SPECTRUM

"ZERO EMISSION STRATEGIES"

ZERO EMISSION
Strategies from Synthetic Fuels to E-Drives

SI HYBRID ENGINE
High Tech or Low-cost?

FEV HECS ECOBRID
Diesel with 48V Hybridization

RANGE EXTENDER
Systems for Medium-Duty Transport Vehicles
Dear Readers,

as the popular saying goes, all roads lead to Rome. This statement also applies with a view to CO2-neutral mobility. Whether through gradual electrification or the use of conventional combustion engines with alternative fuels, the opportunities and options are highly diverse. Finding the right mix for the corresponding boundary conditions seems to be one of the main challenges.

In the current issue of our customer magazine SPECTRUM, we not only present the results of our research on hybrid drives in the personal car and commercial vehicle segments, but also introduce our current studies on the costs and market penetration of electro mobility. In a technical discussion with experts from FEV, we also illuminate perspectives on renewable and synthetic fuels and their contribution to CO2-neutral mobility.

In addition to practical electrification projects, such as our ECObrid diesel hybrid, we have been on the hunt for the optimum hybrid gasoline engine. This needs to be small, light and efficient in order to comply with emissions and spatial requirements while simultaneously fulfilling specific NVH requirements.

Electrification constitutes an important change, and not just on the drive technology side. New challenges are also emerging for the overall vehicle: for example, new solutions are required to address the reduced range of electrical vehicles, particularly in winter, and the lack of waste heat from combustion that is used for heating purposes. We have evaluated the energy conservation potential of radiant heating in an empirical study, and are presenting its findings in SPECTRUM.

We hope you enjoy reading it. Follow us on social media to keep up with the latest news from FEV.

Dr.-Ing. Norbert W. Alt
Chairman of the Executive Board
FEV Europe GmbH
The automotive industry is under pressure. We are experiencing major – even disruptive – changes. The public perception of the automobile is changing, and demands ecologically sustainable drivetrains. In the context of this market dynamic, electrification of the drivetrain has clearly set the stage for the public discussion and is also considered the strongest driving force in the industry. However, the sales volume for electrified vehicles is still strongly inhibited by high costs, weak infrastructure and short range. In 2016, less than 1% of all of the vehicles sold worldwide were primarily electrically driven. Against this background, market forecasts are certainly risky. But, despite this, an attempt has been made, below, to assess how powertrain populations will develop in the world’s most important markets. It becomes clear that despite the uncertainties mentioned some reliable, central conclusions can still be made.

**POWERTRAIN 2030**

**01 "ZERO EMISSION" AND HYBRID TECHNOLOGIES**

The majority of all vehicles sold in Europe will still have combustion engines in 2030.

The CO2 limits are continually being lowered in the European, American, and Chinese markets. The level of allowable CO2 emissions, which is lower on an absolute basis in Europe and China compared to the USA, is an indication of a strong need for electrification in those two markets. The anchor points were set at 2016.

For further information please feel free to contact us.
**Scenario 2: “Compliance”**

In China, by 2030, only 50% to (a maximum of) 75% of all vehicles sold will have a powertrain equipped with a combustion engine.

Market forecast for powertrain populations for Europe 2016 to 2030 (new passenger car registrations)

Drivetrain Topologies in the USA

When market expectations for Europe are compared to those for the USA, a divergent picture emerges, which can be summarized as follows:

- In the near future, sales in the USA will be geared towards the long-ranges associated with liquid fuels and large combustion engines (6-cylinder and 8-cylinder).
- Generally speaking, demands for CO₂ emissions reduction take a back seat to reducing greenhouse gases, allowing a lower degree of electrification.
- In contrast to Europe, CO₂ emissions associated with electricity generation are increasingly being taken into consideration in the assessment of vehicle emissions (trend towards “well-to-wheel” instead of “tank-to-wheel” approaches).

These aspects lead to lower electrification rates for the market in North America, compared to Europe. Consequently, it is expected that mild hybrid drives will only be fully rolled out by 2025. Additionally, it can be assumed that by 2030, 85 to 90% of all vehicles sold will still be equipped with combustion engines. The picture that has been painted can be expanded by the additional analysis of the Chinese market.

In summary, it can be inferred that, even with the electrification of the powertrain increasing sharply, the majority of all drives will still be equipped with combustion engines in 2030, and that these combustion engines will have to work in a variety of drive topologies.

With increasing start-stop events, vibrations due to rigid body modes of the engine-transmission combination must be minimized in this operating condition.

Separate from the body-in-white considerations related to available space, there are additional NVH requirements for combustion engines in hybrid powertrains. These can be summarized in a simplified manner as follows:

- With increasing start-stop events, vibration due to rigid body modes of the engine-transmission combination must be minimized during this operating condition.
- It is desirable that the electric driving experience is not adversely affected by the operation of the combustion engine. This creates increased requirements with regard to acoustics and vibration excitation at comfort points, such as low vehicle seat acceleration.
The automotive industry is currently in the middle of one of the greatest upheavals in its history. The new challenges surrounding connected and autonomous vehicles also pose major tasks for developers, such as the choice of the correct and appropriate drive for achieving a minimum level of emissions. What’s more, experts remain divided as to whether there is any ideal route to follow, or what that would be. Possible technologies include hybridization, partial or full electrification, or even fuel cells. It is a fact that the market penetration of these individual technologies continues to fall below expectations, despite a number of government initiatives. Accordingly, the corresponding infrastructure is also only growing slowly.

These days, referring to the further potential of combustion engines sounds rather anachronistic, and is increasingly perceived by the public as the perspective of those who are permanently behind the curve and have not adopted the change in direction towards alternative drive forms, or have only done so insufficiently. However, synthetic fuels actually offer an enormous amount of potential for ensuring sustainability and reduced pollution.

As an engineering service provider with a strong focus on drive development, FEV not only offers its customers the development of advanced drive solutions, but also provides assistance and advice in the selection of drive concepts. In SPECTRUM, experts from FEV and RWTH discuss e-mobility, fuel cell drives and synthetic fuels.
**Zero Emission Strategies**

*01 “Zero Emission” and Hybrid Technologies*

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**Mr. Ogrzewalla:** It appears that the public has already agreed to say farewell to the combustion engine. As the Vice President of Electronics & Electrification, do you see this as the end of an era?

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**Mr. Adomeit:** With the new power-to-gas and power-to-liquid procedures, in which CO₂ serves as a carbon source, CO₂ savings of well over 90% are achieved. Previously, every carbon atom released into the environment has coexisted with CO₂, which was absorbed into the atmosphere. The approaches for second-generation biofuels. But here, only carbon that has already been converted into biomass through the photosynthesis of atmospheric CO₂ is burned in the engine. In addition to CO₂ reduction, these fuels can also be formulated so that harmful emissions can also be substantially reduced, such as through the synthesis of oxygenated fuels that produce far lower levels of soot than fossil fuels.

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**Mr. Heuser:** On one hand, synthetic fuels are interesting for the passenger car sector. Hydrogenated vegetable oils (“HVOs”) are usually obtained from plant oils, but other fats can also be employed. These are converted to paraffin fuels through the addition of hydrogen. In addition, there is also the new technology of power-to-liquid or power-to-gas. These technologies use electrolysis to generate hydrogen from renewable power and water. In conjunction with CO₂, this can be used to produce methane, which is already used as a fuel for gasoline engines. However, these processes also allow for completely new fuels to be defined, such as the liquid oxymethylene ethers (OME) group. These are as liquid as gasoline and can be mixed with it easily as a result.

