cases can be generated for different simulation environments with the help of automation. This reduces the scope of verification and validation



② *Use case diagram and scenario classification diagram with relationships between use cases, features, and actors*

enormously because larger scenario spaces, which are needed to conduct simulations in cloud environments – as well as model-in-the-loop (MiL) and software-in-the-loop (SiL) testing with a broad range of variations as part of corner case simulations – can be created and covered by the skillful modeling of scenarios with automatically generated test cases. The next step in the plan for using the automatically generated test cases involves support for the OpenSCENARIO format.[2]

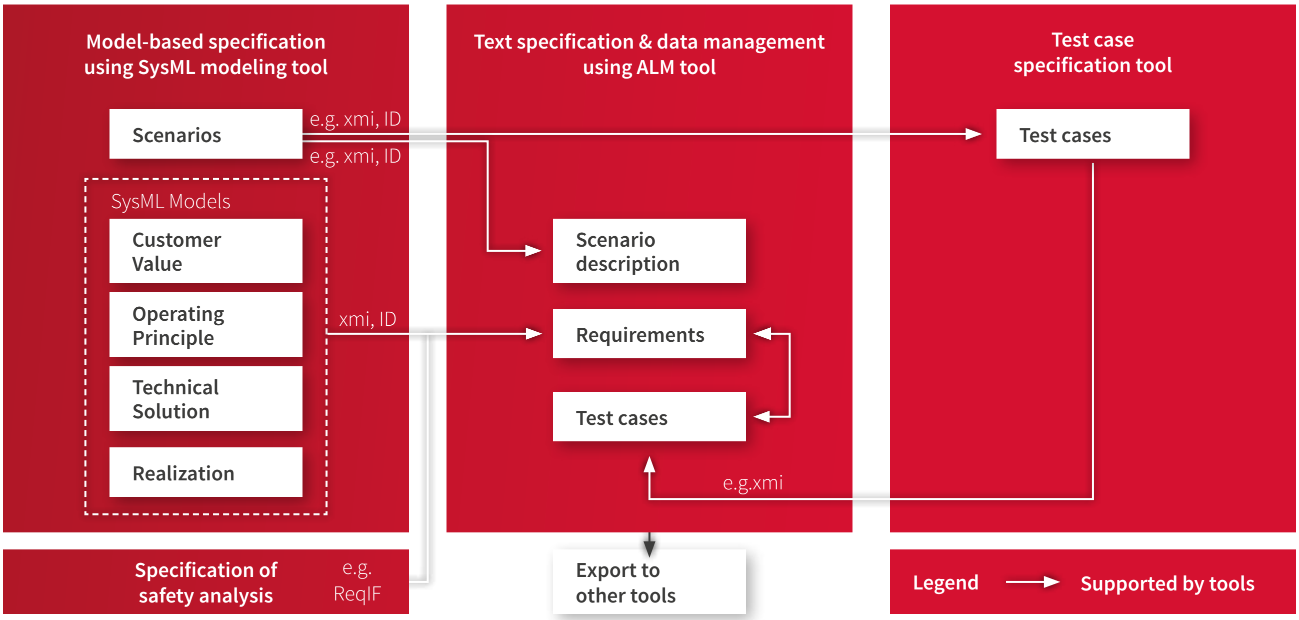
Once modeling has been completed, the corresponding use case requirements need to be classified. They can then be linked to the appropriate use cases with an ALM tool that is also used to administer the lifecycle management, testing management, and fault management systems. Multiple ALM tools equipped with Enterprise Architect interfaces already exist. This methodology can be applied to the development of any driving feature, regardless of the tool platform or SysML modeling tool. The complete toolchain can then be structured according to Figure 3.



The benefits provided by the scenario and model-based systems engineering approach are numerous:

1) The scenarios can be easily traced because they are linked to the use case requirements, which are validated through scenario testing.
2) The scenarios can represent realistic driving situations as well as extreme situations ('corner' or 'edge' cases) that cannot simply be covered by testing in the real world. They can then be validated and tested using dedicated simulation environments (HiL, MiL, or SiL).
3) Predefined scenarios can be adapted at any time and reused in modified form for testing purposes in a wide variety of areas for automated driving feature validation.
4) Predefined scenarios can be used as the primary point oforigin for the entire development process. Scenario specification as part of MBSE enables links to be established with the specified requirements, tests, and collected test data; thus providing future proof of test coverage for safety of the intended functionality (SOTIF) within the development cycle.
5) Autonomous driving features can be developed by feature teams with the aid of the methods described above. That means that multiple teams work on new features independently of each other and can adapt or insert scenarios and sub-scenarios without changing the base scenario.

Diagram of a Possible Toolchain



③ *Possible generic tool chain for supporting the scenario and model-based systems engineering process all the way up to testing*

The L3Pilot research project[3] as part of the EU's Horizon 2020 research program and its predecessors, euroFOT[4] and AdaptIVe[5] in the EU, have already led to the recognition of the subjects of use cases and scenarios as key to the development of systems for vehicle automation.

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Sources:
(1) www.pegasusprojekt.de;
(2) Vires Simulationstechnologie GmbH, 2020
(3) L3Pilot Consortium (www.l3pilot.eu), 2017
(4) euroFOT (www.euroFOT-ip.eu) , 2020
(5) AdaptIVe (www.adaptive-ip.eu), 2020

SOFTWARE

SHIFTING CHALLENGES IN AUTOMOTIVE SOFTWARE DEVELOPMENT

For nearly two decades, FEV has been developing software used in different types of control units for numerous vehicle manufacturers. Present demand is high and steadily rising. Modern-day vehicles contain a large number of electronic control units that execute vehicle functions via software; and the number and complexity of software functions is constantly increasing. One reason for that is the growing number of driver assistance systems, and advancements in automated and autonomous vehicles. Electrical and electronic (E/E) architectures that were once commonplace are reaching their limits, so the trend is moving toward centralized systems with powerful control units that are being increasingly virtualized. This is how supplementary IT system architectures are finding their way into vehicles on top of familiar embedded control units. Increasing vehicle connectivity with the outside world means the range of demands with respect to appropriate expertise in software development is becoming ever more broad.

Our main software topics:

- Model based software development
- Software integration
- Software coding
- Functional module testing
- Hardware-in-the-loop testing

1,000+

FUNCTION DEVELOPMENT AND SOFTWARE ENGINEERS WORLDWIDE

- Central Europe 60%
- Eastern Europe 20%
- Asia 10%
- North America 10%

HIGH END

TEST TRACKS

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At the start of the new millennium, FEV was using worldwide teams for automotive software development on many projects. The first locations with key significance were the facilities in Auburn Hills (FEV North America) and Aachen (FEV Europe). Over the course of years, additional software engineering centers were established around the world. They include, for example, Krakow (FEV Poland), Istanbul (FEV Turkey), Timisoara (FEV Romania), Shanghai (FEV China), as well as Chennai and Pune (FEV India).

What makes this global network special is the very close collaboration and spirit of trust between the facilities. For example, FEV sends experts on temporary assignments to ensure an exchange of know-how across the development facilities. The individual teams are in close contact with each other through the global software engineering product line, and of course, their daily project work. Over the course of the past few years, a culture of opportunity-driven and project-focused development of skills at each facility has arisen, with those advancements being coordinated on a global scale at the same time. This approach is transforming the development centers into centers of excellence with specific technical areas of focus.

The FEV Group now has more than 400 highly qualified software developers working at over a dozen locations, and that number is set to increase.

Focus on the Customer

Customer needs are at the center of FEV's activities, and they benefit from the global teamworking model in numerous ways. First, as a truly global supplier, FEV has locations in most customer's immediate vicinity. Second, FEV leverages its global presence to offer software development services at attractive and competitive prices by appropriately combining development activities. The software teams' global orientation also enables them to include experts on new and cutting-edge fields of engineering in those projects where they are needed, saving both time and money. In addition, the departments for cybersecurity, functional safety software or embedded virtualization are continuously recruiting new staff members around the world.

India: A Location with a High-Tech Tradition

FEV's software centers in India were established in 2014 in Chennai on the country's east coast, and in Pune in the western part of the country. Since then, they have experienced steady growth. Today more than 100 experts work on projects in a local and global capacity. With its integrated coverage of engineering, development, and validation tasks, FEV in India serves as a one-stop shop for software products. The local employees possess a wide range of expertise in the fields of software development and integration, functional safety, cybersecurity, E/E architectures, plus knowledge in the area of driver assistance systems and semiautonomous vehicles. The global infotainment product line is also controlled from FEV in India.

Together with Bangalore and Hyderabad, Pune and Chennai have risen as key centers for software development in India. Numerous prominent IT companies and software firms have set up shop there, where a sufficiently high number of qualified software developers is available. FEV India is therefore also making an important contribution to its worldwide collaborators at other FEV facilities. At the same time, it keeps the costs at which software can be developed while meeting strict quality demands extremely competitive.

Morocco: An Up-and-Coming Location

French automobile manufacturers and suppliers have been transferring their development capacity to North Africa for many years now. Besides advantageous cost structures, the region offers well-trained engineers who can often speak both French and English.

In 2018, the FEV Morocco site was established with the opening of an office in Casablanca. The company has also begun construction of a state-of-the-art engineering development center in Khouribga. It will be complemented by the first automotive development and testing center in Africa, which FEV and its joint venture partner, UTAC CERAM, will open 2021 in the Moroccan city of Oued Zem. The facility will offer a wide range of services, including development, validation, and testing of driver assistance systems; plus coast-down testing on a four-kilometer-track.

Besides concentrating on the development of powertrain applications, as well as functional and mechanical design, the facility will also offer capacity for software development. The focus of the software products at the Morocco site lies in the area of model-based software development, for which tools such as Matlab and Simulink, and instruments for automatic code generation are used. Other services that FEV will increasingly perform at its facility in North Africa include testing of functional models at the module level and documentation of each function; for instance, after being integrated into the respective control unit on a hardware-in-the-loop test bench.

SOFTWARE

SOFTWARE-BASED FUNCTIONALITIES – DECISIVE DESIGN FACTORS IN AUTOMOTIVE

SCALABLE

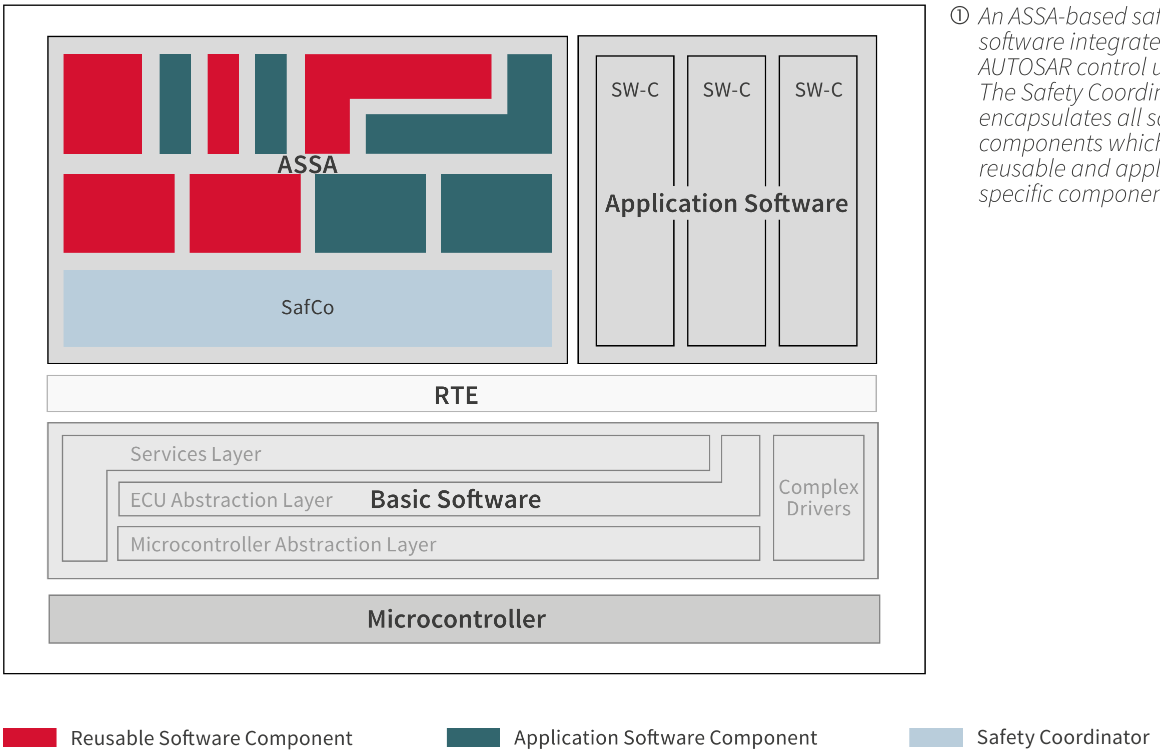
SAFE

PROGRESSIVE

Software has been an essential part of modern automobiles for more than 30 years now, and in many cases, software controls safety-critical functionalities. The automotive industry has managed to establish and enforce development and quality standards, e.g. ISO 26262, that nowadays ensure that safety-critical software meets the required quality targets. Automotive software development is undergoing a significant transformation due to growing functional and technical complexity – software-based functionalities are becoming more and more crucial vehicle features.

At the same time, time-to-market urgency is increasing, and so is the economic pressure that software suppliers are experiencing. All these trends resonate even stronger in the safety-critical software domain where applicable standards and development processes are anyway more heavyweight and rigid. Making efficiency improvements in this area, while taking care not to jeopardize the quality of safety software is more important than ever.

As a leading engineering service supplier with an extensive background in both powertrain components as well as automotive software engineering, FEV has developed a two-fold approach to increase the efficiency and reduce development times of safety-critical software. The first foundational element of FEV’s strategy is the introduction of a generic safety software architecture that helps to leverage synergies by simplifying the reusability of software units. The second aims at making the development process of safety-critical software leaner without risking compliance with safety standards like the ISO 26262.



① An ASSA-based safety-critical software integrated in an AUTOSAR control unit software. The Safety Coordinator encapsulates all safety software components which consist of reusable and application-specific components.

Automotive Safety Software Architecture – Progressive, Scalable, Safe

The generic safety software architecture that FEV proposes is designed to increase portability by decoupling the dependency between safety software and the hardware. FEV's "Automotive Safety Software Architecture" (ASSA) consists of three structural elements: (1) the Safety Coordinator, (2) reusable/generic safety software components and (3) application-specific safety software components (Figure 1). The design of all ASSA elements is predicated on the well-known concept of 'component-based software engineering'. Each software component defined within the architecture therefore reflects the physical components of the underlying system – e.g. a physical powertrain component. In cases where this is not possible, software components are designed according to their logical structure. This generally physics-based alignment ensures high coherence of functionality inside a component and is a well-proven concept widely used by FEV's in-house PERSIST (Powertrain control architecture Enabling Reusable Software development for Intelligent System Tailoring) software architecture standard and AUTOSAR.

The Three Main Pillars of ASSA

The Safety Coordinator (SafCo) is the core element of ASSA. It coordinates and encapsulates all safety software components and takes care of scheduling them through its internal scheduler. Furthermore, all communication to and from the AUTOSAR Runtime Environment (RTE) is routed through SafCo. Based on the list of safety software components and selected configurations, the ASSA code generator will generate the source code for SafCo using parameterized code generation.

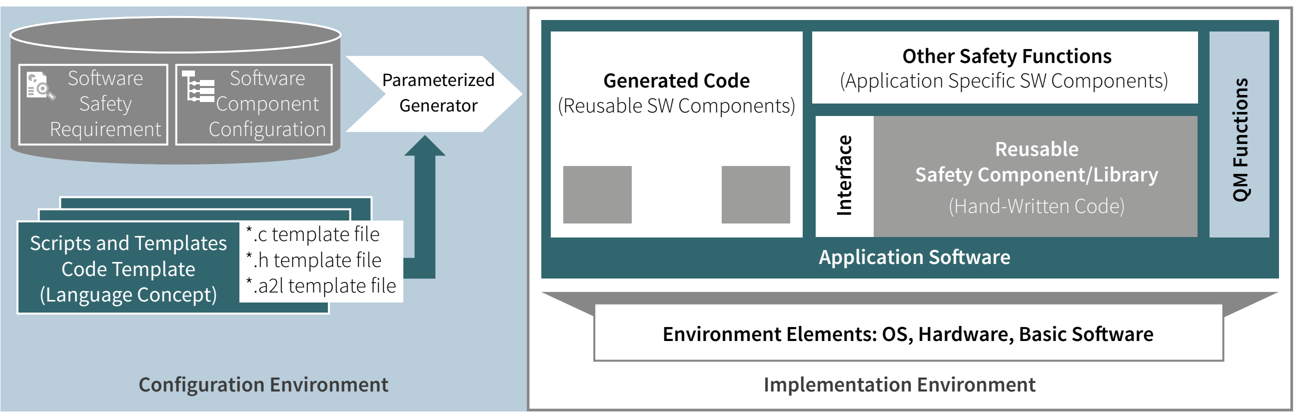
Reusable/generic software components are components that can be deployed freely across different powertrain applications. They are designed to provide their functionality efficiently while still being simple, maintainable and configurable – standardized requirements and interface definitions are key enablers to achieve this goal. As efficient handling of software variants is an important contributor for reusability and portability, a feature-based variant management approach is used. For faster deployment and to reduce development cost, these reusable software components are provided with a toolchain which can validate the selected configuration and auto-generate source code using parameterized code generation (Figure 2).

Application-specific software components can be categorized into powertrain-specific and product-specific software components. Powertrain-specific software components are types of software components that can be reused within a particular powertrain element. On the other hand, product-specific components are non-reusable and serve only a specific purpose. These components are solely designed to achieve a specific functionality for a given system hardware or given edge case. Application-specific software components can be developed using any implementation approach including model-based software development.

As customer needs can differ vastly, ASSA is not restricted to AUTOSAR-based environments. To support the development for legacy non-AUTOSAR control units, ASSA can be configured to run and deployed on non-AUTOSAR systems too.

Automotive Safety Software Development Process

The second foundational element in FEV's strategy to increase the efficiency and flexibility in safety software development is through the introduction of a tailor-made safety-critical process that leverages modern software development methodologies. This process is called “Automotive Safety Software Development Process” (ASSDP) and is designed to ensure a smooth and efficient transition between different development phases of the safety software lifecycle without sacrificing the requirements specified by ISO 26262. ASSDP aims at improving and streamlining the complexity management of safety software development by putting more emphasis on iteration- and increment-based software development techniques. The standard ISO 26262 approach for safety software development employs the V-model to structure the development phases and provides well-defined dependency and traceability links between the individual phases. Usually, the V-model is implemented using a waterfall-like approach in which the different development phases are handled in a linear and strict sequential manner. Such an approach is best in environments where the problem description and requirements are well-known and unambiguous from the beginning. However, in the age of emerging complex high-performance embedded systems, having to deal with incomplete sets of information or essential updates of environmental conditions during project execution, like e.g. hardware updates, is becoming more common in automotive software development than before. So, although the timeline flows towards more complete implementation, verification and validation, it is still possible and even necessary to introduce agile methodologies within certain phases of the safety software development in order to continuously improve the software quality and to meet time and cost objectives.



② *Parameterized code generation for reusable software components: The development of these is performed by using a tailored tool chain which supports configuration selection, configuration validation, as well as parameterized code generation.*

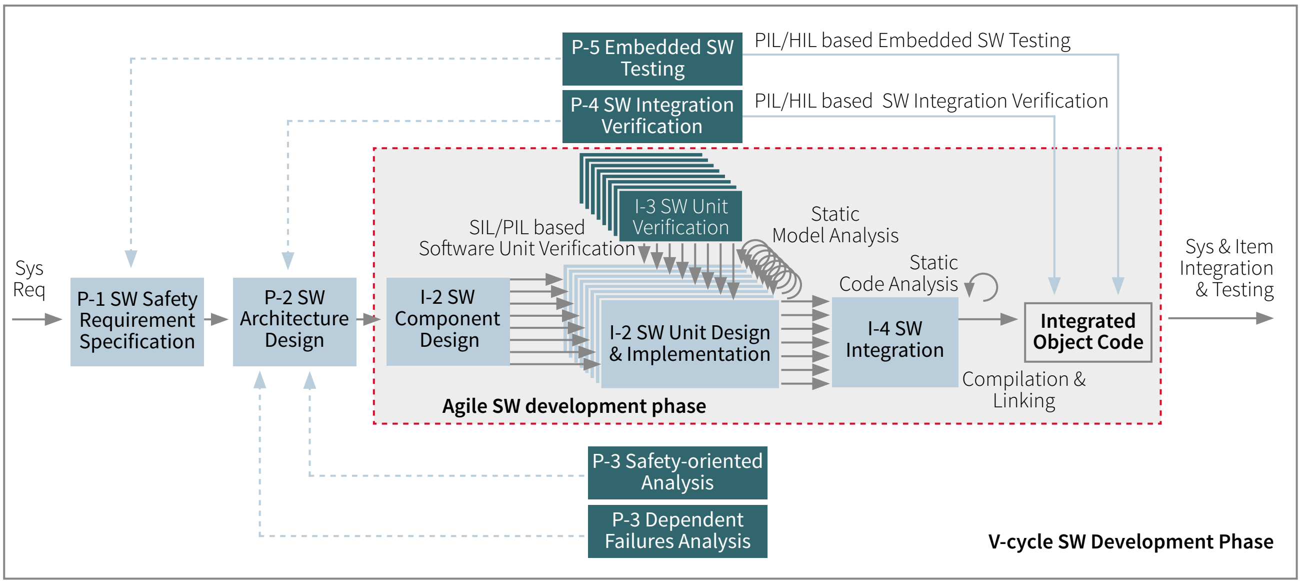
FEV therefore aims at a hybrid approach for safety software development. Although ASSDP is built on the ISO 26262-6:2018 requirements, it deviates from the often-employed overall waterfall-based software development approach. To achieve flexibility and reduce time-to-market, ASSDP uses a hybrid process approach where the main development is divided into two separate phases: (1) a V-cycle software development phase and (2) an agile software development phase. Figure 3 provides an overview of ASSDP including its sequential and more iterative- and increment-based agile development phases.

Agile Best Practices are Used at the Heart of ASSDP

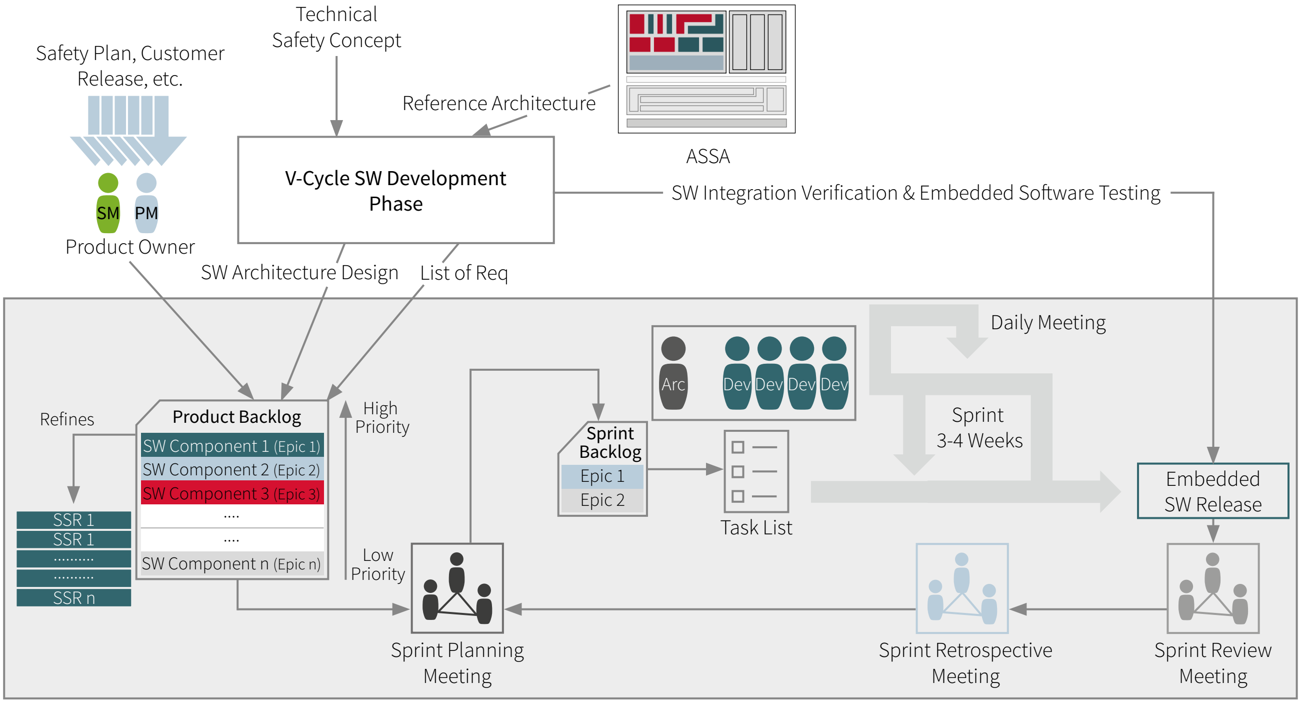
The V-cycle-based software development phase of ASSDP mainly consists of the design, analysis, and verification steps of the development (Figure 3). Starting from the system requirements, P-1 Software Safety Requirement Specification is performed, followed by the P-2 Software Architecture Design activity. After conclusion of P-2, P-3 Software Architecture Analysis comes next and covers the safety-oriented software architecture analyses and the Dependent Failure Analysis (DFA). The P-4 Software Integration Verification follows the I-4 Software Integration step which is part of the agile software development phase of ASSDP. P-5 Embedded Software Testing is the last process step and provides evidence that the integrated embedded software fulfills all requirements when executed in the target environment. Of course both P-4 and P-5 also provide evidence that the integrated software contains neither undesired functionalities nor undesired properties with respect to functional safety.

The agile process steps lie at the very heart of ASSDP which cover the I-1 Software Component Design, I-2 Software Unit Design & Implementation, I-3 Software Unit Verifications and I-4 Software Integration activities (Figure 3). These process steps are characterized by short and repeated iterations; with each development iteration typically lasting three to four weeks. Compared to V-model/waterfall-based processes, the shape of the system rather than its details is designed at the beginning of an agile process, which makes upfront design in an agile process lighter. Furthermore, implementation (and hence testing) are iterative and incremental activities, while being more monolithic steps in V-model-/waterfall-based processes.

Based on the software architectural design description from P-2 Software Architecture Design, the Product Owner along with the Safety Manager create the product backlogs which consist of the list of epics and user-stories. These user-stories inside this product backlog are priority based on project roadmaps and safety-related deliverables. In terms of ASSDP, each safety software component is treated as epic in the product backlog, whereas each user-story assigned within an epic relates to software units of a particular safety software component. During sprint planning, one or many epics can be selected, depending upon the size and complexity. Each sprint is then further divided into the main stages of activities – i.e. I-1 to I-4.



③ *Overview of ASSDP. Waterfall and agile phases are interlaced in order to introduce more iteration- and increment-based phases in the safety-critical software development. For each phase the different process steps are presented with their logical sequence.*



④ *The agile phase of ASSDP. Short and repeated iterations are the core property of this phase which usually last about three to four weeks. Well-known organizational elements from agile software development are used here.*

At the end of each sprint, a sprint review is planned where all the artifacts from a particular sprint are reviewed by the Safety Manager and the Product Owner against the requirements of ISO 26262. This step is soon followed by a sprint retrospective, and then by the next set of sprints (Figure 4).

ASSDP is accompanied by additional support processes and tool support. Continuous Integration (CI) is a core tool allowing users to perform the agile development steps as efficiently as possible. FEV therefore maintains a CI framework that supports development activities ranging from execution of verification activities on different levels and with various methods, code generation, and target software building to software documentation.

Conclusion

Both the safety architecture ASSA, as well as the safety software development process ASSDP, are the main foundational elements to increase the efficiency and time-to-market of safety software development without jeopardizing quality requirements.

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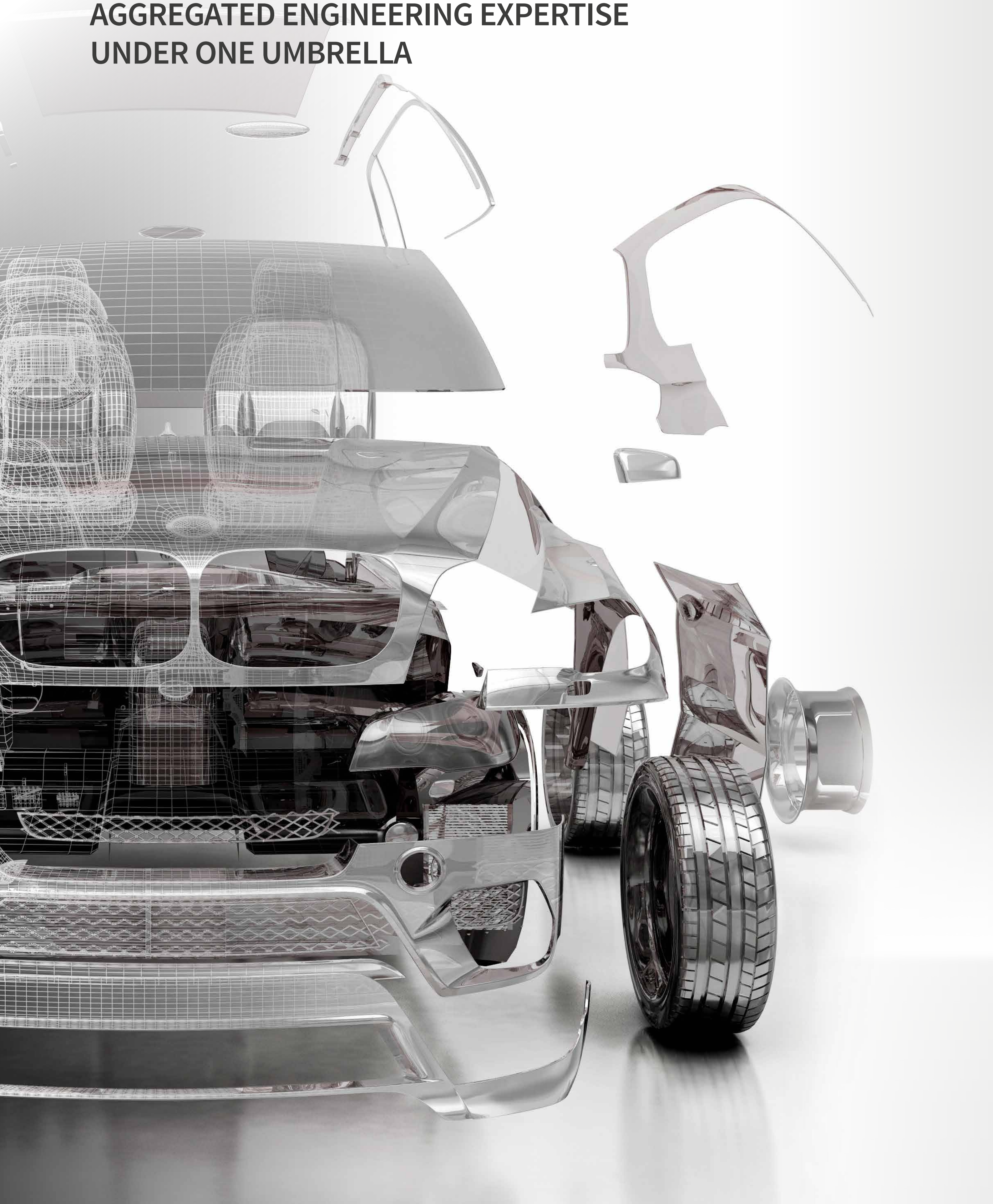
VEHICLE DEVELOPMENT

AGGREGATED ENGINEERING EXPERTISE UNDER ONE UMBRELLA



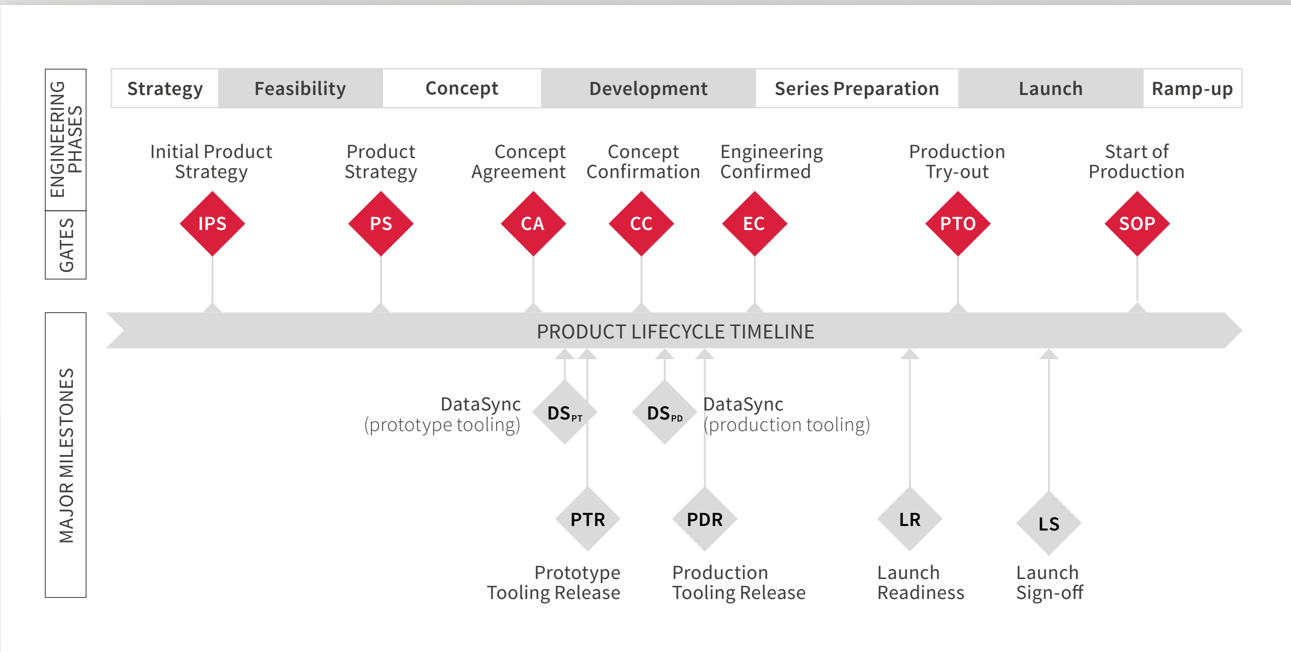
Today's vehicle development process is more complex than ever before; requiring a host of cross-divisional interactions and an ability to integrate resources across various disciplines. FEV meets this challenge with robust systems and teams of experts that have decades of experience in managing complex programs such as powertrain integration, attribute development, and even full vehicle engineering. That expertise extends across both ICE and electrified powertrains, and covers virtually all forms of mobility. Cost engineering, supplier sourcing, advanced quality planning, and release management are just some of the many competencies contained within the FEV portfolio. FEV develops both hardware and software solutions, and validates products using both virtual and test-based methodologies. In addition, the company utilizes state-of-the-art communication tools and flexible team structures to meet the needs of customers globally; and supports those programs at all levels of development, from initial concept to full-scale series production.

FEV Vehicle Development Process

The increasing number of innovations (e.g., ADAS, HMI, electrification, connectivity) and associated complexities pose unprecedented challenges to vehicle development. The result of which is a vehicle development process that continues to evolve. New technologies from other industries are coming faster and span broader applications than ever before in the vehicle world. Furthermore, new players are entering the market regularly, some with radically different views of vehicle products and services. The FEV Vehicle Development Process (FVDP – see Figure 1) integrates these requirements and is well-positioned to support both established OEMs, as well as new start-up companies in their product development.

Alignment of FVDP to Customers' Processes

The FEV Vehicle Development Process is built on decades of experience and our deep knowledge of best practices across industry segments. It is based on a simple baseline process that is highly adaptable and that serves as the backbone for subsequent activities. Clear interfaces are defined at key milestones to facilitate mapping between FVDP and customer-specific processes. This allows for clear and safe transitions from FVDP to the customer process (or vice versa) and gives FEV the flexibly to meet all program needs.



① *The FEV Vehicle Development Process*

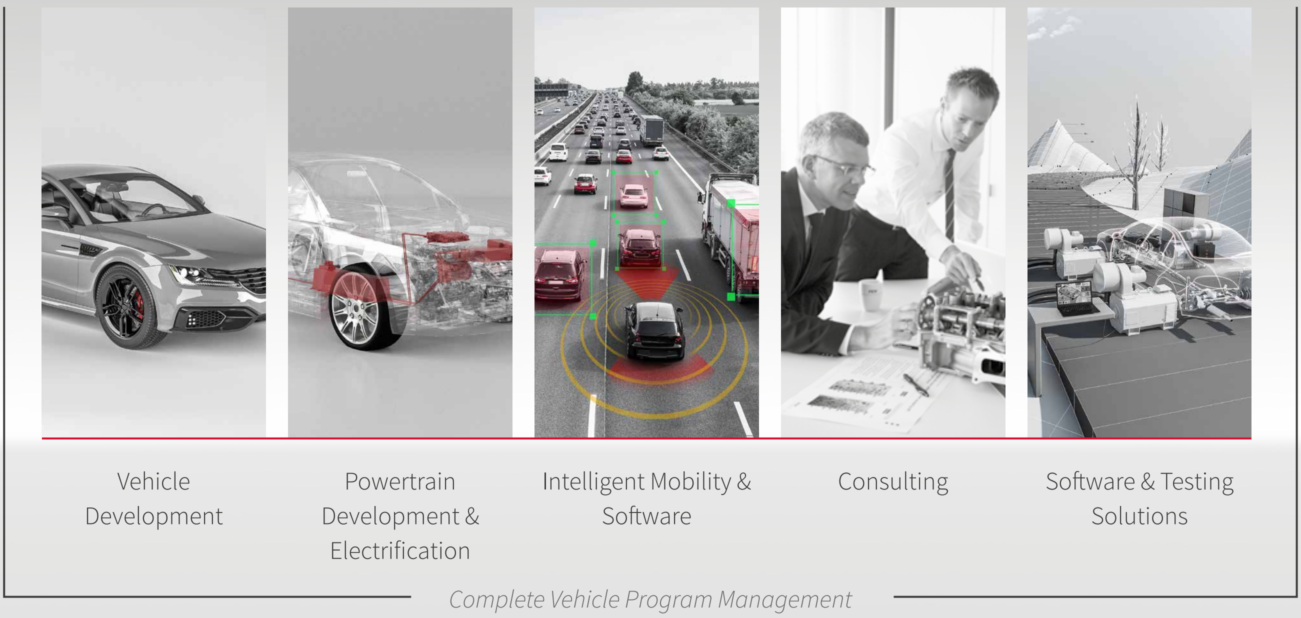
② *Light field technology*

Innovation to reality

Due to its heritage, FEV maintains a strong link with universities and non-academic research partners globally and has unique early access to new technologies. The FVDP methodology provides the framework to bring innovations quickly from research into vehicle development on production programs. One example of a successful transfer from innovation to reality by FEV's Vehicle Development Process is the realization of a three-dimensional (3D) image representation using light field technology. Here, the range of applications extends from taillights with 3D-effects to informative and aesthetically pleasing projections outside the vehicle. An example is shown in Figure 2.