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**Mr. Adomeit:** It is a fact that drive development is entirely dominated by electrification at present. In recent months, virtually every OEM has announced development programs to the tune of millions. Even for us, as a development service provider, electro mobility has been a fixed component of our engineering business for more than a decade. Nevertheless, it needs to be stated that despite all of the advantages, the market penetration of electric vehicles is still low – and so are the growth rates. This means that the combustion engine will still be with us for some time – whether as a part of hybrid systems, range extenders, or as the sole powertrain. Especially in long-distance traffic and the transport sector, there are currently no conceivable alternative solutions.

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**In your opinion, what would a practical solution for this look like?**

**Mr. Ogrzewalla:** The goal of a balanced fleet strategy must be to develop and promote drive solutions that ensure sustainable and clean mobility. With these ends in mind, a mix of electrification, optimized combustion engines and synthetic fuels is highly promising – while e-vehicles can reduce local emissions, especially for short trips. Furthermore, synthetic fuels are extremely promising – while e-vehicles can reduce local emissions, especially for short trips.

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**How are the applications for which synthetic fuels are especially critical?**

**Mr. Heuser:** The term “synthetic fuels” can be used to describe an extremely diverse range of fuel types. It generally refers to any fuel not manufactured on the basis of petroleum. However, there are still fundamental distinctions within this designation, such as between biofuels or e-fuels.

Traditional first-generation biofuels, such as bioethanol or biodiesel, are primarily obtained through the fermentation of seed or fruit sugars into ethanol, or the esterification of vegetable fats with (primarily fossil) methanol. The second generation of biofuels uses all plant material for fermentation into alcohols or for synthesis into long-chain hydrocarbons by means of the biomass-to-liquid procedure. In this process, the plant material is first converted into synthesis gas (CO and H₂) under anaerobic conditions, and is then combined into long chain hydrocarbons. Similar procedures are also applied to produce synthetic fuels from natural gas.

Hydrogenated vegetable oils (“HVOs”) are usually obtained from plant oils, but other fats can also be employed. These are converted to paraffin fuels through the addition of hydrogen. In addition, there is also the new technology of power-to-liquid or power-to-gas. These technologies use electrolysis to generate hydrogen from renewable power and water. In conjunction with CO₂, this can be used to produce methane, which is already used as a fuel for gasoline engines. However, these processes also allow for completely new fuels to be defined, such as the liquid oxymethylene ethers (OME) group. These are as liquid as gasoline and can be mixed with it easily as a result.

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**What are the applications for which synthetic fuels are especially critical?**

**Mr. Heuser:** The efficiency of an electric car is very high, and the vehicles drive with no emissions. In contrast, synthetic fuels have the disadvantage that every step in the production process reduces the overall level of efficiency of the chain. One aspect that is frequently left out of the discussion is the manufacturing of CO₂-neutral fuels. This means that the combustion engine will still be with us for some time – whether as a part of hybrid systems, range extenders, or as the sole powertrain. Especially in long-distance traffic and the transport sector, there are currently no conceivable alternative solutions.

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**Mr. Adomeit:** The appeal of synthetic fuels lies in the fact that they can be used directly, whether in the form of an admixture with conventional fuels, or, depending on the fuel, as a pure substance and without substantial modifications to the engines. In any case, synthetic fuels can directly help to reduce harmful emissions and immediately increase the share of renewable energy in existing fleets in the mobility sector. An admixture of only 30% of OMEs into conventional diesel reduces soot emissions by up to 99% – without any complex adjustment of the engine.

Furthermore, synthetic fuels are extremely important in any area where no alternatives exist for conventional liquid fuels with high energy density. This is especially the case for commercial vehicles, ships and aircraft. For the foreseeable future, the energy density of batteries will remain lower than liquid fuels by orders of magnitude. In the examples mentioned, it is totally impossible to accommodate the necessary energy quantities with batteries due to the enormous volume and weight requirements. With the help of synthetic fuels, it becomes possible to ensure long-term, clean and sustainable mobility in this area.

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**You mentioned the optimization of existing fleets – at present, how far away are we from a more-or-less comprehensive introduction of alternative fuels, and which of the procedures mentioned will become established?**

**Mr. Heuser:** Currently, the EU has stipulated that 10% of the energy consumed in the transport sector be supplied from alternative energy sources by 2020. However, it will still be several years before “e-fuels,” i.e. those from the oxymethylene ether group, are used to refuel in large quantities. We already know that these fuels can be created from CO₂ and renewable energy, but the realization of this on an industrial scale still requires more investment. However, such investment requires the framework conditions to be clear for all participants – certainty is required for planning purposes.

**Mr. Adomeit:** One critical factor in the prompt introduction of CO₂-neutral fuels is their integration with existing infrastructures. This can allow fuel components that can be mixed into current fuels to reduce the CO₂ emissions of existing vehicle fleets immediately. We are currently researching combinations of renewable fuels that approximate standard market fuel characteristics very closely when blended.

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**A MIX OF ELECTRIFICATION, OPTIMIZED COMBUSTION ENGINES AND SYNTHETIC FUELS IS HIGHLY PROMISING**

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**Who exactly should develop these fuels to suit the market?**

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Exemplary overview of tailored fuels from renewable sources which can be used in ICE combustion systems
of the vehicles. For an objective analysis, however, this is indispensable. In this area, electric cars are at a disadvantage compared to optimized drive systems. Battery production, in particular, is demanding and cost-intensive, and the necessary materials create new dependencies on the global market. Both the extraction of these materials and the recycling of the batteries put stress on the environment. However, if renewable energies can be used with unlimited availability – in the future, it will often be the case that more power is produced than can even be used – this fact will no longer play such a large role. In this context, synthetic fuels offer an ideal technology for storing excess power in chemical form.

What role can fuel cells play in the future?

Ogrzewalla: At present, there simply is not a panacea for emissions-free mobility. User behavior is too diverse, and the systemic strengths and weaknesses of various drive forms are too different. In my opinion, however, the essential message is the fact that needs-appropriate drives are the key to success. Not every powertrain can be reasonably employed for every objective. For e-vehicles, one of the major obstacles for buyers continues to be concerns related to range. In Germany, where the car has a special significance, users are reluctant to own a vehicle that does not cover all eventualities. This is illogical, however, since there is no need for a combustion engine for situations such as inner-city driving. An additional combustion engine would simply serve as extra weight for most drives, which is anything but efficient. Various studies have arrived at the result that as much as 87% of all trips could be covered by an e-vehicle. The success of electro mobility thus requires an ecosystem of specific services and new business models and, above all, a change in thinking on the part of consumers. In addition, advanced, quick-charging technologies can also contribute to success, since this will guarantee the range of electric cars for any trip. Until then, we will absolutely need to fall back on other, additional technologies. As mentioned before, there are no alternatives at all for long-distance traffic.

Interview Partners:

Ogrzewalla: Jürgen Ogrzewalla
Ogrzewalla@fev.com

Heuser: Benedikt Heuser
Heuser@vka.rwth-aachen.de

Adomeit: Dr. Philipp Adomeit
Adomeit@fev.com

FEV’s new international conference on “Zero CO2 Mobility” offers a highly focused platform for strategic discussion on the potential and performance of various zero emission strategies ranging from battery technologies to fuel cells and e-fuels.