Vehicle and Powertrain Development From a Single Source

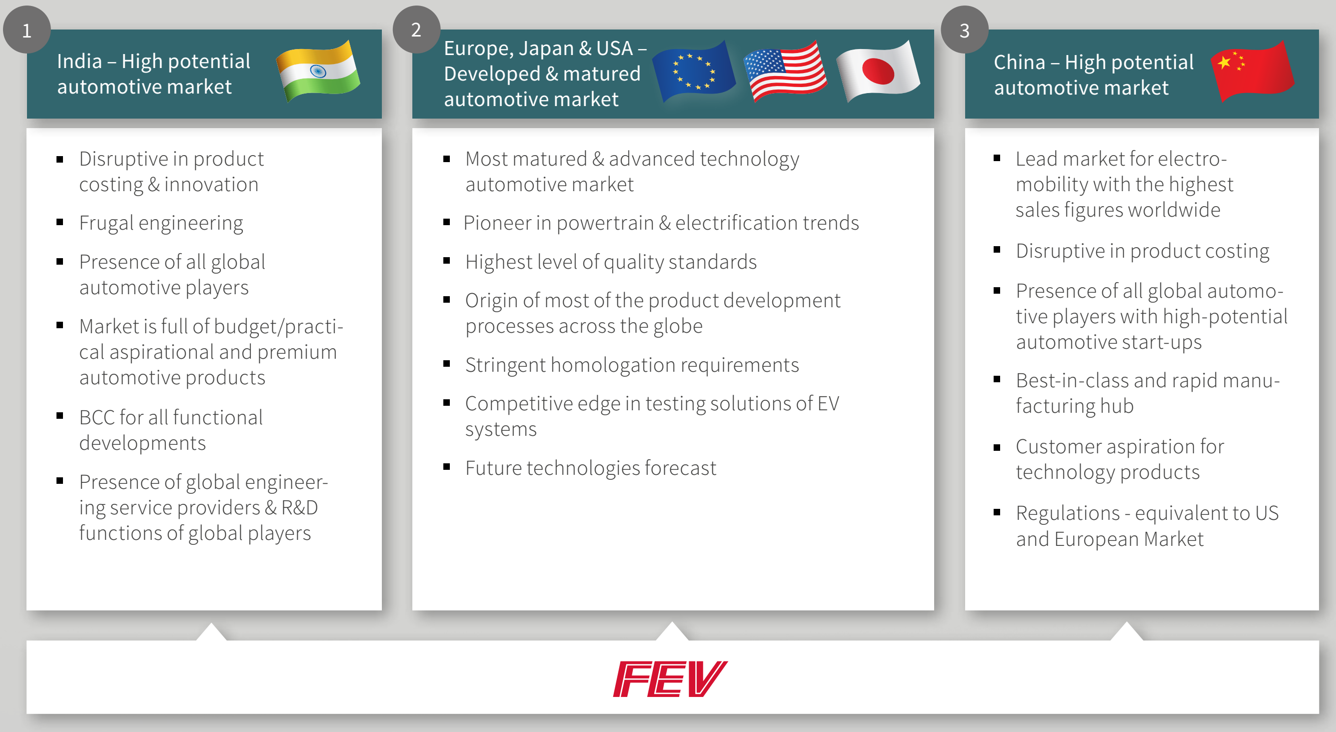
Many customers (especially start-ups) prefer to have one integrator being responsible for the development of all major vehicle systems on their production programs. FEV is uniquely positioned to offer full vehicle development services where requirements are not just for the vehicle, but also include the core powertrain, driveline, and electrical architecture. FEV's expertise in all these domains allows us to offer a systems-view of the product, one that can be developed and optimized across attributes to provide exceptional value to the end consumer.



③ *Integrated development process from FEV*

Global development

FEV maintains global engineering expertise and offers services worldwide. FVDP is a global standard within FEV. Most OEMs develop vehicles for global markets; FEV's worldwide teams work together with the same methods and structure to deliver world-class products. This allows, for example, BCC (best cost country) opportunities to be integrated into development services, such that cost-effective solutions can be offered by FEV to customers.



④ *Advantages of FEV's global presence*

Complete BEV Development Using FEV's Integrated Development Process

FEV is uniquely positioned as an ideal partner for customers in need of complete BEV development. For full BEV development programs, FEV offers an integrated approach that draws from both full vehicle development capabilities, as well as core expertise in the development of batteries and electrified drivetrain components. FEV offers a parallel development process in which the BEV aggregates can either be developed by FEV or leveraged from the OEM's product portfolio for integration into the new vehicle. FEV can provide full turnkey development of the new vehicle or can work together with the customer and offer expertise in desired areas. Expertise in development of drivetrain components and vehicle structures allows FEV to offer an integrated approach, where both drivetrain and vehicle development happens in parallel.

The advantages of this approach are evident in the implementation of FEV's "Cell-2-Chassis" battery development process. Specifically, in FEV's Cell-2-Chassis process, the battery is developed as an integrated part of the body-in-white (BIW) so that the vehicle structure acts as battery housing and provides both occupant and battery protection.

Various levels of designs are conceivable – Module-2-Pack, Cell-2-Pack with and without vehicle floor, Module-2-Chassis, and Cell-2-Chassis. The key drivers for battery pack design are to increase energy density, reduce overall mass, decrease total height and offer a high degree of flexibility with the OEM vehicle portfolio.

The following requirements must be considered across the systems:

- Cost
- Crash and stiffness
- Battery sealing
- Safety and load path concept of BIW
- Production (design for manufacturing, assembly, and serviceability)
- Recycling
- Logistics chain and production sites with reference to UN38.3
- Homologation of either separate battery or entire vehicle

The FEV team analyzes the customer portfolio and offers guidance in defining the optimal concept taking all relevant factors into consideration including target markets, customer demographics, vehicle volumes, and platforms.

FEV thus offers a variety of attractive solutions for new battery concepts, platforms, and vehicle architectures for its customers. Many products developed by FEV have already been brought into production. Further examples for FEV's outstanding capability in finding the right tradeoff between performance, cost, and timing for a BEV development are shown below.

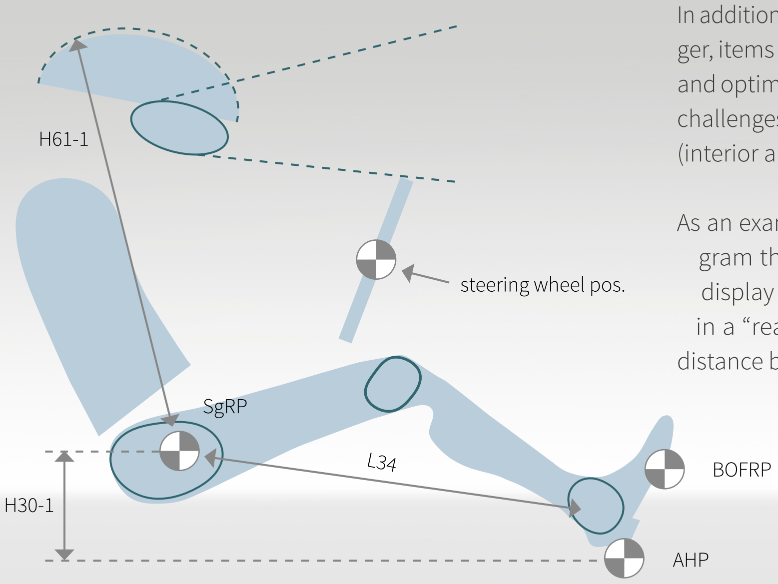
Vehicle Layout and Ergonomics

BEV development offers new styling opportunities like shortened front overhang, enlarged cabin space, or optimized ergonomics to improve consumer needs. Nevertheless, there is a challenge to strike the best balance between the emotional side of vehicle engineering (styling) and achieving technical requirements driven by safety targets, legal requirements, and ergonomic package needs. To ensure the best result for the full vehicle product a novel styling and engineering convergence process is required. The development of the ergonomic package process starts with early target setting and fixing relevant dimensions based on benchmark values from FEV's database and customer clinics with competitor vehicles.

To maximize the efficiency during the ergonomics development phase and to enable a fast decision process together with the customer, a parallel digital and physical validation process is required. Virtual validation using ergonomics simulation software tools (e.g. Ramsis) and physical verification with an "Ergo-Buck" are done in parallel. This validation process starts with a coarse approach to evaluate the basic ergonomics concept dimensions and ends with a detailed seating buck showing interior and exterior design details for full ergonomics validation and approval.

In addition to the basic ergonomics package of driver and passenger, items such as HMI (Human Machine Interface) accessibility and optimization of ingress/egress dimensions are examples of challenges where a balance needs to be struck between styling (interior and exterior) and ergonomics targets.

As an example, in a former FEV full vehicle development program the interior styling theme dictated a straight center display design in line with the cluster display. This resulted in a "reachability" concern because of the relatively long distance between the driver and the display. The solution was a balance between styling and ergonomics in combination with a modified HMI concept which ended up in splitting the user interface layer.



⑥ *Ergonomic concept build-up*

In this specific case the reachable zones on the display were identified for the relevant target customer percentiles and the HMI content was adjusted appropriately. This allowed FEV to preserve the desired styling theme without disadvantaging the end-user in the daily operation of the vehicle, creating greater market acceptance.

Attribute Development

FEV's vehicle development team handles the entire spectrum of attribute development. This includes:

- Safety
- Vehicle dynamics
- NVH
- Thermal management
- Aerodynamics
- Efficiency
- Performance
- Dimensions, weight and geometry
- Water, dust, and corrosion management
- Quality
- Compliance

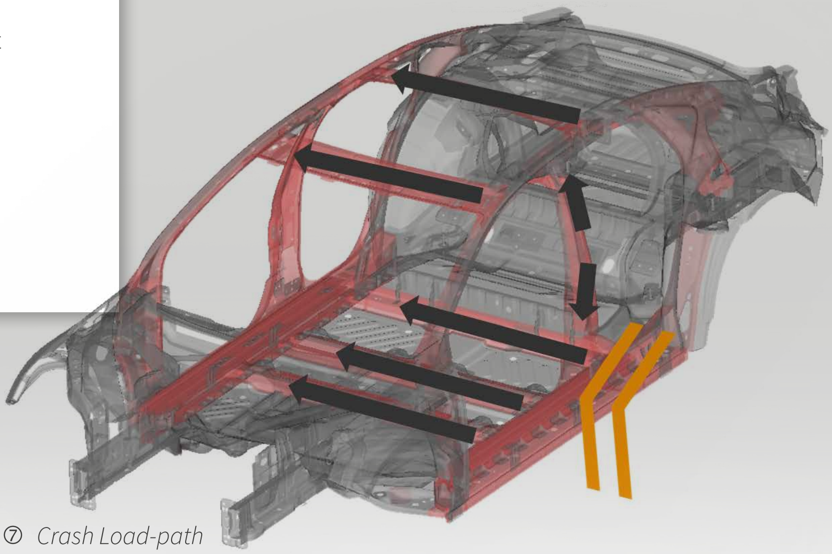
» Safety and aerodynamics attributes are detailed in the following.

Lateral Pole Impact

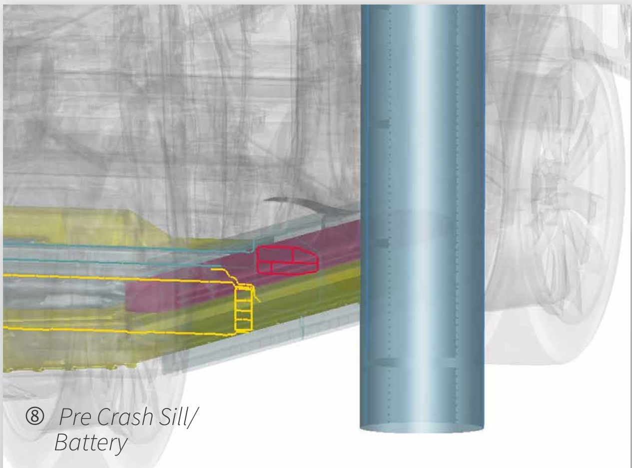
Side pole crash is one of the NCAP tests used to assess the ability of a vehicle to provide protection during a side crash. Significant emphasis is given to battery safety, because high deformations of the floor and battery, if not controlled, could lead to a thermal runaway. In this test, the vehicle is impacted on the fixed rigid pole at 32.2 km/h at an oblique angle of 75°, simulating vehicle impacting a tree or a post.

The need for a dedicated underbody floor load-path (a structural design with high energy absorption and intrusion resistance capabilities to manage the impact forces) is identified in the early design phase. Through structural topology optimization, using state-of-the-art simulation tools, the best trade-off between styling, functionality, performance, and weight can be achieved. Development targets are derived from the functional requirements of body structure, minimum deformation of the battery and biofidelic safety requirements.

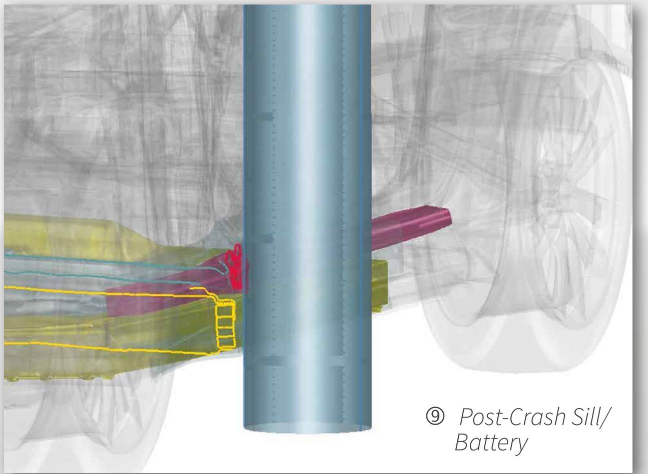
The design of rocker section and the backup structure are critical for achieving the best safety results. The rocker section is designed to achieve maximum energy absorption during a crash and distribute the crash energy to the bigger area along the sill.



⑦ *Crash Load-path*



⑧ *Pre Crash Sill/ Battery*

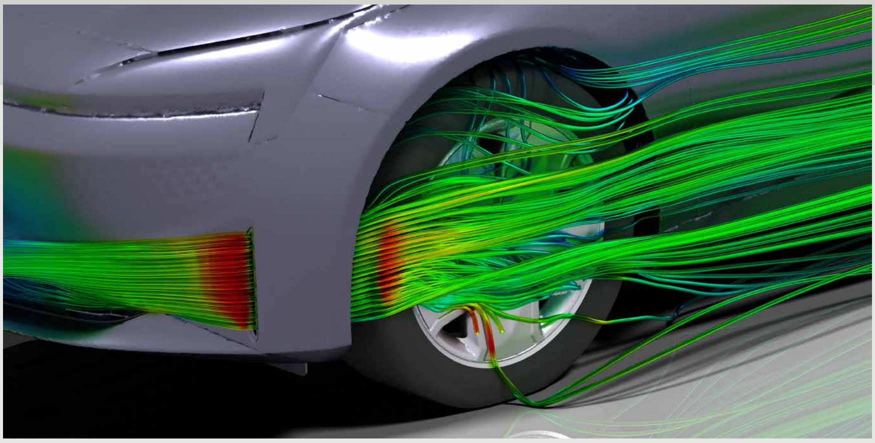


⑨ *Post-Crash Sill/ Battery*

The rocker reinforcement (aluminum extrusion profile) is strategically positioned to provide maximum overlap with the backup structure on the body floor. The backup structure is designed as a very stiff continuous cross-member to provide crush resistance and strengthen the passenger compartment. The use of aluminum for rocker reinforcement can provide optimal tradeoff between weight reduction and high structural performance. Also, through such a design concept, a reasonable balance between styling (minimizing crush space) and structural requirements can be achieved.

The design of dedicated "underbody floor load-path" and well-integrated battery into the BIW maximizes the load transfer (ca. 45 percent of crash load) to the upper floor load-path. The engagement of the battery housing as an active crash load-path is delayed, thereby reducing the crash forces on the battery (ca. 28 percen of the crash loads). Remaining loads are distributed over the stiff upper body structure (B-pillar, door, A-pillar) maintaining the integrity of the safety cage. The stiffer outer profile of the battery housing provides relatively high bending resistance in the lateral direction, thereby reducing intrusion into the module and greatly reducing the risk of battery damage, helping to keep the module design space uncompromised.

⑩ *Air curtain with velocity streamlines*

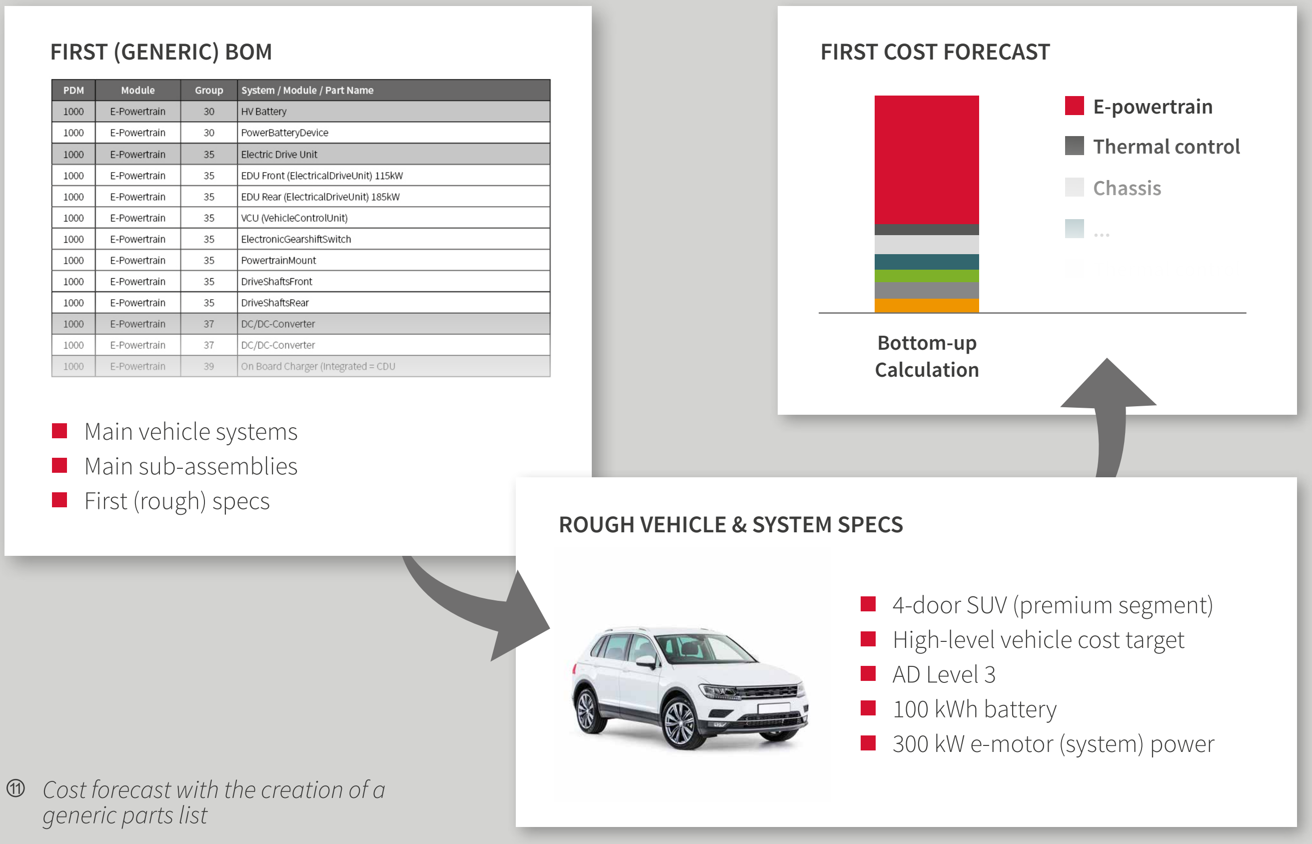


Aerodynamics Development

In each vehicle development process, aerodynamic optimization plays a fundamental role to realize various performance targets. For ICE-powered vehicles, aerodynamic drag has a high impact on fuel consumption and, consequently, CO_2 emissions. Regarding BEVs, the driving range as a key customer attribute is significantly influenced by aerodynamic drag. Thus, FEV offers a versatile and flexible optimization toolchain, which covers the entire development process from first styling sketch to SOP.

A key challenge in achieving a best-in-class drag coefficient is to find the perfect balance with other vehicle attributes and stakeholders. These consist of styling, packaging, ergonomics, thermal management and many more. Especially styling and aerodynamics can often have conflicting requirements. In a recent FEV program, a best-in-class drag coefficient was required while no significant changes to the styling theme were permitted. Among various detail optimizations, one of FEV's solutions was to integrate an air curtain in the front bumper (Figure 10). This prevented the front flow separation, which originally was caused by the combination of a short overhang with a high bumper sweep angle.

In aerodynamics development, both CFD (Computational Fluid Dynamics) simulation and wind tunnel testing methods are utilized. Especially in the early development phase, FEV focuses specifically on CFD simulations. This enables both an early identification of optimization measures and the visualization of the entire flow field. Due to result approximation of the numerical methods, simulations are enhanced by wind tunnel testing before styling freeze. For this purpose, a full-scale clay model was built up in a recent FEV program. This approach enabled both validation of the numerically predicted drag and further optimization in the wind tunnel. In this context, a precise wind tunnel correlation of the FEV simulation method was proven and the challenging vehicle drag and lift targets were successfully reached.



PDM	Module	Group	System / Module / Part Name
1000	E-Powertrain	30	HV Battery
1000	E-Powertrain	30	PowerBatteryDevice
1000	E-Powertrain	35	Electric Drive Unit
1000	E-Powertrain	35	EDU Front (ElectricalDriveUnit) 115kW
1000	E-Powertrain	35	EDU Rear (ElectricalDriveUnit) 185kW
1000	E-Powertrain	35	VCU (VehicleControlUnit)
1000	E-Powertrain	35	ElectronicGearshiftSwitch
1000	E-Powertrain	35	PowertrainMount
1000	E-Powertrain	35	DriveShaftsFront
1000	E-Powertrain	35	DriveShaftsRear
1000	E-Powertrain	37	DC/DC-Converter
1000	E-Powertrain	37	DC/DC-Converter
1000	E-Powertrain	39	On Board Charger (Integrated = CDU

⑪ *Cost forecast with the creation of a generic parts list*

BOM Cost Development

In the area of product costing, FEV offers a unique service portfolio of cost estimation covering the entire product development process from the pre-concept phase through SOP (Start of Production). Understanding product costs in detail along with technical content of the components is an important factor for successful supplier negotiations. These details are typically not available in the beginning of a vehicle development project.

FEV's cost benchmark experience with detailed analysis of all vehicle components enables it to make reasonable evaluations for component specifications, design and potential production technologies in the early stages of product development. On this basis, FEV can estimate the cost of components with reasonable accuracy, even when technical details are not fully defined.

FEV starts an early cost forecasting process by setting up a generic BOM (Bill of Materials) for the entire vehicle. Therefore, main systems and components (such as BIW, seats, infotainment, HV battery, etc.) are evaluated. Using cost analysis databases, parametric cost models, and bottom-up cost calculations, the process is able to forecast initial design costs with relatively high accuracy, in a very short time frame. This initial cost forecast is used to support the decisions of the development team, by meeting all technical program requirements at the lowest possible cost. As more technical details become available on this program, the cost analysis is refined continuously to improve transparency and accuracy so that decisions can be made with confidence in a timely manner.

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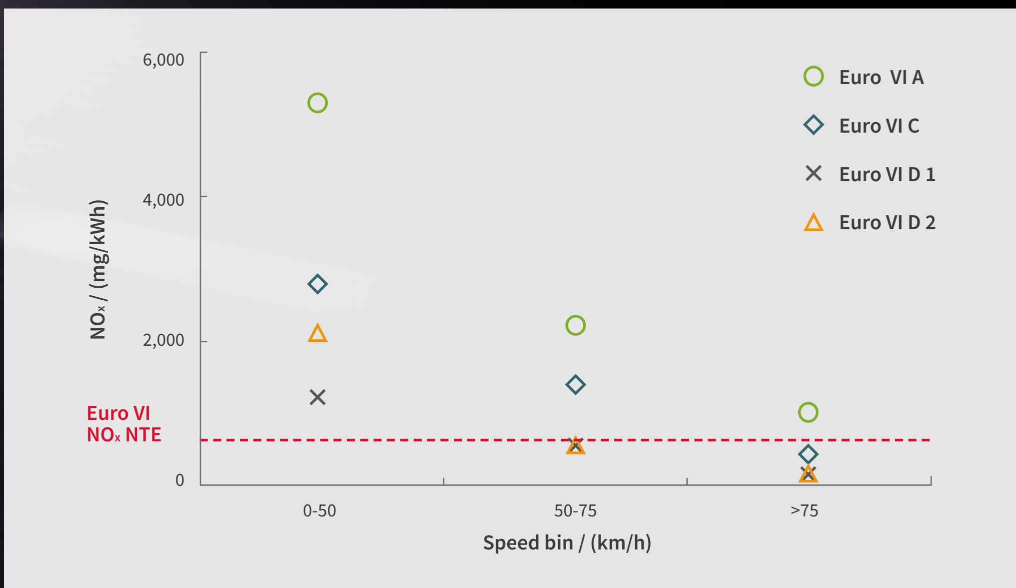
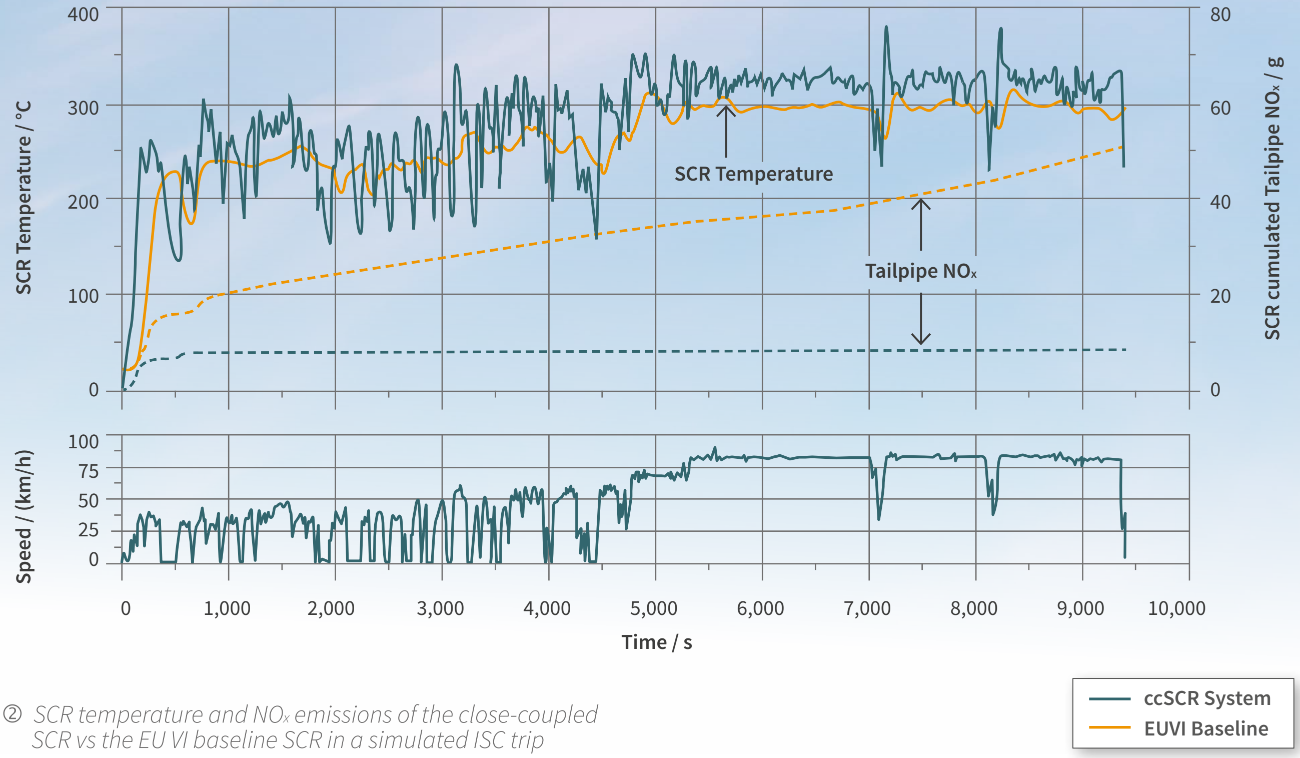
TRUCK EATS

A NOVEL EXHAUST AFTERTREATMENT SYSTEM FOR HEAVY-DUTY TRUCK APPLICATIONS WITH LOWEST NO_x EMISSIONS

This article looks at a novel exhaust aftertreatment system (EATS) design and integration, which is used to demonstrate how the adaption of current technologies can be used to meet future regulatory emission requirements for long-haul truck applications. The main motivation for a heavy-duty demonstrator vehicle is that future emissions legislation will most likely cover all driving scenarios and remove the post-processing of emissions data which is currently used to standardize data evaluation methods in the EU. Recent studies have shown that many vehicles show higher NO_x emissions when these post-processing methods are removed. This is especially true in cold-start or urban driving conditions. Examples of tested vehicles, shown in Figure 1, indicate that emissions from vehicles complying with the various Euro VI emissions standards are above current NO_x limits in urban and rural driving conditions, and some of the older Euro VI variants also show high NO_x emissions during motorway operation.



① *NO_x emission performance of Euro VI heavy-duty vehicles*



② *SCR temperature and NO_x emissions of the close-coupled SCR vs the EU VI baseline SCR in a simulated ISC trip*

These results highlight the importance of further reducing NO_x emissions in cold-start and city driving conditions for the overall potential to meet future emission standards. Additionally, any system that is developed must also be compliant under conditions which were formerly deemed irrelevant, such as stop-and-go traffic. Another issue that needs to be considered in the future is that additional emissions such as particulate number (PN_{10}), ammonia (NH_3) and Nitrous Oxide (N_2O) will be limited. To fully control these pollutants, an optimal design and layout needs to be established to ensure the best possible temperature and gas flow uniformity for all operating conditions.

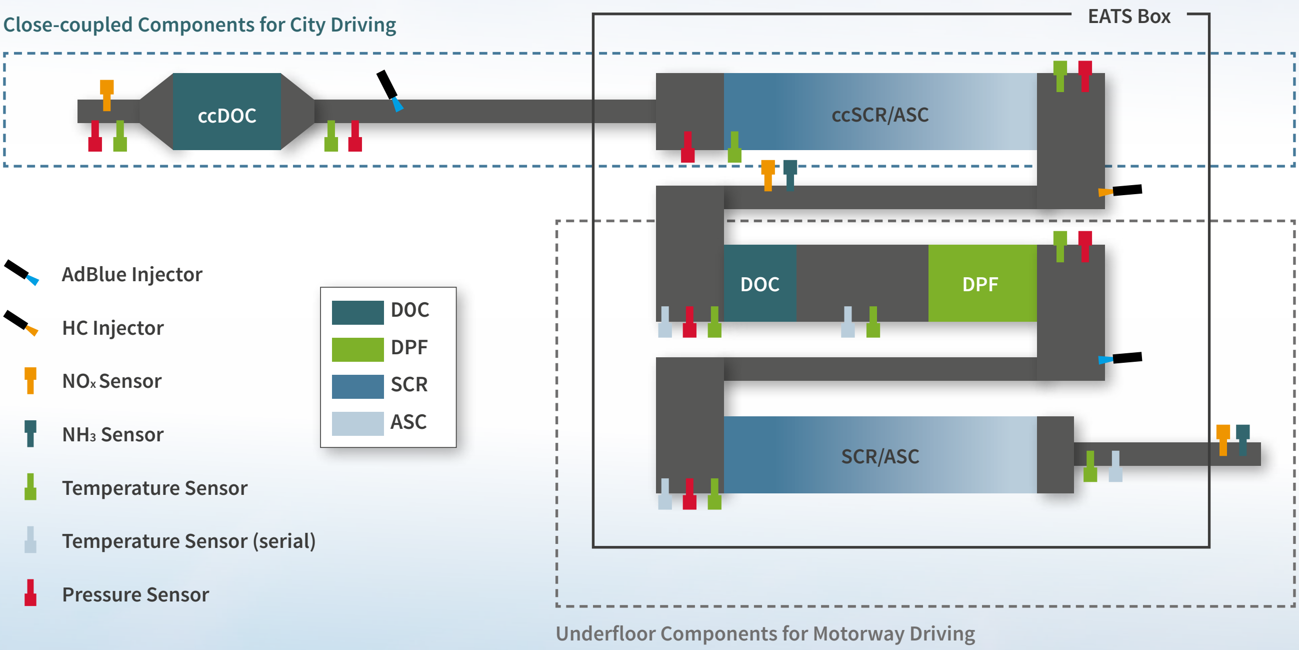
Consequently, a demonstrator exhaust aftertreatment system was designed to reduce tailpipe NO_x emissions to ultra-low levels in a broad range of operating conditions. The use of two Selective Catalytic Reduction (SCR) systems allows for strongly improved conversion. The first SCR system at the entry of the EATS box enables a very early start of the NO_x conversion due to fast warm-up in low speed and load conditions. However, the integration of two fully operational systems into the currently available package space creates significant design challenges. To determine an optimized EATS layout for achieving the emissions targets, a series of simulations were conducted using FEV's

xMOD software. The study evaluated the impact of different layout combinations, catalyst volumes and materials versus the emission targets.

The simulation study was conducted with 50 percent and 100 percent payload for the WHVC (World Harmonized Vehicle Cycle) emission cycle, for a Euro VI In-Service Conformity route and additional routes (urban and rural delivery) focusing on worst-case cold-start driving scenarios. The new system layout was compared to conventional EU VI-EATS (DOC, DPF, SCR, ASC) systems to determine the potential for improved NO_x conversion and thermal management, particularly after a cold-start. The integration of the close-coupled components significantly improves the NO_x reduction efficiency in all investigated cycles and routes, especially within the cold-start and long-idling phases.

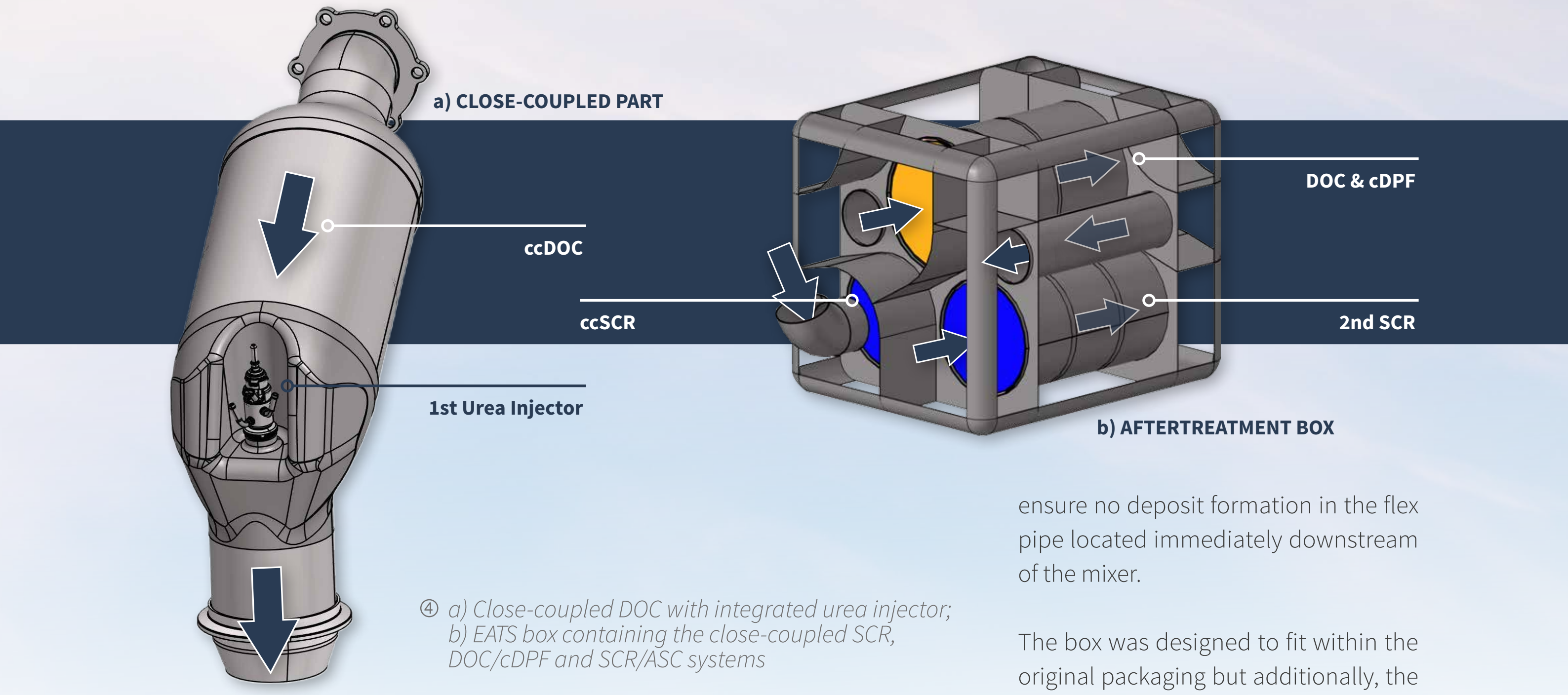
Figure 2 shows the simulation results with the improvement in the heat-up temperature of the close-coupled SCR compared to the underfloor SCR of the base system for one ISC cycle.