For more information please visit: http://www.fev.com/zero-co2-mobility

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ZERO CO2 MOBILITY

9th - 10th November 2017,
HOTEL PULLMANN QUELLENHOF, AACHEN
COST DEVELOPMENT OF ELECTRIC VEHICLES CONSIDERING FUTURE MARKET CONDITIONS

MARKET STUDY AND COST ANALYSIS OF ELECTRIC, HYBRID AND FUEL CELL VEHICLES

With a market share of only about 1% of new vehicles sold, battery driven electric vehicles and plug-in hybrid vehicles (“xEVs”) stand, from a European market perspective, for below expectations. In Germany, the xEV share is 0.6%, corresponding to about 25,000 vehicles sold in 2016. Germany is below the EU average. It is clear that the purchase and tax subsidies from the German government have, so far, not had a significant impact: In the first 3 months, only 4,500 sales were realized. Despite the subdued market demand, the number of public charging stations for electric vehicles tripled between 2015 and 2016. Against this background, FEV Consulting conducted a market and cost study to answer the question of how electric vehicle costs will develop in the future under conditions of increased sales volumes, growing demand for raw materials, and developing production capacities. The main objective is to assess the extent to which xEV vehicles can be cost competitive with conventional vehicles and which powertrain type will dominate the market.

FEVs study answers the following core questions:

- What are the latest trends in electrification and hybridization?
- What are key market and technology trends regarding xEVs towards 2025/30?
- How high are costs for alternative powertrains today, and what will they be in 2025/30?
- What are the primary cost drivers and how will they develop?
- Will combustion engines still be the cost leaders in 2025/30?
- Which additional costs are expected in order to meet statutory and supervisory requirements?
- How cost competitive will fuel cell technology be in 2025/30?

Driven by “diesel gate”, statutory regulations, regulatory pressure and technological advances, alternative drives (or xEV vehicles) have developed into a key trend in the automotive sector. Many European OEMs are convinced that the tipping point for electric vehicles will soon be reached. OEMs and suppliers are currently investing heavily in the development of their EV fleet and EV component portfolios. Volkswagen just recently released the launch of its xEV platform (MEB) with a goal of achieving a 600 km electric driving range in its compact car concept, “ID.” Daimler showcased an electric SUV Coupé called “Generation EQ,” at the Paris Motor Show that is based on a dedicated EV architecture. Other manufacturers are planning similar concepts, including purely electric as well as hybrid, and fuel-cell electric vehicles with electric ranges exceeding 350 km. Aside from the regulatory and legislative motivation, the financial implications for OEMs over the next 10 years are still not clear. The question of whether xEVs will be able to attain a significant market share largely depends on future price competitiveness compared with their conventionally powered counterparts.

Methodology and Assumptions

Several alternative powertrain vehicle concepts and a conventional compact vehicle were compared in a cost analysis study. The selected models included typical plug-in hybrids (PHEV), pure battery-electric vehicles (BEV) and fuel-cell electric vehicles (FCEV) in the compact car segment. In order to capture market and technology uncertainties, 3 scenarios were developed that reflect technology development costs and fluctuations in raw material prices. For all 3 scenarios, a set of boundary conditions reflecting technology development costs and fluctuations in raw material prices. For all 3 scenarios, a set of boundary conditions were determined to allow a fair cost comparison between the different concepts.

Selected boundary conditions for the 2016 cost baseline:

- Vehicle segment: Compact car
- Baseline vehicle for cost comparison is a conventional ICE with start-stop and 12V
- Low production volume for Fuel Cell Vehicles
- Battery specifications based on current market concepts

Selected boundary conditions for the 2025 cost forecast:

- Vehicle segment: Compact car
- Conventional baseline vehicle is MHEV (48V) with an additional 12 kW of electric power
- Production volume for FCEV has been increased to 50 thousand units
- Higher specific energy [Wh/kg]

Exemplary cost split for selected fuel cell component in 2025 (in €)

COSTS OF ELECTRIFICATION

“ZERO EMISSION” AND HYBRID TECHNOLOGIES

COSTS OF ELECTRIFICATION
Selected Study Results

In 2016, the manufacturing costs of plug-in hybrids and battery electric vehicles (PHEVs & BEVs) were about one-third higher than a conventional ICE-powered vehicle with a Start/Stop automatic transmission. Fuel cell electric vehicles (FCEVs) manufacturing costs are nearly 5 times as high as those for a conventional vehicle. The reasons for this are lower sales volumes and high development cost in 2016. By 2025, it is expected that the electric range of xEV vehicles will nearly double, with marginal cost savings of approximately 5% (Allrounder EV). Compared to mild hybrid comparison vehicles with 48V technology, the costs are about 20% higher. The cost of fuel cell electric vehicles, with an electrical range of approximately 800 km, is expected to fall to one-fifth of today’s price, leaving a remaining cost gap of 60% compared to the 2025 baseline vehicle (48V mild hybrids). Battery costs are expected to decrease by 50% in addition to the comparison of the total cost and the delta analysis of the selected xEV vehicle configurations, detailed powertrain cost splits are provided in the study for key components like the electric motor, controller, battery, transmission, etc. Each key component has been further broken down into the main cost drivers, including material costs as well as overhead costs which were determined using the FEV “should cost” methodology. Uncertainties in future production volumes are considered in the “conservative,” “most likely” and “progressive” scenarios.

Impact on the Automotive Industry

Fully electric drivetrains are far less complex than their conventional counterparts with internal combustion engines, since many components of a conventional drivetrain are no longer necessary. The sales potential of injectors, fuel pumps, filter systems and turbochargers is adversely affected by increasing EV sales. Conversely, the strategic importance of new components, such as the electric motor, battery, and power electronics increases. For the future, manufacturers need to decide what share of the added value they want to provide from within (vs outsourcing). This decision is strongly influenced by endogenous factors such as cost competitiveness, exogenous factors such as raw material prices, vehicle range and future development of charging infrastructures. Suppliers – especially those with a product range for traditional OEMs due to economies of scale associated with increased production volumes and improvements in cell technologies. The electric capacity of a typical BEV is expected to grow significantly by 2025 from 36 to 70 kWh (500-600 km).

Today: Strategic Analysis and Preparation of Realignment

Although the industry is in a state of upheaval, there is still partial restraint. On the one hand, the change to the development of alternative propulsion systems is already visible in the organizations of major manufacturers and large or specialized suppliers. On the other hand, traditional suppliers that are active in the internal combustion engine market are still in the preparatory phase. As soon as market shares of xEVs have increased, product and service portfolios must be realigned and value chains have to be reorganized. The orchestration of an orderly ramp-down of the traditional business requires a solid strategic plan and dedicated implementation. It is very likely that the early inefficient suppliers will fall victim to the industry transition and exit the market. As a further consequence, the future R&D focus of the OEMs will shift even more clearly toward electrification and other value-added product offerings, such as automation and (digital) mobility services.

2020: Implementation of the Realignment and Transition

As soon as market shares of xEVs have increased, product and service portfolios must be realigned and value chains have to be reorganized. The orchestration of an orderly ramp-down of the traditional business requires a solid strategic plan and dedicated implementation. It is very likely that the early inefficient suppliers will fall victim to the industry transition and exit the market. As a further consequence, the future R&D focus of the OEMs will shift even more clearly toward electrification and other value-added product offerings, such as automation and (digital) mobility services.