From the simulation results, it was determined that the final layout resulted in an EATS containing two separate SCR systems – one close-coupled, and another one in a regular underfloor position (Figure 3). The simulation determined that the system components should be sized as follows: a close-coupled 7L Diesel Oxidation Catalyst (DOC), followed by a 25L SCR, a second 7.5L DOC, an 18L Diesel Particulate Filter (DPF) and a 25L underfloor SCR/ASC (Ammonia Slip Catalyst). The two SCR catalysts were sized large to allow for both SCR systems to work independently for full flexibility during the potential study of the system.



③ *Schematic layout of EATS including sensor setup*

» IN ORDER TO MEET WITH FUTURE EMISSION STANDARDS, NO_x EMISSIONS UNDER COLD-START AND CITY DRIVING CONDITIONS MUST BE REDUCED EVEN FURTHER



④ *a) Close-coupled DOC with integrated urea injector; b) EATS box containing the close-coupled SCR, DOC/cDPF and SCR/ASC systems*

Based on the initial volume determination, the definition of the full exhaust system layout, including connecting pipework, mixers and sensor layouts and locations, was created considering the packaging constraints of the current EATS housing as this would show the best potential with minimal changes to the vehicle layout. The new close-coupled DOC was fitted directly downstream of the turbocharger for fast CO/HC reduction and to allow optimal heat transfer into the EATS system. The outlet cone of the DOC was modified to integrate a urea injector (Figure 4, left), allowing the use of the downpipe and the compensator for optimal mixing of the injected urea before entering the close-coupled SCR (ccSCR) contained directly at the box entry. The ccSCR contains a zone coated Ammonia Slip Catalyst to minimize resulting secondary emissions. Downstream of the ccSCR, the component layout resembles that of a conventional truck EATS design (Figure 4, right), containing a DOC and DPF with integrated HC doser for DPF regeneration support. Downstream of the DPF, there is a second urea injector and mixing pipe before the second SCR system with an integrated ASC to minimize ammonia slip. This system is to support low NO_x motorway driving and allow the potential for passive regeneration capability to be maintained to allow for longer active regeneration intervals with a potential cost and CO_2 saving potential. All components were hydrothermally-aged prior to installation into the EATS to realize full-useful-life-aged conditions.

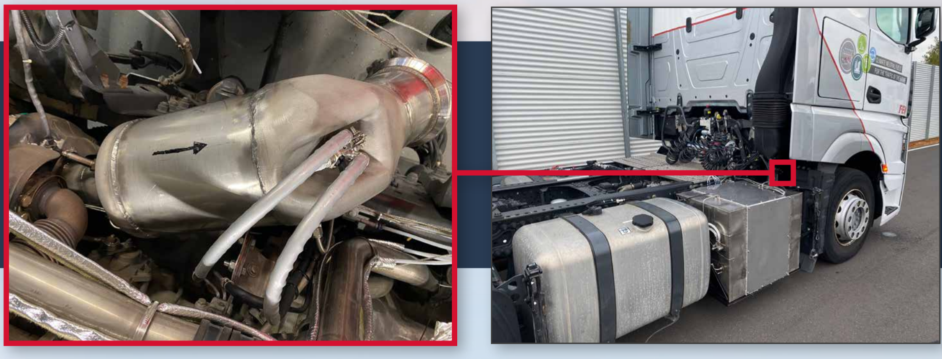
The pipework was modified as required to allow optimal flow, temperature and NH_3 uniformity throughout the full system. The design allows for a simple drop pipe to the exhaust line, ensuring easy instrumentation for PEMS measurements.

Owed to the very small package space for close-coupled components, the first SCR was incorporated to the box which allows optimal mixing length post DOC to ensure the best NO_x conversion and ammonia slip control. The close-coupled components required a special design to allow their packaging around the chassis, suspension and wheels. For similar reasons the injector is mounted within the DOC outlet cone. It is designed in such a way that it injects directly on an in-house designed mixer, proven to create very low urea deposit formation. The additional logic behind this configuration was to ensure no deposit formation in the flex pipe located immediately downstream of the mixer.

The box was designed to fit within the original packaging but additionally, the setup allows for increased simplicity in the design and increased amounts of common parts for overall cost reduction potential (see Figure 4, right). No deep drawn parts were included to keep the design simple but effective. The box also incorporates access panels for simple replacement of any broken prototype components.

The final design was then created using a combination of 3D printing for the close-coupled DOC module and standard sheet metal cutting and welding. It was constructed in the FEV workshops and fitted to an N3 Daimler Actros 1845 LS 4x2 tractor demonstrator vehicle (Figure 5). The vehicle was equipped with a 12.8L engine with high pressure EGR homologated to Euro VI-C. While the engine was still controlled with the original control logic, the EATS was operated with a Rapid Control Prototype (RCP) system.

Baseline for control of the updated dual SCR EATS is FEV's latest dual-dosing SCR control software that includes slice-based substrate temperature modeling, reactions kinetic-based conversion calculation and coupled-SCR control logic in order to adapt the urea dosing strategy for both SCR systems to achieve lowest NH_3 slip and low urea consumption. The fully integrated and commissioned EATS



⑤ *HD demo vehicle and the new EATS installed*

was then calibrated to a demonstrator level with the NO_x conversion additionally balanced against N_2O formation and NH_3 slip. Next, the truck was operated in a series of drive cycles to determine the performance of the EATS system. The results of 2 ISC cycles are shown in Figure 6. The total conversion rates recorded for the tests were ~99.3 percent for the sensor-based measurements and ~99.4 percent for the PEMS measurements.

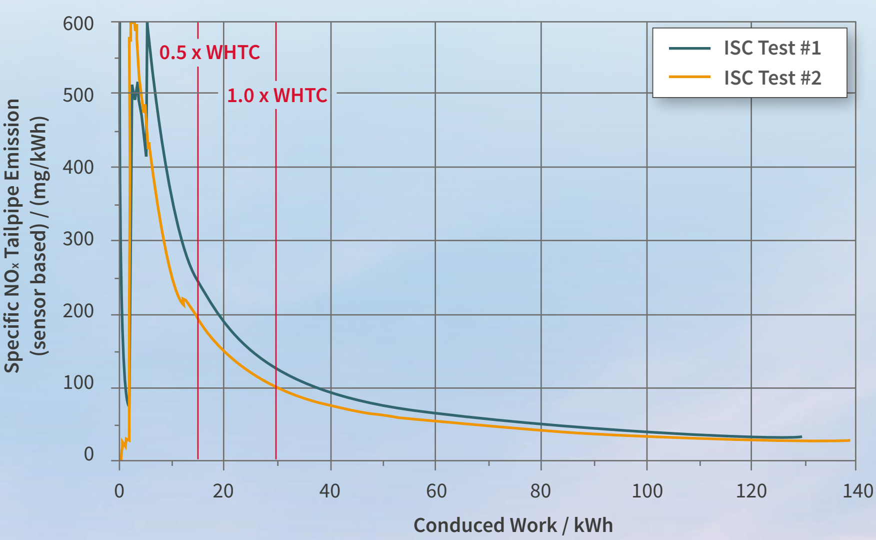
The key benefit of the system is the improved overall heat transfer from the engine to the EATS. The proximity of the EATS components allows the system to reach 200°C (392°F) temperature required for robust urea metering much faster than is the case with a standard EURO VI emission control technologies layout. Additionally, the splitting of the SCR into two systems with two independent urea dosers and the optimized volumes allow NO_x emissions to be reduced to extremely low levels even after a short period of vehicle operation.

The truck demonstrates that the NO_x emissions of a heavy-duty truck diesel engine can consistently be kept at very low levels over a wide range of driving conditions by combining existing advanced catalyst technologies with improved engine and aftertreatment control functions. The design of the EATS layout demonstrates that these extremely low NO_x emissions can be achieved within the constraints of a typical truck application.

It should be noted, however, that the conducted program cannot cover all possible combinations of driving and boundary conditions required for a series development. Further optimization with respect to dimensioning based on existing cabin and frame layouts, passive regeneration potential, pressure drop, and extended lifetime requirements must be carried out.

A follow-up article in SPECTRUM will address in detail further drive cycle results including PEMS measurements using an extended analyzer kit for N_2O, NH_3 and PN_{10} measurements.

The authors would like to thank the members of the AECC, IPA, Corning Inc. and the CEFIC Automotive Grade Urea Sector Group for their financial support, the provision of catalyst and filter parts, and for their extremely valuable contributions to this study and finally, HJS for their assistance in canning the emission control system.



⑥ *Cumulative specific tailpipe NO_x emissions for an ISC trip*

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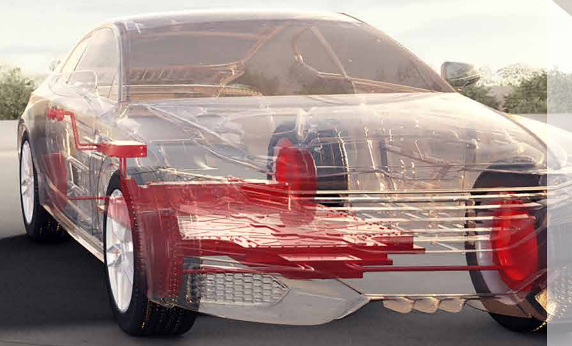
The content of this article was first published at this year's International Vienna Motor Symposium.

HYBRID DRIVE

xHEV-CONCEPT ACHIEVING THE 2030 CO_2-TARGETS

The topic of environmental sustainability is rapidly becoming a greater part of the public consciousness. The discussion about climate change impacted by CO_2 emissions is affecting all major industries including the automotive and transportation sector. CO_2 emission regulations for the automakers' vehicle fleets are considered ambitious political goals. The reduction of -37.5 percent (-55 percent could be adopted as part of the EU's Green Deal) for Europe in 2030 is based on 95 gCO_2/km in the New European Driving Cycle (NEDC) and considers a mark-up for the transfer to the more realistic Worldwide Harmonized Light Vehicles Test Procedures (WLTP) cycle.



In a previous study[1], FEV has shown that with a C-Segment vehicle, which represents the EU-fleet average, the -37.5 percent CO_2 reduction target can be met using an optimized HEV powertrain — in a 100 percent HEV fleet. The following study also considers the expanded potential future target of -55 percent and includes it in the powertrain technology roadmap for a representative fleet. The following powertrains are considered for this fleet in 2030:

- 48V or high-voltage full-hybrid vehicles (HEV)
- Plug-in-hybrid vehicles (PHEV)
- Battery electric vehicles (BEV)

In order to calculate the average fleet consumption of a generic OEM in 2030, the three mayor vehicle segments (A/B, C, D/E) were investigated.

Powertrain Architecture and CO_2 Results for 2030 Vehicles

The results of an analysis of the customers' usage behavior were used to derive the performance target for each segment. The ICE is based in FEV's DHE (dedicated hybrid engine) family. With a cost-effective technology package it can achieve more than 43 percent brake thermal efficiency. Even higher values are under investigation. The ICE-power (as well as the power of the e-machines) is tailored for each powertrain concept to achieve the segment performance targets. Vehicle improvements leading to reduction of weight, aerodynamic drag and rolling resistance have a significant impact on the powertrain architecture and CO_2 emissions. Therefore, results from the previous study[1] were used to estimate the development of aerodynamic drag and rolling resistance for 2030.

The drag and rolling resistance varies significantly between the segments, which is partly based on the vehicle type (leading to higher values in the D/E-segment). In addition, the cost sensitivity in the A/B-segment is considered, which prevents the introduction of certain add-on technologies for cost reasons. The corresponding CO_2 emission results for the A/B-segment are shown in Figure 1. Despite the lower voltage level of 48V, there is quite a significant benefit associated with the hybrid system.

The combination of vehicle improvements and further adaptation of the ICE results in a 13 percent CO_2 reduction, starting from an already best-in-class value using FEV's DHE and improved aerodynamics for the 2020 vehicle. It should also be recognized that already with today's best-in-class technologies significant improvements can be made (~20 gCO_2/km between benchmark and base vehicle)

The results for the C-segment are summarized in Figure 2. It must be emphasized that the advantage of the powersplit system results (in part) from the defined boundary conditions.

When the 0-100 km/h acceleration is emphasized, the results shift towards the other options. The CO_2 emission reduction when comparing the 2020 vehicle (48V P0) and the 2030 vehicle with 400V powersplit can be divided into:

- Vehicle improvements and powertrain weight impact with a contribution of about 44 percent
- Hybrid topology including transmission with a contribution of about 34 percent
- ICE upgrade, optimization of load point distribution and downsizing with about 22 percent contribution

The CO_2 emission results for the D/E-segment are shown in Figure 3. For the interpretation of the results it is important to mention that, in contrast to the other 2020 segments, a conventional gasoline and diesel ICE powertrain is used due to the current shares in this segment.

With an electric range of more than 80 km in WLTP, the CO_2 emission results of the series and series/parallel hybrid architectures are significantly below 20 gCO_2/km. Due to the change in regulation, the NEDC results are slightly higher than the WLTP results.

Fleet CO_2 emissions are even more important than the results for the individual vehicles/segments. Hence, a representative fleet is built on the results shown earlier. The following boundary conditions are considered:

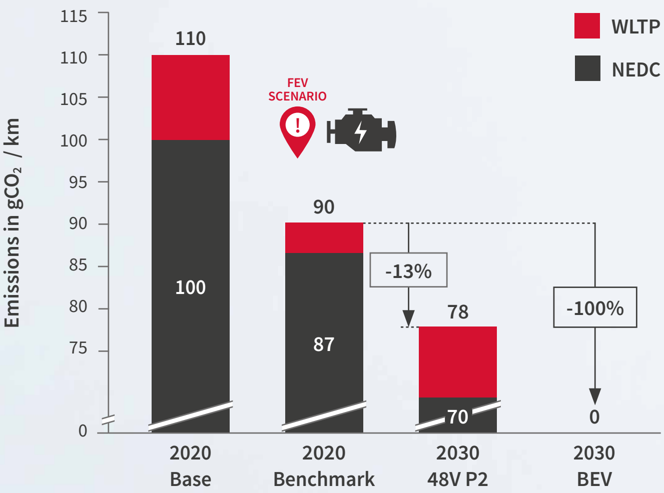
- The baseline is defined by the 2021 CO_2 emission target of 95 gCO_2/km.
- Diesel and gasoline ICE (as well as xHEV and BEV) are considered in the baseline according to their market share of 2019.
- The distribution between the segments is considered constant between 2019 and 2030.

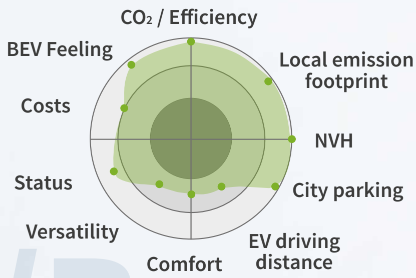
For simplicity, the results are displayed under NEDC boundary conditions and a mark-up for WLTP (based on the results for the segments displayed before) is added.

In this case, the improvements from the 2021 targets to 2030 are 40 percent for (P)HEV only, and 55 percent for 27 percent BEV shares. With a significant 27 percent BEV share, the anticipated target of the European Commission (55 percent) is reached, but already requires a significant contribution by way of vehicle improvements as well as an optimization of the ICE and the hybrid system itself.

Of course, the fleet CO_2 improvements for 2030 are partly driven by the legislation for PHEV, which is often critiqued since the real-world fuel consumption (and therefore the CO_2 emissions) of PHEV are much higher than the official homologation results. The main disadvantage is that the customer/driver does not use the plug-in-functionality often enough, as is addressed in the next section.

EVALUATION – FUN-TO-DRIVE, SECONDARY CAR USER, COST-SENSITIVE DAILY COMMUTER

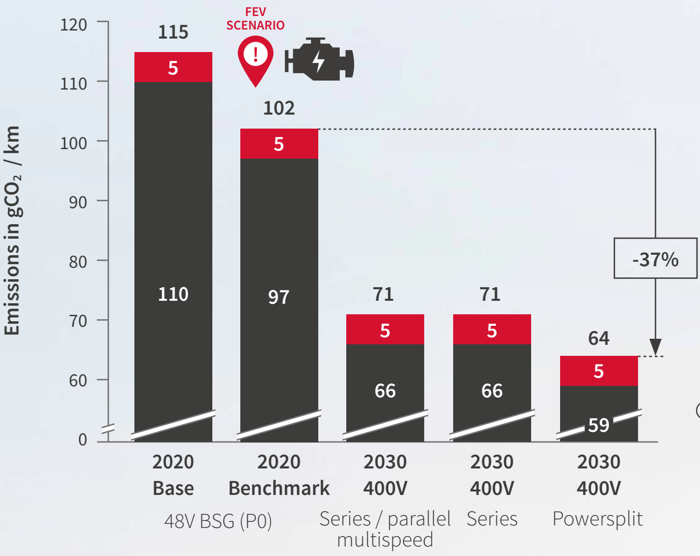


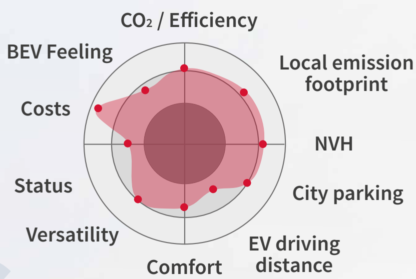


A/B SEGMENT

① CO_2 emissions of conventional 2020 base and benchmark ICE vehicles in comparison with a 2030 48V P2 HEV and a BEV for the A/B-segment

EVALUATION – DAILY COMMUTER

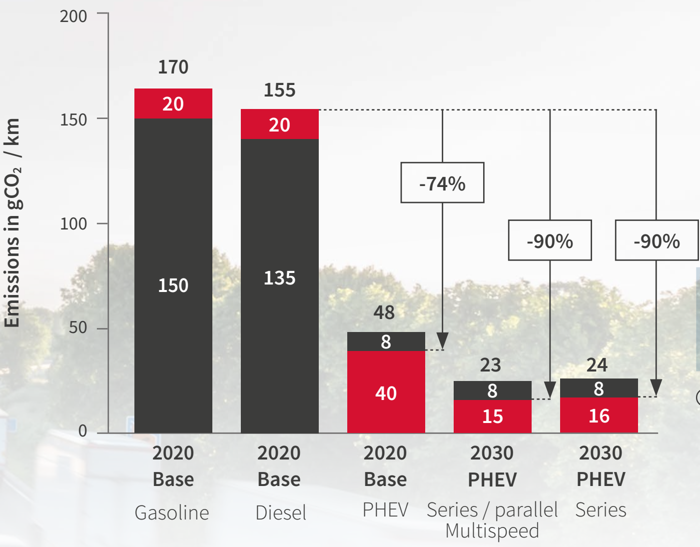


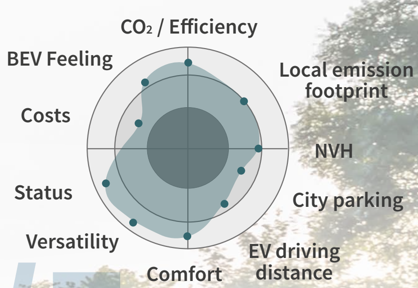


C SEGMENT

② CO_2 emissions of 2020 48V MHEVs base and benchmark vehicles in comparison with different 2030 high voltage HEVs for the C-segment

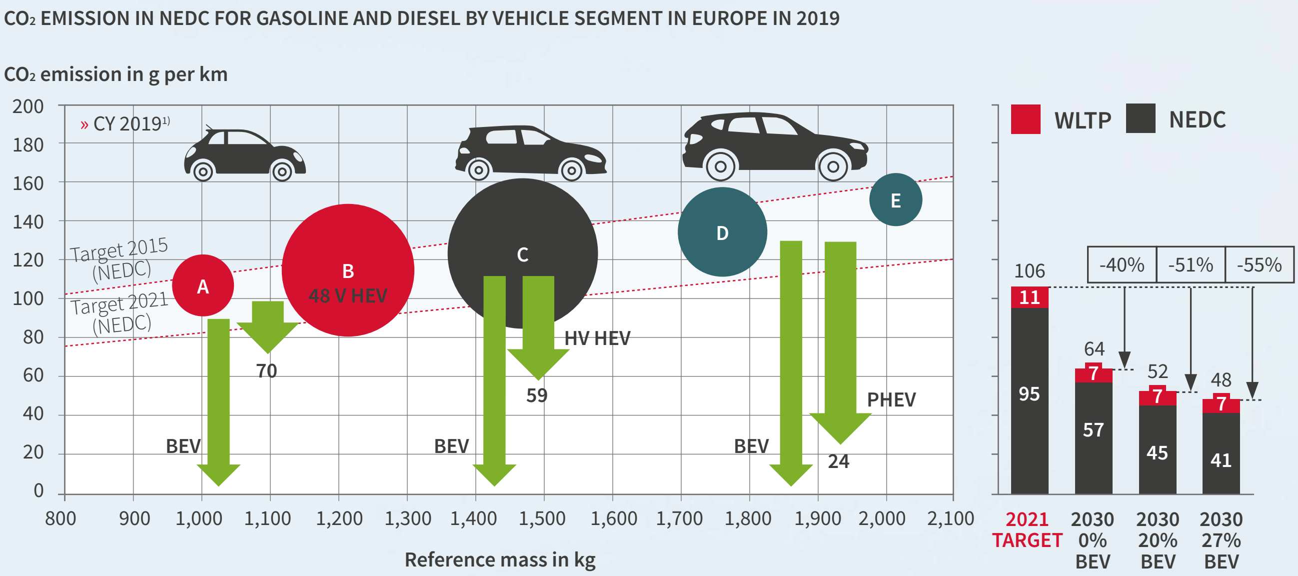
CAR EVALUATION – BUSINESS TRAVELER / FAMILY





D/E SEGMENT

③ CO_2 emissions of 2020 gasoline and diesel base vehicles (without hybridization) in comparison with a 2020 base PHEV and 2030 high voltage PHEVs for the D/E segment



④ *Segment specific and fleet averaged EU passenger car NEDC CO_2 emission targets (WLTP considered with a mark-up) for 2021 and outlook to 2030 considering only gasoline (P)HEV and up to 27 percent BEVs*

Real-life Fuel Consumption Considering Battery Charging Behavior

The differences between homologated CO_2 emissions and real-world fuel consumption of PHEV has been discussed in numerous articles in an often heated debate. However, PHEV have significant potential to combine the best of both worlds and can achieve very low pollutant emissions.

Not using the plug-in-functionality (Charge Sustaining mode "CS") has corresponding impacts in different cycles. In the NEDC/ WLTP cycles, the CO_2 emission is significantly higher than the certification value. This is true almost regardless of the hybrid method chosen. Results of driving cycle simulations have shown that in CS-mode the CO_2 emissions will be 24 to 28 percent lower in 2030 than those of the current conventional vehicles, with the series/parallel PHEV offering a 6 percent CO_2 advantage over the series PHEV in CS WLTP.

In particular, the small advantage of the series/parallel hybrid appears surprising, as the losses in the electric path of the series hybrid (the energy of the ICE has to be converted into electric power by the generator) have typically always been higher than the losses in the transmissions of the series/parallel hybrid.

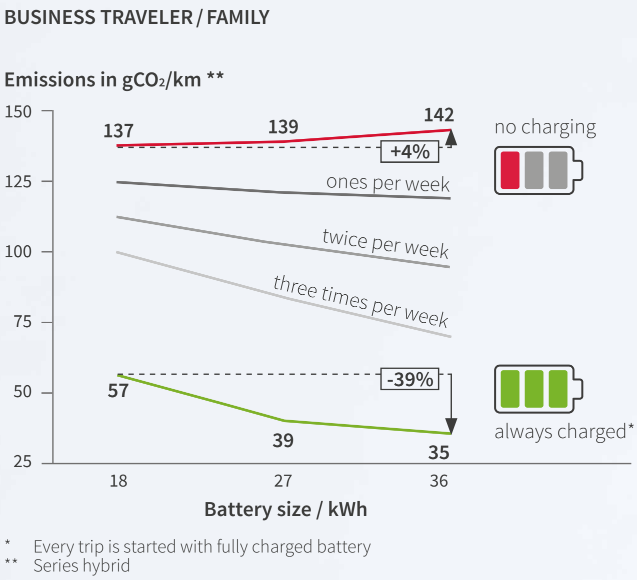
However, this is partly compensated by:

- Higher maximum ICE efficiency for the more phlegmatized ICE in the series hybrid
- Operating the ICE in a slightly better load point at long-distance travel speed, which was determined by the chosen boundary
- An efficiency increase in the electric path (inverter/e-machine) which is higher than the efficiency increase of the transmission until 2030
- Bypassing the battery during long-distance driving as the energy is directly transferred from the generator to the e-drive

An important point of discussion in the evaluation of PHEV is the dimensioning of the battery and the impact on driving behavior. The evaluation in combination with the charging behavior is based on a FEV "business driver cycle" assuming a 23 km trip to work and a weekly business trip of 300 km as well as a monthly family trip of 200 km (all one-way distances). Travel speed on the long-distance trip is assumed to be 130 km/h. The battery size is chosen to achieve 80 km electric range in WLTP as a baseline value and then increased by 50 and 100 percent.

Driven mainly on the long-distance trip without charging (CS-mode), CO_2 raises towards 137 gCO_2/km. Notable is the CO_2 increase by 4 percent when doubling the battery size.

Mainly due to the higher vehicle weight, which cannot be overcompensated by higher battery efficiency since C-rates are already at a low level, CO_2 emissions drop to 57 (39 and 35) gCO_2/km for 18 (27 and 35) kWh batteries with the battery always charged before every trip. Charging the battery only once (twice; three times) a week already leads to CO_2 emissions of 121(103; 84) gCO_2/km (all based on the 27 kWh battery). In summary, for a typical business car driver, a 27 kWh battery achieves a very favorable compromise with low CO_2 emissions independent of the plug-in behavior. Most noticeable, the decision regarding the hybrid topology is nearly independent of the CO_2 emissions in certification and in real-world driving, but can be based purely on customer strategy and production/development costs. Of course, this analysis neglects the carbon footprint of the battery production, which increases as battery size grows, given the trend toward CO_2 neutral production.



⑤ *Impact of battery sizing and battery charging behavior on real-world CO_2/fuel consumption*

Summary and Conclusion

To comply with the 2030 EU CO_2 emissions legislation and to avoid penalties, carmakers are forced to reduce their fleet CO_2 emissions by 37.5 percent for new passenger car registrations. Even higher emission reduction targets with values towards -55 percent and lower are in discussion.

In this study, a "representative vehicle fleet" of a generic OEM was created using today's segment distribution in the EU for three different segments and considering different driving profiles. It has been shown that with a (P)HEV-only-strategy, a 40 Prozent CO_2 emission reduction can be achieved compared to the 2021 fleet targets. This was realized with the following assumptions for the three segments:

- A/B Segment - low cost 48 Volt P2 HEV achieving 70 (78) gCO_2/km in the NEDC (WLTP) cycles
- C-Segment - high voltage powersplit HEV achieving 59 (64) gCO_2/km in the NEDC (WLTP) cycles
- D/E-Segment - high voltage PHEV achieving ~16 (24) gCO_2/km in the NEDC (WLTP) cycles

It could also be demonstrated that a PHEV with a FEV Dedicated Hybrid Engine (43+ percent brake thermal efficiency) achieves a CO_2 emission benefit of 24-35 percent compared to today's conventional diesel/gasoline variants, even if the battery charger is never plugged-in. In a real driving cycle of a business car, a 27 kWh battery (120 km WLTP range in pure electric mode) is a good compromise, leading to a significant reduction of the CO_2 emissions if the vehicle is charged via plug-in only one or two times per week.

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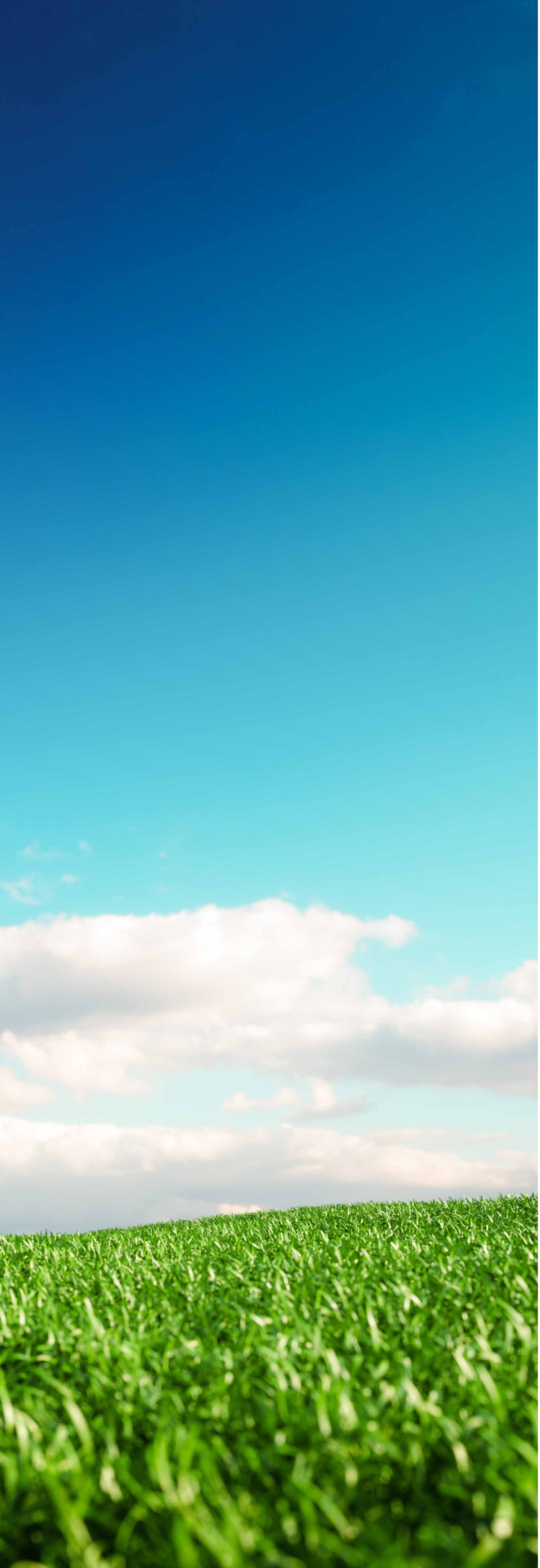
Source:
(1) Uhlmann, T. et al.
High efficient gasoline HEV meeting 2030 CO_2 targets – The road towards 59 g/km fleet CO_2 – The road towards 59 g/km fleet CO_2, 29. Aachen Colloquium Sustainable Mobility 2020

E-Fuels

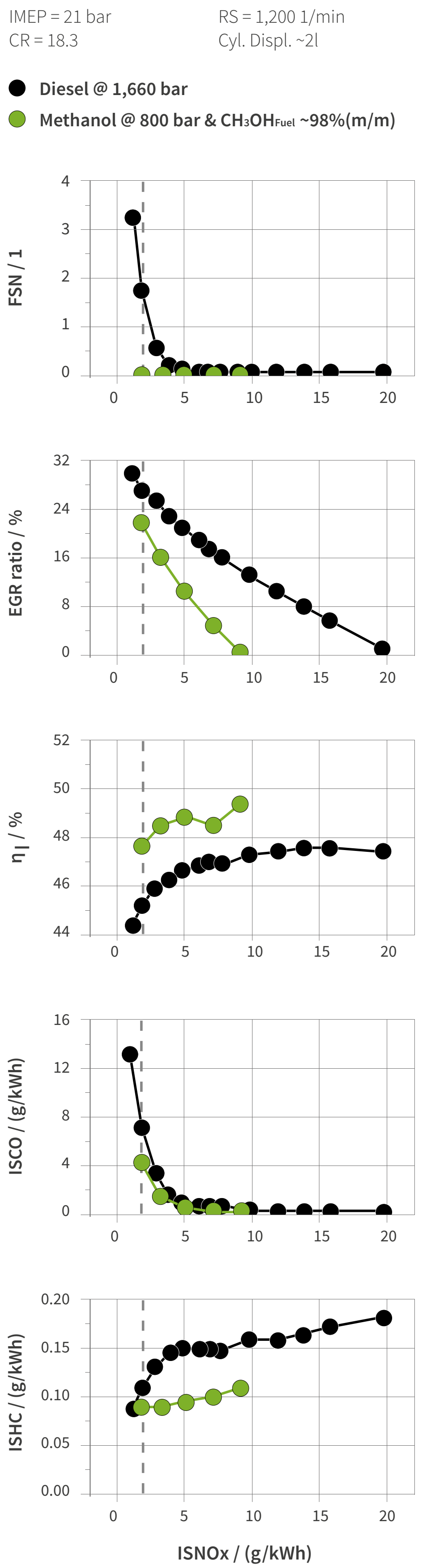
GREEN METHANOL – A CO_2-NEUTRAL FUEL TO ACHIEVE HIGHEST EFFICIENCIES WITH LOWEST POLLUTANT EMISSIONS



The decarbonization of aviation, shipping and long-distance hauling of goods represents significant challenges. In this context, the application of synthetic fuels is a timely feasible alternative for these sectors and their specific requirements. Derived from renewable electric energy, methanol is the simplest synthetic liquid fuel, and one of the most promising for shipping.

Methanol is suitable for both compression- and positive-ignition combustion. For applications with high power demand, such as shipping, internal combustion engines remain the main propulsion system due to their combination of high power density, high efficiency, and relatively low costs.

Methanol is no novelty for use in internal combustion engines either. Besides the experiments with methanol in California during the oil crisis, MAN's two-stroke methanol engines and the Wärtsilä four-stroke methanol engine that powers the Stena Germanica ferry are more recent examples of the use of this fuel. While these methanol engines realize diffusive combustion initiated by a small pilot injection of diesel fuel, spark ignited Otto cycle applications of methanol are also possible (e.g. former Indy cars). This raises the question of which combustion principle and exhaust gas aftertreatment layout is best suited for the above-mentioned applications. A short summary of the assessment of FEV and the Institute for Combustion Engines (VKA) of RWTH Aachen University is given in this article.



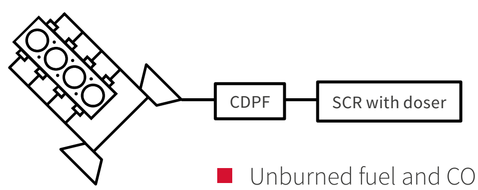
① *EGR variation for methanol DDI CI and conventional diesel operation*

Methanol Dual Direct Injection Compression Ignition (DDI CI)

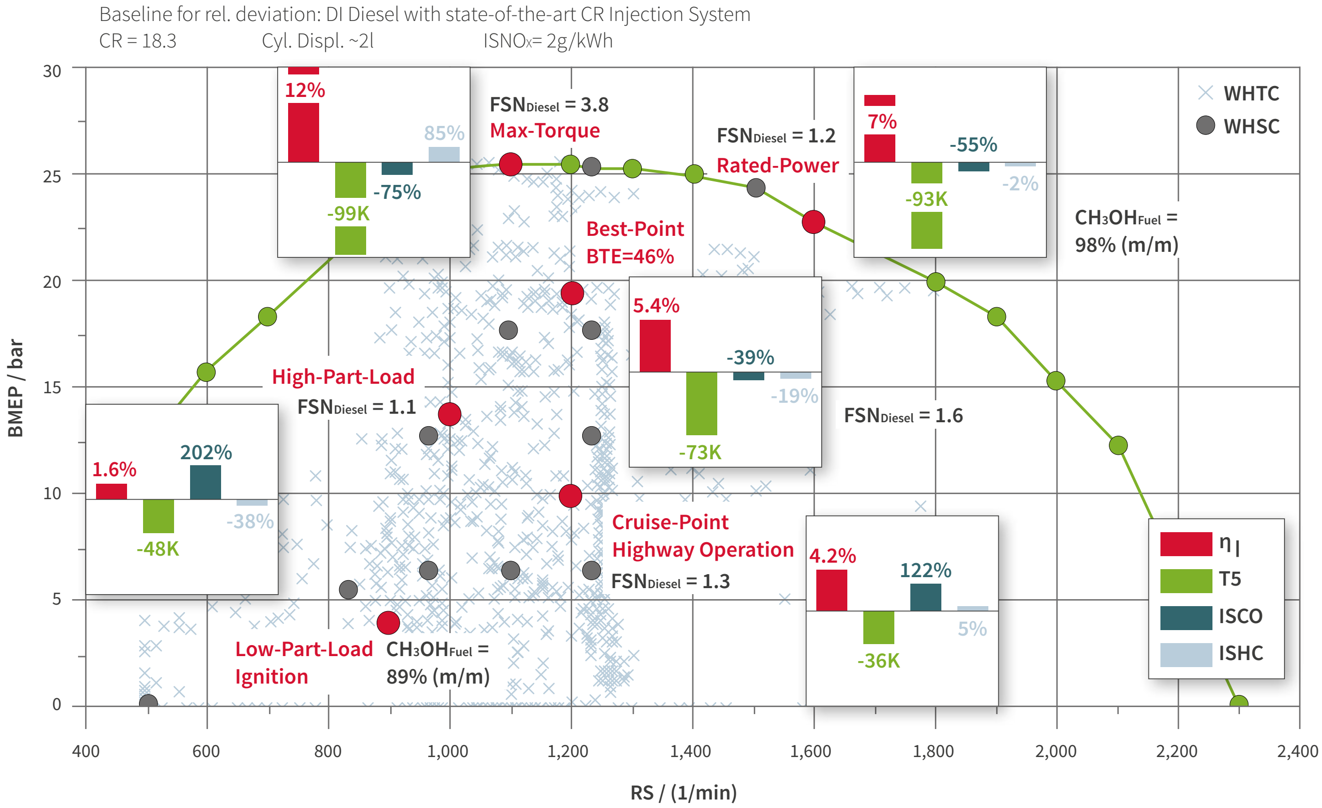
Due to the liquid state, methanol is well suited for high-pressure direct injection. This enables diffusive combustion. Since methanol requires higher temperatures for ignition than diesel fuel, either elevated compression ratios (with drawbacks in terms of NO_x emissions and load range) or ignition support with methods like pilot diesel injection is required. To ensure ignition in cold start conditions, pilot diesel injection support is the most attractive option. This however, requires direct injection of two fuels, or dual direct injection (DDI). The scalability as a diffusive combustion system is superior and both heavy-duty and large bore high speed applications have been investigated.