2025+: Completion of Transition Phase

Depending on the respective scenario, market shares for conventional powertrains (ICE only) will shrink significantly. In one radical scenario, ICE vehicle sales are likely to drop to 75% of the 2016 level. On the other hand, as a result of shrinking market volumes, further (and even stronger) consolidation of the remaining suppliers in the field of conventional powertrains is expected. On the other hand, market participants will be well positioned with an early strategic focus on the realignment and transition toward the new boundary conditions for the future xEV market and technology competition.

Written by Alexander Nase
Nase@fev.com
Mirko Engelhard
Engelhard_m@fev.com

If you are interested in the details of the study or would like to discuss implications and possible actions, please don’t hesitate to contact us.
**HIGH TECH OR LOW COST?**

FEV INVESTIGATES THE OPTIMAL SI ENGINE FOR HYBRID POWERTRAINS

Recent market studies performed by FEV for Europe, the USA and China predict a shift toward environmentally sustainable drive systems. The main factor in this trend is the electrification of the drivetrain. Although the majority of all vehicles sold in Europe (75 to 85%) will still have a combustion engine in 2030, a high proportion of these combustion engines will be operated with hybrid powertrains. How can gasoline engines be designed to achieve low CO₂ emissions in different hybrid topologies (as mild hybrid, plug-in hybrid, etc.) at optimal cost? FEV addressed this question in a broad study based on a D-segment vehicle. The reference powertrain was a conventional powertrain with a 2.0 liter gasoline engine (135 kW, TC DI with a 2-stage variable valve train and Miller cycle), a 7-speed dual clutch transmission and a 12V electrical system.

**TURBOCHARGED 3-CYLINDER ENGINES AS WELL AS NATURALLY ASPIRATED 4-CYLINDER ENGINES WITH LARGER DISPLACEMENT ARE BOTH SUITED TO ACHIEVE LOW CO₂ EMISSIONS AT LOW COSTS**

With the aim of identifying the optimal combustion engine for hybrid drives, these technologies have been evaluated regarding their costs and CO₂ emissions. The CO₂ emissions are mean values from WLTP-L and -H. The cost scenarios relate to 2025 and a production volume of 200,000 drives/year. In addition, emission in RDE were tested and evaluated.

**Engine Variants for Mild Hybrids with 48V BSG**

The electrification of the reference powertrain with 48V BSG without changes to the combustion engine costs 740 € and reduces the CO₂ emissions by 8.6 g/km which means costs of 86 €/g CO₂. Starting with this drive, several technology combinations optimal for hybrids were identified. They arrived at the following possible constellations.

**Cost-Benefit Comparison**

A comprehensive technology matrix was examined within the framework of FEV’s study. This matrix includes turbocharged and naturally aspirated engine concepts with displacements from 1 to 3 liters. In addition, the selection focuses on technologies that are already in series production or show a high degree of maturity, indicated by a series production launch within the next 3 years. All engines comply with current and future emissions legislation such as EU6d and CN6b. They are operated stoichiometrically (λ = 1) throughout the engine map, and they are equipped with particulate filters.

**Architecture of Hybrid Powertrains**

Hybrid drives are, by definition, combinations of various drives in the same powertrain. Therefore, there is a correspondingly high number of possible constellations. In this broad study, the FEV experts focused on hybrid combinations with gasoline engines and topologies with particularly high market shares or particularly high market prospects. These are:

- Mild hybrid with 48V belt starter generator (BSG)
- Mild hybrid with integrated 48V starter generator (ISG)
- Plug-in hybrid (PHEV)

**Plug-in hybrid (PHEV)**

With the aim of identifying the optimal combustion engine for hybrid drives, these technologies have been evaluated regarding their costs and CO₂ emissions. The CO₂ emissions are mean values from WLTP-L and -H. The cost scenarios relate to 2025 and a production volume of 200,000 drives/year. In addition, emission in RDE were tested and evaluated.

**Turbocharged 3-cylinder engines**

These turbocharged 3-cylinder engines as well as naturally aspirated 4-cylinder engines with larger displacements are both suited to achieve low CO₂ emissions. Rather simply designed “On/Off” technology packages are also suited for the scaling of the performance requirements of the combustion engine for various hybrid drives. The conversion to a naturally aspirated 3.0 liter 6-cylinder engine with part fuel injection (PFI), Atkinson cycle and cooled EGR neither appears favorable from the cost perspective nor from that of CO₂ emissions.

**Ref. engine in hybrid powertrain**

Reference powertrain: 2.0 L TC DI w/ Miller, int. exh. manifold, dual VVT, 2-stage CTA, start/stop, 12V integrated starter/generator, 143 g/km CO₂ in WLTP.

**Evaluation of technology packages of gasoline engines for mild hybrids with 48V belt-driven starter generator (BSG mild hybrid) relative to the reference powertrain with regards to the ratio of costs and CO₂ emissions**
conclusions for the D-segment vehicle evaluated in the WLTP cycle: Naturally aspirated 4-cylinder engines and turbocharged 3-cylinder engines are particularly well suited for use in a mild hybrid with a 48V belt-driven starter generator. Naturally aspirated engines require 2.5 liters displacement, variable valve timing on the inlet and outlet sides (dual VVT), direct fuel injection (DI) and a variable intake system to meet performance demands. The costs of the BSG drive train can be reduced to 490 € by conversion to a naturally aspirated engine with a simultaneous increase of the CO2 emission reduction to 10.4 g/km (47 €/g CO2 is achieved). With the addition of cylinder deactivation (CDA), the costs increase again to 560 €; however, the CO2 emission reduction is disproportionately increased to 12.3 g/km (46 €/g CO2 is achieved).

With the simplification of the combustion engine to a 3-cylinder engine and the elimination of the inlet valve lift variability, the Miller cycle has to be omitted to continue meeting performance requirements. Therefore, the powertrain has a lower CO2 emission reduction of 8.9 g/km, but only costs 460 €/52 €/g CO2 is achieved). If inlet valve lift variability and the Miller cycle are retained for the 3-cylinder engine, the performance requirement can also be met via a high temperature-proof turbine with variable geometry (950 °C- VTG). A CO2 emission reduction of 11.3 g/km is therefore achieved at 46 €/g CO2. The technology package inlet valve variability, Miller cycle and 2-stage charging system can also be replaced at a favorable cost and CO2 emissions level by a 2-stage VCR system (44 €/g CO2).

Water injection can also serve as a substitute technology and allows a further downsizing to 1.3 ltr with its strong knock-suppressing and simultaneously performance-enhancing effect. This variant with direct water injection does not yet have the same production maturity as VCR, but will yield good results for costs and CO2 emissions for the 2025 horizon in hybrid drives, too (33 €/g CO2 is achieved).

**Engine Variants for PHEV**

The influence of the combustion engine technology package on achievable CO2 emissions reduction is small for the plug-in hybrid drive concept. The design is characterized by compliance with the performance requirements at optimal cost. Small, simplified turbocharged engines with knock-reducing technologies like Miller valve timings on VCR and larger, naturally aspirated engines like a 2.5 ltr 4-cylinder with PFI, Atkinson cycles and cooled exhaust gas recirculation (cEGR) meet this requirement.

**Assessment Under Real Driving Conditions**

In the WLTP cycle, the influence of the combustion engine on the CO2 emissions reduction decreases with an increasing degree of electrification. At the same time, the increasing influence of the e-motor allows for the simplification of combustion engine technologies, thus achieving cost benefits. The influence of the combustion engine increases under real driving conditions (RDE) compared to the WLTP cycle significantly. This is due to higher loads and a smaller pro-portion of electric driving. Turbo-charged engines with more advanced technology have a more favourable cost and CO2 emissions ratio under these terms of comparison. In the light of real driving conditions, the use of a variable inlet valve lift (VVL) or the compression ratio (VCR) appear advantageous. In the Charge-Saving-Mode, high tech turbo-charged engines with knock-inhibiting technologies gain clearly, because they drive a heavy vehicle (battery weight) without purely electric driving.