To assess the performance and emission behavior of methanol Dual Direct Injection Compression Ignition (DDI CI) compared to conventional diesel operation in heavy-duty applications, engine test results of EGR variations are depicted in Figure 1. Due to the diffusive methanol combustion, the engine behavior is similar to standard common rail diesel engines. Soot emissions can be negated with methanol (FSN = 0). Mostly due to the evaporative cooling, the combustion peak temperatures are reduced in methanol operation, leading to a distinct reduction of the NO_x emissions without EGR — in this case by more than 50 percent. Furthermore, the efficiency is increased by ~4 percent compared to the diesel baseline due to the overall faster heat release and lower combustion temperatures. CO and HC emissions without EGR are similar or lower compared to the operation with diesel fuel. Since unburned methanol emissions are very low, formaldehyde is not a major challenge for the DDI CI process.

As the EGR rate increases, emissions and performance of the methanol DDI CI process change similarly to the diesel engine. NO_x (and HC) emissions are reduced, while CO increases quite sharply as the diesel engine approaches the soot limit. Since smoke is absent from the exhaust gas of the methanol DDI CI engine, there is no smoke limit. However, the rise in CO emissions remains. Partly due to the zones in which the pilot injection has consumed part of the oxygen, CO emissions also increase at higher EGR ratios for methanol DDI CI. Hence, CO emission reduction is one of the major optimization tasks for methanol DDI CI. This also applies to the reduction of the efficiency losses at higher EGR ratios.



- Unburned fuel and CO at low load
- PN and NO/NO_2 ratio
- SCR with reducing agent



② *Emissions and performance of the methanol DDI CI concept in the engine map with fixed pilot injection timing and quantity compared to the diesel baseline*

The comparison of diesel and methanol DDI CI under iso-$ISNO_x$ conditions rounds off the differences between both combustion modes. A comparison at $ISNO_x = 2$ g/kWh is chosen to consider future emission standards. This comparison is performed for several operating points in Figure 2.

Starting with the Best-Point shown in Figure 1 at 1,200 1/min and BMEP ~20 bar, efficiency increases by ~5 percent, while the exhaust gas temperature is reduced by ~73 K. At the same time, CO and HC emissions are slightly lower than those of the baseline diesel engine. This is partly due to the diesel engine being operated with a relatively high EGR rate close to the smoke limit (FSN = 1.6) to achieve the required NO_x level.

Moving on to Rated Power at 1,600 1/min and BMEP = 23 bar, the trend is mostly identical. The efficiency increase amounts to 7 percent, while CO and HC are both reduced and the relative reduction in the exhaust gas temperature remains similar. The methanol share at Rated Power is ~98 percent by mass. Max-Torque is not achievable at 2 g/kWh NOx with the diesel engine. FSN is ~4 and therefore beyond a sensible smoke limit. HC emissions are higher for methanol DDI CI; however both values are below 0.1 g/kWh.

At Cruise-Point and High-Part-Load, only minor changes in efficiency are observed, while CO emissions increase (~4 g/kWh at Cruise-Point and ~6 g/kWh at High-Part-Load). At High-Part-Load, methanol DDI CI suffers more from the relatively low boost pressures than the diesel. A trend towards diminishing efficiency gains and poorer emissions is evident. A direct comparison with diesel is not possible at Low-Part-Load since this point was changed from BMEP = 6 bar to 4 bar in order to cover more critical ignition states for methanol DDI CI operation. Overall, the trend described for Cruise-Point and High-Part-Load continues. Part of the reason for the poorer performance at low loads is the relatively high diesel share required (~11 percent by mass) with advanced timing. The diesel injection quantity per stroke was kept constant throughout the engine map to ensure both good ignition quality at low load and injector cooling at high load.

Besides the different fuel injection systems, the overall engine layout can remain mostly unchanged for realization of the DDI CI concept. Adjustments of the turbocharger, as required for spark ignition operation, are not mandatory. The exhaust gas temperature is lower, but the heat capacity is ~1 percent higher at identical boost pressure, resulting in a slightly lower reduction in exhaust gas enthalpy. The exhaust gas aftertreatment system layout comprises a Coated Diesel Particulate Filter (CDPF) for PN, HC and CO reduction especially at low loads. The SCR system can be adopted from the diesel engine and, depending on the calibration, operated with less reducing agent.

Methanol DDI CI vs. PFI SI – A direct Comparison for Large Bore High Speed Applications

Both premixed and diffusive methanol combustion are promising concepts regarding emissions and efficiency. Which combustion system to use for a particular application depends on many variables.

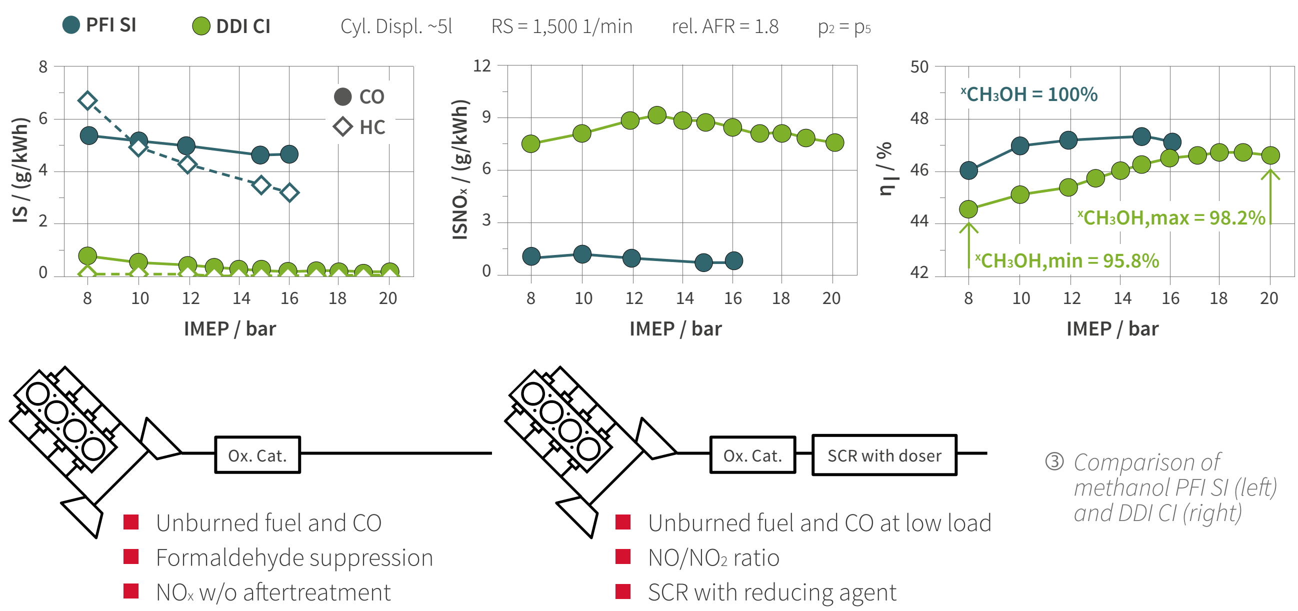
For the high speed applications compared here (Figure 3), both combustion systems are evaluated without EGR. The comparison is performed at 1,500 1/min with $p_2 = p_5$ at rel. AFR = 1.8 for both combustion systems. The base engine is identical. For methanol DDI CI without EGR, HC and CO emissions are mostly negligible. NO_x emissions peak at 9 g/kWh. This provides potential to achieve IMO Tier II level without NO_x aftertreatment. Only in Emission Control Areas (ECA), an SCR would be required to match the ~2 g/kWh limit imposed by IMO Tier III. Methanol Port Fuel Injection Spark Igniton (PFI SI), on the other hand, produces significant concentrations of CO and HC typical for premixed combustion. However, as with natural gas engines, this combustion mode allows NO_x emissions of ~1 g/kWh over the entire load range.

The comparison of the efficiency of methanol PFI SI and DDI CI shows that the selection of the most suitable combustion system for the specific application depends on two essential points: the pollutant emission behavior and the achievable load range.

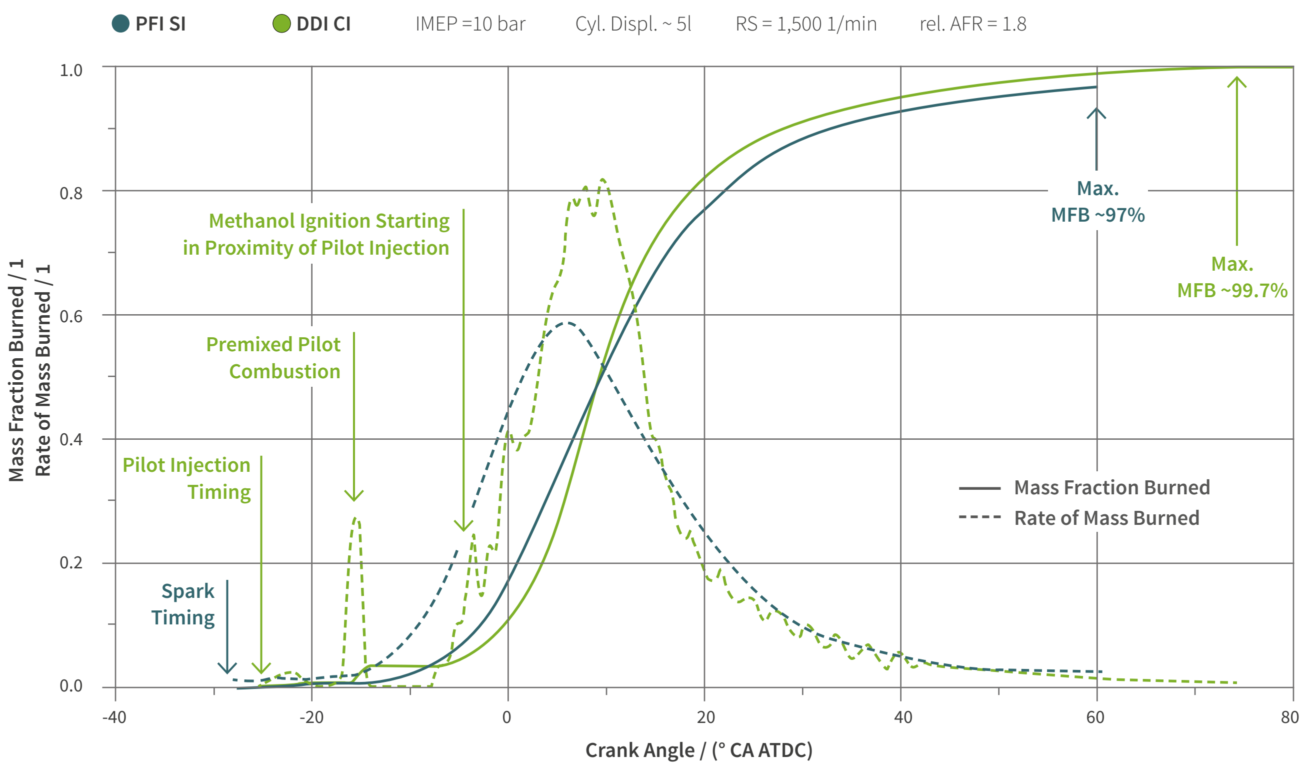
» WHEN HIGH POWER DENSITIES ARE REQUIRED, THE DIFFUSIVE CONCEPT IS PREFERABLE, WHILE FOR APPLICATIONS FOCUSED MORE ON THE SYSTEM COSTS, THE LESS COMPLEX PFI SI SOLUTION IS MORE FAVORABLE

The achievable efficiency is quite similar for both combustion systems. Considering the boosting system and thus the possible scavenging pressure, the PFI SI combustion system with external mixture formation is less favored, and therefore the resulting peak effective efficiencies are quite similar. PFI SI will still achieve slightly higher efficiencies at medium load. However, if a similar high load range is targeted with PFI SI as with DDI CI, the compression ratio must be reduced to prevent knocking combustion. This then reduces the efficiency. Thus, PFI SI is better suited for stationary applications with lower specific power requirements, while DDI CI can cover all applications but is the more complex system and may require a more complex exhaust gas aftertreatment system. To assess the efficiency of both combustion systems in more detail, Figure 4 compares the heat release rates at identical COC, IMEP and rel. AFR.

The heat release rate for PFI SI is quite typical for a large bore spark ignition engine. For the lean operation with rel. AFR = 1.8, the combustion duration is quite fast considering the bore diameter (10 to 90 percent mass fraction burned within 36° CA). Besides the fast combustion, the lower in-cylinder temperatures in particular lead to significant advantages for methanol PFI SI. The evaporative cooling of methanol reduces the compression work and heat losses. The energy for fuel evaporation is then released during combustion. This is the major reason for the high efficiency of methanol PFI SI when compared to DDI CI where the fuel is introduced close to TDC and hence the energy for fuel evaporation must be compensated during combustion.



③ *Comparison of methanol PFI SI (left) and DDI CI (right)*



④ *Mass fraction burned for methanol DDI CI and PFI SI*

The pilot injection required for DDI CI results in an early heat release, which is thermodynamically unfavorable. In the initial stage, the spray plumes ignite near the combusted pilot injection, reducing the peak pressure rise rate by limiting the fraction burned in premixed mode. The fast burnout for DDI CI is comparable to PFI SI. The combustion duration is even shorter with 28° CA, and typical for diffusive combustion, the maximum MFB reaches almost 100 Percent.

Compared to the operation with conventional diesel fuel in particular, methanol DDI CI has the advantage of faster combustion, which, in addition to the lower combustion temperatures and the associated lower heat losses, results in a significant increase in efficiency. Another factor in this regard is the smokeless combustion, which also contributes to reduced heat losses through radiation.

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Final assessment

In summary, there are two major combustion systems for methanol applications: Premixed Spark Ignition (PFI / DI SI) and diffusive Dual Direct Injection Compression Ignition (DDI CI) combustion. The diffusive DDI CI combustion mode is very similar to a diesel engine running on conventional diesel fuel, but has significant advantages in terms of efficiency and smoke emissions especially at high EGR rates, which are required for lowest NO_x emission levels. The premixed PFI SI combustion mode is very similar to that of current natural gas engines, albeit with increased efficiency. Depending on the application, lean burn (large bore high speed) or stoichiometric (heavy-duty) combustion with a three-way catalyst are applicable. In a direct comparison, both DDI CI and PFI SI have their specific advantages. When high power densities are required, the diffusive concept is preferable, while for applications focused more on the system costs, the less complex PFI SI solution is more favorable.

The results shown in this study were obtained in a project which was funded by the "Bundesministerium für Wirtschaft und Energie" (Federal Ministry of Economics and Energy), Germany (Förderkennzeichen 19I18006P). The content of this paper is in the authors' responsibility.

H2 ICE

HOW TO IMPROVE TRANSIENT ENGINE PERFORMANCE OF HD HYDROGEN ENGINES WHILE MAINTAINING LOWEST NO_x EMISSIONS

CO_2 emissions are largely responsible for increasing global warming within the last decades. In order to achieve the goals of the Paris Climate Agreement and keep global warming below +1.5°C, the European Commission has set strict reduction targets.

The long-term vision until 2050 is to realize a CO_2-neutral economy, which means that the transport sector must cut its emissions by 90-95 percent within the next 30 years.

In this context, it is necessary to make use of all technologies available and to optimize every aspect of vehicle technology. OEMs must employ a combination of measures to avoid failure[(1)]. To comply with the CO_2 emission targets, not only are the technical challenges significant, but the associated development and product cost increases will also play a considerable role in maintaining profitability. FEV recognizes that the use of hydrogen will play an important role to achieve decarbonization of the automotive industry.

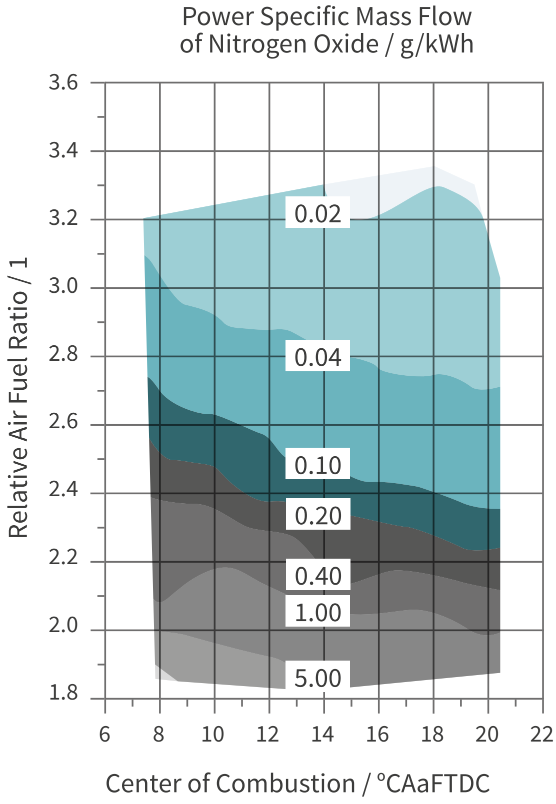
Hydrogen-based propulsion systems should keep changes to existing powertrain technology to a minimum. Converting an existing internal combustion engine to run on hydrogen demonstrates the best prospects. The changes to known engine hardware are minimal and thus offer a reliable and cost-effective solution for the implementation of CO_2-neutral long-haul transportation solutions. In conjunction with an optimized exhaust gas aftertreatment system, it is possible to achieve extremely low tail pipe NO_x emissions.

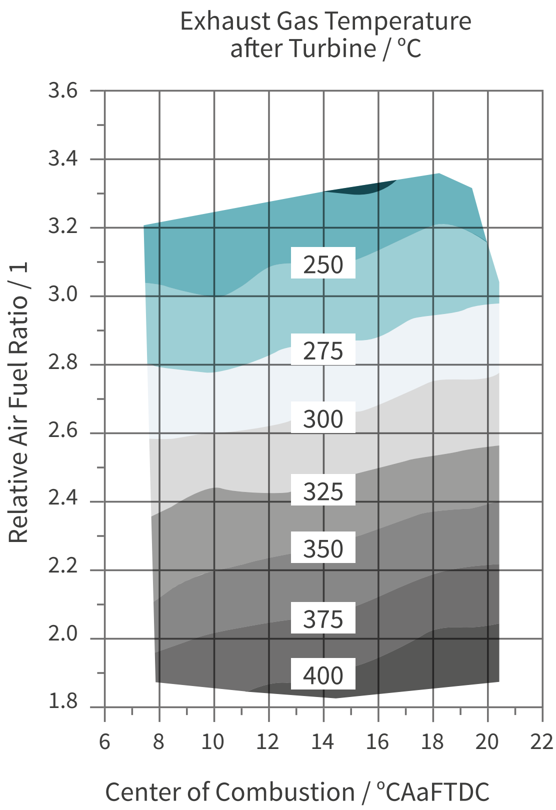
Experimental Testing on a Multi Cylinder Engine

FEV has used all the gained know-how from simulations and single cylinder engine testing to convert a serial 7.7 liter multi cylinder gas engine into a hydrogen engine. The demonstrator is equipped with a two-stage turbocharging system, which replaces the original single stage turbo. It enabled operation with lean air-fuel ratios even at full load. To achieve diesel and natural gas engine-like Brake Mean Effective Pressure (BMEP) levels, the piston design was also optimized to ensure knock- and pre-ignition-free operation even at the highest engine loads. No significant reduction in engine efficiency was observed with this optimized piston design. A BMEP of 19.6 bar and an engine efficiency of almost 42 percent were achieved. Furthermore, the same engine power as the diesel and natural gas variants could be achieved with 220 kW.

NO_x raw emissions mainly depend on the relative air/fuel ratio and the center of combustion. As expected, both increased air/fuel ratios and retarded centers of combustion will result in lower NO_x emissions. To achieve the lowest tailpipe NO_x emissions, a combination of low NO_x raw emissions and high exhaust gas aftertreatment efficiency is required. A leaner air/fuel ratio lowers the NO_x raw emissions, but also leads to lower exhaust gas temperatures, which – depending on the operating point – can result in decreased conversion efficiency of a Selective Catalytic Reduction (SCR) catalyst. On the other hand, a delayed center of combustion brings an advantage for NO_x raw emissions at slightly higher exhaust gas temperatures. Figure 1 illustrates this behavior for a steady-state operating point (1,400 min-1, 8 bar BMEP).

The results of the steady state investigations show that a good balance between NO_x raw emissions, engine efficiency and exhaust gas aftertreatment performance is possible with control of the air-fuel ratio and the center of combustion.





① *NO_x and exhaust temperature level with respect to AFR and CoC combination.*

TEST CONFIGURATION	TARGET-LAMBDA	TARGET-CoC*	IGNITION RETARDATION DURING LOAD STEP	RAW NO_x-EMISSION REDUCTION
1	2.0	≈8° CAaTDC	Basis	-
2	2.3	≈8° CAaTDC	Basis	≈75%
3	2.3	≈8° CAaTDC	Basis x2	≈83%

② *Test configurations used for WHTC testing.*

*CoC = Center of Combustion

Emission Control During Transient Operating Conditions

Warm WHTC (World Harmonized Transient Cycle) tests were performed to demonstrate the NO_x reduction potential during transient operating phases. The focus here is on comparison of three test configurations. Figure 2 shows the main differences between the test configurations and the associated impact on NO_x raw emissions.

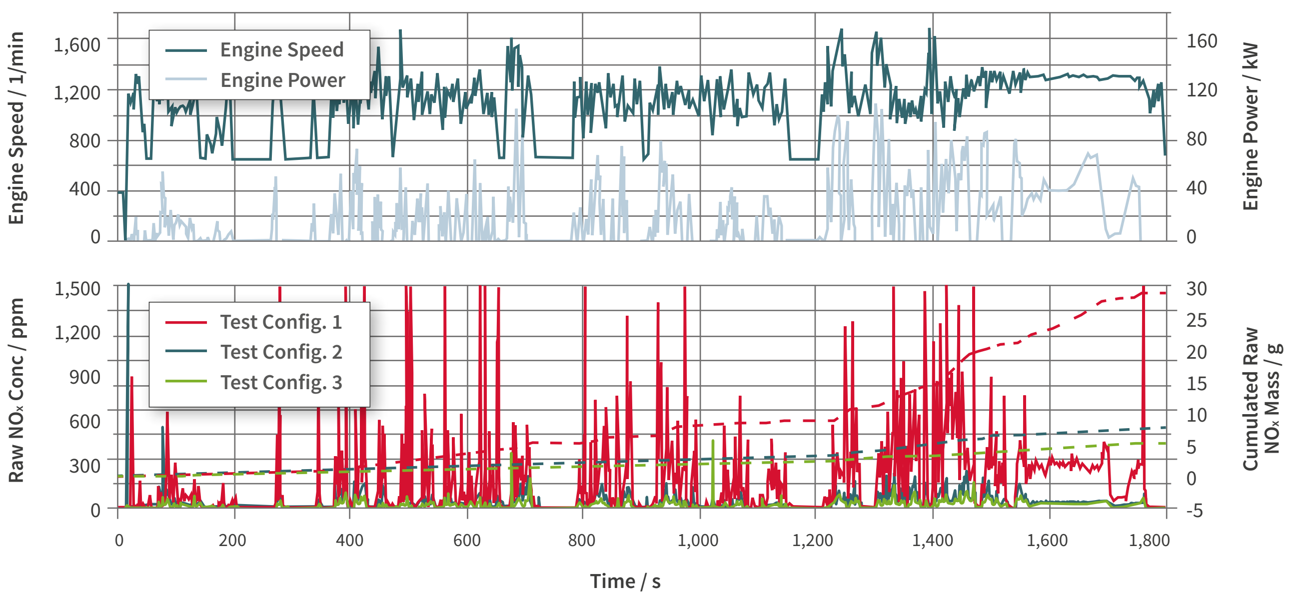
As shown earlier, the influence of the air-fuel ratio on NO_x emissions is significant. In addition, retarding the ignition can reduce NO_x peaks. During fast load requests, an enrichment of the air/fuel ratio supports rapid load buildup. To avoid resulting NOx emission peaks and knocking combustion during a fast load increase, the ignition timing should be retarded. This retardation will have a negative impact on engine efficiency. By using an adapted control algorithm, it is possible to maintain a favorable balance between engine efficiency and low NO_x raw emissions. Figure 4 shows the influence of the test configuration on WHTC NO_x raw emissions.

With leaner air/fuel ratios, the NO_x level can be reduced by 75 percent, with the resulting lowered exhaust temperature being a disadvantage for exhaust gas aftertreatment. In addition, NO_x peaks can be trimmed, and the overall NO_x level can be decreased by 35 percent via ignition timing calibration while maintaining a similar exhaust gas temperature level.

Attractive NO_x raw emission levels can be achieved with specific values of 0.51 g/kWh over a warm WHTC. To comply with the current emission standards of 0.46 g/kWh for on-road commercial vehicles, only moderate NO_x aftertreatment reduction efficiencies need to be reached when using an optimized calibration during weighted c/w cycle.

Different aftertreatment configurations can be considered for a hydrogen engine. Since SCR offers a high reduction potential (at optimum temperature conditions up to 100 percent conversion efficiency), it would be a favored solution. However, the composition of the exhaust gas must be considered.

③ *Comparison of test configurations on WHTC NO_x raw emissions.*



The water content in the exhaust gases of a hydrogen engine is much higher compared to diesel. For relative air/fuel ratios between two and three, the water concentration is about 15-20 percent. Therefore, standard copper zeolite is not the best choice for SCR. A substrate which does not age due to an increased water content would be preferred.

In addition, the SCR should perform well at low to medium temperatures. The temperatures to be expected go up to 400-450°C, so there is no need for high temperature NO_x reduction efficiency or resistance to high temperature aging. Also, no significant concentrations of hydrocarbons (HC) will be present in the exhaust gas of a hydrogen engine, so potential poisoning by HC can be neglected when choosing the substrate.

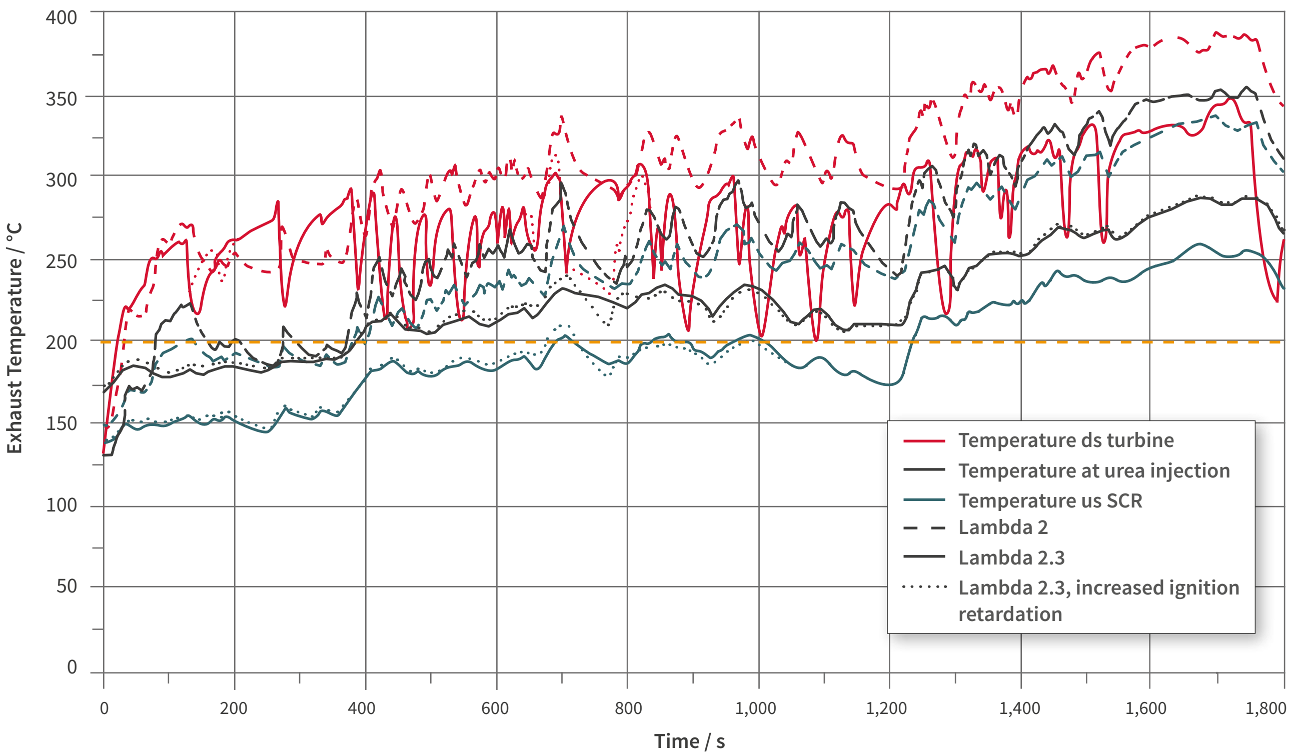
To further assess the potential and challenges of the aftertreatment system, a warm WHTC was run and analyzed. Pre-conditioning was performed as in the certification procedure with a pre-condition-WHTC and 10 minutes soak-time. The temperature traces of the warm WHTCs with the different calibrations are shown in the following graphs.

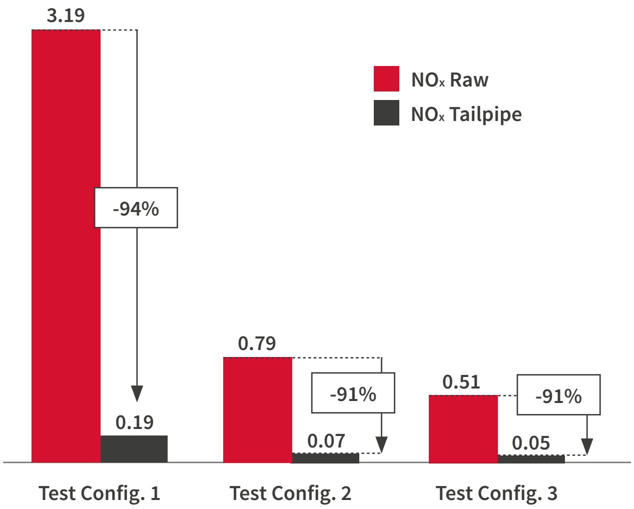
As already discussed, the increase of the targeted relative air/fuel ratio leads to a decrease of the exhaust gas temperature, while the increased ignition timing retardation hardly has an impact on the temperatures.

With a urea dosing release at 200°C, the dosing would start after less than 100 seconds with a calibration target of lambda 2. For a lambda target of 2.3, 400 seconds are needed to start the dosing. However, considering the strong decrease of raw NO_x emissions with increased lambda, there is still enough temperature to achieve high SCR efficiency. The benefits of leaner calibration optimization are significant compared to the drawback in temperature. With the temperatures and space velocities, the achievable SCR conversion efficiencies were calculated using a map-based model calibrated for a standard SCR. The results are shown in Figure 5.

The higher exhaust gas temperatures of the first test configuration lead to an earlier urea dosing and increased SCR efficiencies, which result in an overall NO_x reduction of approximately 94 percent. With a relative high NO_x raw emission level of 3.19 g/kWh, tailpipe emissions of appr. 190 mg/kWh can be achieved. For test configurations 2 and 3, the same SCR efficiency of 91 percent can be reached, as the measures taken hardly affect the temperature, which is the main driver for SCR efficiency. The resulting tailpipe emissions are on a very low level of 70 mg/kWh and 50 mg/kWh, respectively.

④ *Averaged exhaust temperature level and warm WHTC NO_x raw emissions.*





⑤ *Simulated SCR efficiencies and resulting tailpipe emissions for an SCR only aftertreatment system*

In summary, the main challenge in addressing NO_x emissions from a hydrogen engine is to match the air-fuel ratio and ignition timing with the aftertreatment capabilities to achieve moderate NO_x raw emissions while maintaining sufficient exhaust temperatures for exhaust gas aftertreatment.

The results already achieved without complete optimization demonstrate the great potential of a hydrogen internal combustion engine. Further important functionalities are still under evaluation. For example, FEV has developed a control algorithm to achieve an optimal matching of calibration and exhaust gas aftertreatment for lowest emissions and/or dynamic response. The performance of the exhaust gas aftertreatment system is constantly modeled by this algorithm which can decide which ignition timing can be applied.

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Sources:
(1) Van der Put, D., et al.: Efficient Commercial Powertrains – How to Achieve a 30% GHG Reduction in 2030, In: Proceedings of the FISITA 2020 World Congress, Prague, 14 – 18 September 2020

Summary

When high constant power and less transient vehicle operation are required, an internal combustion engine fueled with hydrogen represents a cost-effective approach to realize CO_2-free long-haul transport with a long service life using proven technology. In other applications, a hydrogen combustion engine can offer extremely low pollutant emissions combined with attractive engine efficiencies.

The NO_x emissions can be reduced to extremely low levels with properly selected and dimensioned exhaust aftertreatment systems and dedicated control algorithms. WHTC runs demonstrated a great potential to reduce also transient NO_x raw emissions via a suitable combination of air-fuel ratio setting and ignition timing. The results of the WHTC measurements and simulations of the exhaust gas aftertreatment system performance showed that emission levels of 50-70mg/kWh in a warm WHTC can be considered achievable. With further optimization and alignment of calibration and aftertreatment system, the hydrogen engine can be successfully developed towards a zero-impact emission propulsion system.

eDLP

COMPONENT ENVIRONMENTAL TESTING – UNPARALLELED CAPABILITY

High-voltage batteries, electronics, and other vehicle components are exposed to a variety of punishing environmental influences during their life cycle. FEV supports manufacturers and suppliers with a comprehensive test facility capable of accounting for virtually all environmental factors.

With the new e-Dauerlauf Prüfzentrum (e-Duration Test Center) or eDLP, FEV boasts the world's largest development and endurance test center for electric powertrain components. The facility is situated near Leipzig, Germany, and provides around 70 test systems dedicated to performance, durability, abuse testing, and more on a total area of 42,000 m^2 (452,100 sq-ft.).

At the eDLP, 15 stations cover all common environmental tests in an area of approximately 2,500 m^2 (27,000 sq-ft.). Special attention is given to the requirements of ISO 16750 (Road Vehicles – Environmental conditions and testing for electrical and electronic equipment) as well as UN Standard 38.3, proving suitability for transport.

The environmental test capabilities of eDLP:

- **Climatic tests/condensation:** climatic cabinet and temperature chambers for temperature and humidity profiles between -40 and 90 °C (-40 and 194°F) and 10 to 95 percent rel. humidity
- **Chemical resistance:** climatic and temperature chambers to test the general resistance of materials to the effects of chemicals at different temperature and humidity profiles between -40 and 90 °C (-40 and 194°F) and 10 to 95 percent rel. humidity
- **Surge water:** temperature chamber with surge water system (ice water, dirty water) for thermal shocks
- **Corrosion testing/salt fog:** climatic chambers with salt fog spraying systems for different temperature and humidity profiles
- **IP protection class:** dust, strong jet water, hot water, etc.
- **Dust testing:** dust chamber with high air circulation for use with SAE J726 standardized Arizona Road Dust or talcum powder
- **Dip tanks:** two 14 m^3 (3,700 gallon) masonry dip tanks, in which test specimens can be immersed to a depth of one meter (over 3 ft.)
- **Negative pressure test:** Vacuum temperature chamber for changing air pressure conditions
- **Stone impact:** Multi-impact tester with chilled cast iron granules

Also, the behavior of batteries and electronic components with regard to warranty commitments is a critical concern resolved for eDLP customers. In addition, components of other vehicle assemblies can undergo environmental testing at the eDLP as well. FEV's team of experts at the eDLP provides advice and support in the specification of individual test objectives. If required, suitable test cycles are also developed and their execution is taken over. Data from the findings and error detection are fed directly back into the customer's development process. This not only shortens virtual iteration loops, but also reduces real test requirements; and thus saves both time and money on the way to product series maturity.

» FEV'S TEAM OF EXPERTS AT THE EDLP PROVIDES ADVICE AND SUPPORT IN THE SPECIFICATION OF INDIVIDUAL TEST OBJECTIVES

The dimensioning and performance profiles of the individual test rigs are designed for maximum flexibility and to meet or exceed the requirements of all testing standards commonly used in the U.S., Asia and Europe. Like all test rigs in the eDLP, environmental tests run in 24/7 operation to ensure the fastest possible processing of projects and the continuous flow of information to customers. Clients can also be connected to selected test benches in real time and follow test runs of their product live. Once test cycles have been completed, there is also the option of being present virtually during the findings: This allows results to be exchanged directly and solution approaches or next steps to be coordinated together with the eDLP experts for unparalleled efficiency.

More information
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