**Vehicle Integration Concepts**

Package and NVH are of special importance in the integration of the combustion engine into hybrid powertrains. Additional drive components compete for consistently limited space. At the same time, electrification can be employed in an intelligent way with the simplifications and the elimination of existing components. FEV has developed a parametric procedure to be able to evaluate early concepts from a package perspective.

Again, FEV considered the D-segment vehicle with a transversely mounted combustion (“east west”) engine for the 48V hybrid variants with belt-driven starter generators or starter generators, respectively, as well as with the P2 plug-in hybrid powertrain. The evaluation of the results revealed that the reference engine (4-cylinder 2.0 liter TC DI) has no significant space disadvantage in the P0 mild hybrid configurations examined. This is primarily due to the elimination of the alternator, which compensates for the additional belt and belt-driven starter generator (BSG). As expected, the ISG variant in transverse mounting is less favorable from a package perspective when comparing the mild hybrids. This is due to the extension in length caused by the ISG and the additional clutch.
01 "ZERO EMISSION" AND HYBRID TECHNOLOGIES

SI HyBRId ENgINES

powertrain. The package parameter considers this flexibility, which leads to a lower weighting of the turbocharging components compared to other measures – for example, a change of the engine mounting. The connections observed here are more pronounced with an increase in starter speed, the integration of balance shafts (or balancing weights with a high balancing degree), the adjustment of the engine mounting and the use of dual mass flywheels. With the help of such measures, 3-cylinder engines can replace 4-cylinder engines in hybrid drives without significant NVH disadvantages.

Emission Calibration Under Real Driving Conditions

The important influence of electrification is the intermittent decoupling of the combustion engine from vehicle propulsion. The connections observed here are more pronounced with an increasing degree of electrification. Therefore, a comparison between the emissions of the powertrains with the highest electrification differentiation was performed.

The highly electrified plug-in hybrid powertrain was examined with two "hybrid-optimized" combustion engines. In view of EU6d limits and RDE, both drives were equipped with a particulate filter. They did not need mixture enrichment for component protection (λ = 1 throughout the map), and had an injection system for reduced particle emissions (turbocharged engine: 350 bar DI and naturally aspirated engine with PPI).

Particle Emissions in Electrified Powertrains

Particle emissions in the electrified powertrain (PHEV) shift when compared to the purely combustion engine-driven vehicle dependent on the battery charge status. Generally, the emissions are lowered by emission-free electric driving. When using a plug-in hybrid with an empty battery, a particle emission increase of 18% occurs. The main effect is that purely electric and, therefore, emission-free driving is not possible in that case. In addition, a smaller combustion engine (1.5 liter) is driving a heavier vehicle in the plug-in hybrid compared to the reference vehicle. The higher engine load spectrum increases the particulate raw emissions and the particulate filter slip.

Comparison of NOx Emissions

The emissions for all powertrains also maintain a safe distance from the EU6d limit (even without CF) for NOx and demonstrate behavior analogous to the particle emissions in the comparison of the drives. Therefore, the electrification of the powertrain also lowers the NOx emissions if a fully charged battery and Charge-Depletion mode allow for purely electric driving. Along the same lines, with an empty battery, the NOx emissions increase, as well.

Exhaust Aftreatment

A significant simplification of exhaust aftertreatment technology is not recommended. An electrically heated catalyst (e-cat) can even be a solution for the trade-off between a maximum electric driving experience with a switched-off combustion engine and regular engine starts for exhaust aftertreatment.

The whole study which also includes evaluation for power split hybrid powertrains is available as a download at www.fev.com/whitepaper

Written by
Dr. Johannes Scharf
Scharf@fev.com

Dr. Alexander Tolga Uhlmann
Uhlmann@fev.com

For the plug-in hybrid, a critical package parameter value has now been exceeded ("No Go"). The naturally aspirated 4-cylinder variants reach the critical value already in the 48V mild hybrid variants and exceed it clearly in the plug-in hybrid. The increase in engine length in the transverse mounting is especially critical. The increase of the overall height in particular with regards to the transverse influence on passive pedestrian protection and noise encapsulation measures also reduces the package parameter. This cannot be compensated for by the elimination of the turbocharging components when the transition from the turbocharged to the naturally aspirated engine is made, as these can be placed in a comparatively flexible manner. The package parameter considers this flexibility, which leads to a lower weighting of the turbocharging components compared to other measures – for example, a change of the engine block.

All 3-cylinder variants allow for a significant relaxation of the space problem for the 48V mild hybrid variants. By way of an increase in the degree of downsizing (displacement reduction to 1.3 liter), a small advantage even for the plug-in hybrid variant, whereas with a larger displacement (1.5 liter), the package parameter is almost neutral compared to the reference variant, whereas with a larger displacement (1.5 liter), the package parameter is almost neutral compared to the reference variant.

The main effect is that purely electric and, therefore, emission-free driving is not possible in that case. In addition, a smaller combustion engine (1.5 liter) is driving a heavier vehicle in the plug-in hybrid compared to the reference vehicle. The higher engine load spectrum increases the particulate raw emissions and the particulate filter slip.

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Written by
Dr. Johannes Scharf
Scharf@fev.com

Dr. Alexander Tolga Uhlmann
Uhlmann@fev.com

FEV’s studies show that the NVH requirements for the combustion engine in the hybridized powertrain are controllable if suitable measures are considered in the design concept of hybrid drives. Examples are the increase in starter speed, the integration of balance shafts (or balancing weights with a high balancing degree), the adjustment of the engine mounting and the use of dual mass flywheels. With the help of such measures, 3-cylinder engines can replace 4-cylinder engines in hybrid drives without significant NVH disadvantages.
FEV HECS ECOBRID WITH 48V HYBRIDIZATION

FEV ELECTRIFIES DIESEL

Over the next few years, a significant increase in 48V “mild hybrid” concepts is expected, since they offer considerable potential to reduce fuel consumption as well as pollutant emissions. At the same time, they are relatively easy to implement, since they do not require a complete redesign of the powertrain.

As part of a joint project with Valeo, FEV has equipped a D-segment test vehicle with a 48V electrical system, a belt-driven starter generator (BSG), and an electrically driven compressor (e-Compressor). The result: the optimizations contribute to a CO2 reduction potential of approximately 11% in the Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP).

DIESEL HYBRID ENGINE

Thanks to highly efficient exhaust gas aftertreatment systems, current diesel engines can comply with the lowest NOx emissions. However, in very transient operating situations – for instance, during strong acceleration – a significant, short-term increase of NOx raw (engine-out) emissions can occur which to some extent reach the tailpipe. The reason for this is that the Exhaust Gas Recirculation (EGR) system and the turbocharger can only deliver the necessary EGR rate or the required charge pressure after a certain delay time (“turbo lag”).

Potential of Electric Components

Electrically driven components offer meaningful support; a belt-driven starter generator (BSG) can provide additional torque, allowing the engine to be operated in a lower load range. In addition, an e-Compressor can generate the desired boost pressure with virtually no delay and independently of EGR, thus bridging the “turbo lag” of the turbocharger. As an additional measure, the exhaust gas turbocharger can alternatively be optimized with regard to higher efficiency or higher rated power.

48V Components

The 48V e-Compressor is installed downstream of the water-cooled charge air cooler (WCAC) and the turbocharger, which has variable turbine geometry. This installation position leads to a reduced volumetric flow downstream of the e-Compressor, which improves transient behavior. The reduced flow also allows the selection of a smaller compressor with additional response time improvements. Intercooling also reduces the power requirements of the e-Compressor, since the compression takes place at a lower temperature level.

The test vehicle has a 12V/48V electrical system with 2 batteries. The 48V system consists of the BSG in “P0” position, a lithium-ion battery, and the e-Compressor. A bidirectional DC/DC converter is used to establish the connection to the 12V system, which was taken over from the production vehicle, which also powers the Diesel engine’s electric water pumps.

Air path of the HECS ECObrid

FOR A SHORT-TERM OVERBOOST, THE EGR RATE CAN BE FURTHER INCREASED, WHICH REDUCES NOx EMISSIONS

THROTTLE

E-COMPRESSOR

CHARGE AIR COOLER

TURBOCHARGER

EXHAUST GAS AFTERTREATMENT

HD-EGR

LP-EGR

AC FE 3105

HECS ECObrid Concept

The HECS ECObrid test vehicle uses the third generation of the FEV-HECS - a 1.6 liter 4-cylinder engine with single-stage supercharging and combined high-pressure / low-pressure EGR. A 48V e-Compressor and a 48V BSG were also integrated. The complete electronic control system for the engine and the hybrid system are handled by a proprietary FEV model-based software, which was implemented on a dSPACE 2.8 Rapid Control Prototyping System (RCP).

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The 48V prototype battery from Voltabox is based on a NMC/LTO cell chemistry and has a nominal capacity of 20 Ah. This comparatively high capacity enables a high degree of freedom for demonstration applications and in conjunction with air cooling enables peak currents of up to 15 C. The battery module consists of 20 cells connected in series, resulting in an operational voltage of 44 to 48V in the relevant SoC area (SoC = State of Charge).

The Valeo 48V e-Compressor is driven by a switched reluctance motor and can be supplied with power of up to 6.5 kW. The low mass inertia leads to a very short response time of less than 150 ms.

Special Control Concept

The additional hybrid components of the HECS ECObrid require new control functions, which have been integrated in the software environment of the existing engine control unit.

Hybrid mode is the most important mode of operation for mild hybrid applications. In this mode, the energy management module (EgyMgt) defines the battery power split for the 48V BSG and e-Compressor. The EgyMgt collects all power requests and prioritizes them according to the operating mode. This allows easy exchange of components. In the case of a missing software feature, it can be added within the software module of the respective hardware component.

The torque and speed setpoints are calculated in the modules of the BSG and the e-Compressor, considering charge/discharge current, the limitations of the 48V strategy module, and torque request from the driver of the vehicle.

The software architecture includes functions for all common components of the 48V system, such as batteries, starter generators, e-Compressors, DC/DC converters, and their interfaces. Individual functions for component management, system coordination, and diagnostics are also included. The interfaces of the individual hardware components are transferred to universal and hardware-independent signals via input/output functions that are analogous to the basic functions for a diesel engine. This enables peak currents of up to 15 C. The battery module consists of 20 cells connected in series, resulting in an operational voltage of 44 to 48V in the relevant SoC area (SoC = State of Charge).

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Battery Aging

Life-long Availability of the Battery System

BMS Algorithm for State of Health Determination in Hybrid and Electric Vehicles

With the increasing application of lithium-ion battery technology in the automotive industry, lifetime battery-aging behavior is an important topic for today’s xEV vehicle applications. Aging influences available battery capacity, which is a crucial value for EV/PHEV applications, as well as battery internal resistance, a crucial value for PHEV/HEV applications. Knowing the aging status (SOH, State of Health) of battery systems is important, since OEMs, workshops, and even customers are interested in the SOH of the battery and some Battery Management System (BMS) functions need to be adjusted during operation to ensure the availability of the battery system throughout its lifetime.

FEV’s Online Adaption Approach May Improve System Behavior in Development Projects that are Very Cost and Time Sensitive.

Technical Challenges of Aging Prediction

Battery cell aging mechanisms are susceptible to two kinds of effects:
- Calendric aging (depending on SOC and temperature)
- Cyclic aging (depending on depth of discharge and C-rate)

Both cases result in capacity fade and internal resistance increase, which is a direct drawback for system performance. To get sufficient information for the onboard aging model such as capacity fading prediction and internal resistance prediction, exhaustive battery cell testing must be performed. These tests include storage and cycling under defined conditions for a long period of time.

Alternatively, accelerated aging can be applied – for example, using very high operating temperatures during tests for cyclic aging, resulting in faster aging and, therefore, time saved. However, in this case, the extrapolated fuzziness of the results for estimating cell behavior over a lifetime under normal operating conditions might harm the accuracy of aging prediction over the full product life cycle, compared to the non-accelerated approach. In both cases (accelerated and non-accelerated aging analysis), unadapted static models might not be accurate enough to perform a reasonable aging prediction over a lifetime; they should be adapted online during operation when comparing measured and estimated battery parameters using real-time vehicle data.

FEV’s Approach

FEV developed an online adaption concept without using complex aging prediction models. This offers a potential reduction in effort during battery cell testing, as well as in complexity of the BMS software and hardware. The concept is to determine SOH by monitoring fundamental BMS functions, calibrated at the beginning of life (SOC calculation and Power Prediction) of battery operation, since these BMS functionalities will be affected by aging. The system will not be capable of delivering the power given by the power prediction due to the increase in internal resistance, and SOH will then no longer be calculated correctly, assuming beginning-of-life battery capacity, which will be reduced. Monitoring is performed by way of a smart comparison of the operating data and related expected values under specific operating conditions. Furthermore, the BMS functions are adapted according to this comparison to ensure availability of the battery system over the course of its lifetime.

Outlook

This approach was designed to be a cost- and effort-optimized method of determination for SOH during a battery life cycle and to adapt relevant BMS functions accordingly. The goal is not to replace established methods, but may improve system behavior in development projects that are very cost and time sensitive.

Written by:
Dr. Mirco Küpper
Kuepper_m@fev.com
Vehicles equipped with a 48V mild hybridization offer a potential to save fuel compared to conventional vehicles. This advantage is leveraged by introducing full hybrid features like a greater amount of regenerative braking, supporting the internal combustion engine by load shifting and adding additional functionalities like sailing and advanced stop/start. The 48V system is also adding power for additional consumers for comfort systems like air conditioning and active suspension. Furthermore, electric supercharging from a 48V system can be introduced for Otto and Diesel internal combustion engines which is increasing the fuel economy and can also be used to meet emission regulations by simplifying exhaust gas aftertreatment systems. In a recent study, FEV evaluated which of these features can be supplied by the powernet only from regenerative braking. For the evaluation, vehicle measurements from a 48V powernet are enhanced with simulations in real driving conditions.

System Layouts and Functionalities

In the course of its study, FEV used a representative C-segment vehicle with a 1.4 liter gasoline engine, 7-speed dual clutch transmission and a conventional 12V powernet as a reference vehicle. The 12V powernet topology features an intelligent controlled alternator, conventional sprocket starter and 12V AGM lead acid battery. The 48V topologies adopted in the study feature a downsized 1.2 liter combustion engine with the same dual clutch transmission and consist of a belt-driven starter generator (BSG, with integrated power electronics) which substitutes the alternator, 48V lithium ion battery and DC/DC converter to connect and supply the 12V powernet.
Various 48V topologies with different functionalities were considered. Starting from a reference baseline with a conventional powernet and a stop/start at 0 km/h, this study analyses the impact of expanding a stop/start system up to 120 km/h. The study focuses on a balanced final SOC and an initial SOC for less energy recovery and SOC constraints of the lead acid battery. On the other hand, electrical charging using the BSG can profit from intelligent load shift operation. In contrast high load scenarios lead to lower benefits of the hybridization due to further limitation of the 48V functionalities. At the same time the limitation of functionalities like advanced stop/start engine off sailing can also influence the driving experience negatively.

**Sensitivity Analysis: Powernet Consumption**

Identification of powernet consumption in real driving is very complex due to a large range of applications, vehicle variants and the influence of customer behavior. Based on a systematic approach, FEV set up a comprehensive database containing detailed powernet measurements for different drive cycles, including real world driving.

The powernet consumption was varied according to varying loads. In the high load scenario, all selectable consumers were switched on at maximum stage. During the normal load scenario, just low beam lights, infotainment, radio and automatic air conditioning were activated. Average powernet consumption is between 6.5 and 12 kW (depending on environmental conditions and user profile). However peak consumption can be up to 3 times higher.

**THE NEED FOR ACTIVE CHARGE ENERGY, WHICH HAS TO BE SUPPLIED BY FUEL, IS DRastically INCREASING WITH HIGHER POWERNET LOAD**

Starting from minimum powernet load, fuel saving slightly increases from 6% up to 9%. This improvement is affected by two aspects. On the one hand stop/start function of the conventional vehicle is limited due to lower energy recovery and SOC constraints of the lead acid battery. On the other hand electrical charging using the BSG can profit from intelligent load shift operation. In contrast high load scenarios lead to lower benefits of the hybridization due to further limitation of the 48V functionalities. At the same time the limitation of functionalities like advanced stop/start engine off sailing can also influence the driving experience negatively.

**Average Power Distribution during FEV Cycle**

The need for reactive charge energy, which has to be supplied by fuel, is drastically increasing with higher powernet load. At the same time it is restricting 48V functionalities, like BSG boost, since the energy is not free by recuperation and has to be generated from fuel along the engine and BSG efficiency. The amount of regenerative braking energy is also limited due to the effect of idling in stop phases and therefore not the full regeneration potential can be leveraged.

**Fuel and CO₂ Saving Potentials in the FEV Cycle**

For the FEV Cycle, a real world driving cycle with average load profile was taken into consideration and compared to a reference case of a 12V powernet with stop/start functionality at 0 km/h. All cases were evaluated with 12V and 48V balanced final SOC and an initial SOC for the 48V systems of 70%. The analyzed real world driving cycle consists of 80 km in urban, extra-urban and highway driving with an average speed of 50 km/h and a maximum speed of 121 km/h. During this drive cycle the 48V system achieves high fuel savings of 6-7% by supporting the powernet with the energy recovered during the braking phases. Due to the high powernet load, very limited energy is available for boosting, resulting in a large share of engine operation above optimal conditions. Due to the highly dynamic and demanding driving cycle, the eCharger is extensively used. This component increases engine low end torque and avoids turbo lag enabling combined “downsizing” and “downspeeding” with a resulting benefit in term of fuel consumption of 1-2 gCO₂/km. Sailing functionality (with engine off) during deceleration and downhill phases enables a further fuel consumption benefit of 4%. However, this potential is highly depending on the driver’s anticipation.

**48V High Performance Powernet**

- Enabling of further electrification and sufficient energy supply of
  - Electrical A/C Compressor
  - Active roll stabilization
  - Electrical Power Steering
  - Electrical heated catalyst
  - PTC heater, Electrical pumps, Cooling fans

**48V Starter Generator**

- Assist of ICE by electrical charger to avoid turbo-lag of downsized engines
  - Higher low end torque
  - Reduction of back pressure

**48V Electrical charger**

- Additional Hybrid functions
  - Electrical creeping
  - Engine off coasting
  - Load point shift

**48V Mild Hybrid**

**48V system – new features and functionalities**

**Author:**

Dr. Andreas Balazs

Balazs@fev.com
The growth of the global population, along with a disproportionate increase in transportation capacity, represents one of the biggest challenges with regard to sustainable mobility concepts. In particular, increasing urbanization and the simultaneous intensification of the debate regarding the reduction of pollutant emissions in metropolitan areas is leading to the electrification of commercial vehicle powertrains. For lightweight transport vehicles, such as courier service and mail distribution vehicles, there are already large numbers of corresponding, electric-only solutions on the market. It is to be expected that this technology will also find its way into the heavier vehicle classes.

The combination of electric motors with an additional range extender represents an obvious solution for the typical medium-duty commercial vehicle segment, which also considers changing daily requirements with regard to the delivery routes to be served. A serial arrangement of the drive sources already offers significant potential, and can be implemented fairly easily.

Computational simulation

As part of a simulation study based on a purely electric vehicle, FEV has examined various drives and has assessed them with regard to consumption potential and operating costs. The base vehicle was defined as a typical, two-axle distribution vehicle with an authorized total weight of 12 tons.

To dimension the purely electric drive, fleet data from a shipping company, located in the Cologne-Aachen area, were used, which indicated a daily delivery route of about 100 km, corresponding to about 50% of all journeys over a period of 10 days. The battery capacity for all hybrid drives was then calculated, resulting in a total capacity of 100 kWh in the selected driving cycle, considering 50% of the maximum payload and a usable energy content of 75% of the battery. A larger battery for a range of 200 km in pure electric operation was also investigated.

Due to the torque characteristics of electric motors, an electric power of 150 kW was selected.

Range Extender Concepts

In addition to a 7.5-liter 6-cylinder diesel engine with a rated output of 180 kW, representing a typical conventional drive unit in this vehicle class, low-cost passenger car engines were also chosen as possible range extenders, including a 2-liter diesel engine and a 1.8-liter Otto motor with 130 kW nominal power. A fuel cell system with 100 kW electric power was also considered. Different exhaust gas aftertreatment systems and tank sizes were applied to the engines investigated, and the corresponding weights were taken into account. All systems were investigated from a design perspective with regard to packaging feasibility by means of existing data from a typical vehicle. The batteries were placed in the frame for safety reasons. As an electric drive, two motors on the rear axle with the above mentioned total power of 150 kW were considered.
Power and Fuel Consumption

Using a simulation tool that is based on a model library, the power and fuel consumption of the vehicle for the different drive variants are calculated into the Worldwide Harmonized Vehicle Cycle (WHVC), as well as the Urban Delivery Cycle (UDC). The UDC was established in various studies and also takes height profiles into account. The operation strategy foresees the initial provision of the power components increases by 21% when a gasoline engine is used as an additional drive source. In this context, it should be noted that the consumption of the conventional drive with an additional weight equivalent to the electrical components increases by around 7% in WHVC.

If this is used as a basis, the consumption of the hybrid systems is, accordingly, more cost-effective. The comparison with the results in the Urban Delivery Cycle, which are characterized by a lower share of high speeds, more frequent acceleration and braking processes, as well as a hilly profile, shows a higher basic consumption, but also offers more significant savings potential in hybrid operation. Overall, the power to be used for the cycle is less than what electric-only operation shows.

Calculation of Costs for Daily Operation

Generally speaking, the concepts must be assessed in real operation, using the daily driven distance, with regard to the running costs and the power requirements of the vehicle. As part of the FEV analysis, the pure power costs are used, but initial costs, depreciation and wear costs for the systems are not taken into account. In order to take the currently prevailing uncertainty with regard to future energy costs into consideration, the costs for fuel and power are reflected in two scenarios. In the first scenario, moderate fuel prices based on average prices between 2011 and 2016 are used, while the power price is based on the household price. In the second scenario, the maximum fuel price from the period considered is used, while a reduced power price for industrial clients is applied as an alternating classification of fleet operators can be predicted with an uncertainty with regard to future energy costs. This changes upon switching to serial hybrid operation: starting at a daily distance driven of 100 km, the cost gradient decreases in accordance with the calculated fuel consumption and power costs.

Within the delivery distance considered (that of up to 200 km per day), the operation costs for serial hybrid operation with Diesel engines are always cheaper than those of a conventional engine. With gasoline engines, however, due to the higher power prices and the higher specific consumption, there is also a price disadvantage in scenario 1. The operation costs for a fuel cell, due to high hydrogen prices – which were kept constant at EUR 7.70/kg in both scenarios – are higher than the basic operation, starting at 125 km, respectively 150 km.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Diesel / (l/100 km)</th>
<th>Gasoline / (l/100 km)</th>
<th>Electric Energy / (€/l)</th>
<th>Hydrogen / (€/l)</th>
</tr>
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<tbody>
<tr>
<td>Scenario 1</td>
<td>1.07</td>
<td>1.19</td>
<td>0.24</td>
<td>7.70</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>1.22</td>
<td>1.35</td>
<td>0.37</td>
<td>7.70</td>
</tr>
</tbody>
</table>

Results

The costs for the conventional, or electric-only, drive increase linearly with the distance driven, as per the respective cost scenarios. This changes upon switching to serial hybrid operation: starting at a daily distance driven of 100 km, the cost gradient decreases in accordance with the calculated fuel consumption and power costs.

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Written by:
Stefan Wedowski
Wedowski@fev.com
Johannes Maitherth
Maitherth@vkv.rwth-aachen.de
Christopher Marten
Marten_c@vkv.rwth-aachen.de
In conventionally powered vehicles, a portion of the excess radiated heat energy from the internal combustion engine is used to heat the passenger compartment. In electric vehicles, this heat source is not available due to their higher tank-to-wheel efficiency. Instead, an additional heater is necessary that is powered by the battery. The cruising range of electric cars is reduced by 50% when the heater is turned on as a result. Increasing the efficiency of the vehicle or the passenger compartment air conditioning system is a major challenge on the road to making electric cars competitive for everyday use.

In a recent study, FEV focused on the potential for energy savings from heating surfaces in the immediate vicinity of the driver. The heating system was installed in an electrical test vehicle and consists of an electric PTC air heater and electrically operated, radiating surfaces in the passenger compartment. Extensive measurements were conducted on the test vehicle in a climatic chamber and the energy consumption of the heating systems was recorded. By comparing the energy consumption in both heating processes, an energy savings potential of as high as 9% was identified.
Operating Temperature

The heating system uses both convection and heat radiation to heat the cabin. Therefore, measuring the air temperature alone is insufficient. In order to adequately consider the interaction of both the heat transfer mechanisms, another method for evaluation of passenger compartment heating must be used. One good possibility is the so-called operating temperature. The operating temperature weights the heat transfer coefficients of convective and radiative heat transfer. For this measurement, a dedicated sensor for measuring the radiant heat was developed as a first prototype. Experience from the construction sector shows that using the operating temperature instead of the air temperature in the control of a room’s heating system reduces energy consumption and improves thermal comfort.

Temperature Measurement

In order to assess passenger compartment heating, various temperature measurement points were determined inside the passenger compartment. Since the aim of the new measurement method was not to evaluate the heating performance but to compare the two heating methods, obtaining the temperatures at the front seats was sufficient. Temperatures were taken at head and foot levels. 8 temperature measuring points were set up in the test vehicle; 4 measuring points were installed in the driver and the passenger sides, respectively. 2 of the 4 measuring points were attached to the headrests on each side.

A self-developed flat sensor with a 3 cm edge length was used for detecting the operating temperature at foot level. This is because the heat-radiating surfaces were installed in the foot wells of the driver and the passenger sides. The average cabin temperature can be calculated by averaging the air temperatures at head level and the operating temperatures at the foot level.

Heating System

The conventional heating system, consisting of a pure electric air heater and a fan, was extended by electrically operated, heat-radiating surfaces in the vehicle’s foot wells.

Measurement Procedure

A series of measurements was conducted in a climatic chamber at an ambient temperature of -10 °C. The outlet of the air flow in all measurements was set to feet only. The test setup was not influenced by either wind speed or solar radiation. The test vehicle was heated for about 25 minutes. To compare the thermal output of all test configurations, three different temperature measurement locations were considered - at foot level, at head height, and the average temperature of the passenger compartment.

Average Passenger Compartment Temperatures and Energy-saving Potential

At the average passenger compartment temperature, the results showed that the PTC heating output was either too high (measurement combination 1) or too low (measurement combination 2). Therefore, the resulting temperature profiles from measurements Combination 1 and Combination 2 were interpolated, thus providing an estimate of the temperature profile for a measurement with the corresponding PTC heating power. The power consumption of the interpolated measurement was calculated according to the power consumption of measurements Comb. I and Comb. II. Using radiative heating, only 90.7% of the heating energy is necessary to achieve heating performance equal to that of a conventional system. Since the results are based on an interpolation, the potential for energy savings is not justified physically. It can be used as a prediction of energy-saving potential.

Subjective Impression of the Radiative Heating System

During winter in Alsdorf, Germany, subjective tests were conducted in order to adjust the settings of the various heating systems and to check the temperature sensors. During these tests, the radiant heating system was subjectively assessed. The ambient temperature during the test was 3 °C, providing realistic conditions for the vehicle heating. A human subject was placed in the front seat of the equipped vehicle while the heating system was operated. The test subject’s clothing was appropriate for the winter conditions, consisting of jeans, a winter jacket and low shoes. Approximately two minutes after the start of the heating process, the radiant heat was sensed by the subject.

The air temperature was lower than that of the radiant surfaces. In general, the radiant heat was perceived as pleasant. The test subject deliberately touched the radiating surfaces with his legs during the test, thereby improving thermal comfort. Due to the proximity of the radiant surfaces to the legs, this possibility could be taken by the driver while driving the car. The test subject reported a positive overall impression of the radiant heating. Objective measurements, even those employing a thermal mannequin, do not consider behavioral responses such as those described above.

Written by
David Hemkemeyer
Hemkemeyer@vka.rwth-aachen.de
Daniel Persak
Persak@leu.com
Klaus Wollf
Wollf@leu.com
Ralf Stienen
Stienen@leu.com

Measurements taken:
- Ref. I: Maximum PTC power of 3.2 kW and 0.1 kW of fan power
- Comb. I: Same as Ref. I with an additional 0.2 kW radiation heating power
- Comb. II: PTC power of 2.4 kW, 0.1 kW fan power and 0.2 kW radiation heating power

Measurements recorded:
- Ref. I
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<tr>
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<tbody>
<tr>
<td>Feet</td>
<td>3.2</td>
<td>0</td>
<td>100</td>
<td>3.3</td>
</tr>
<tr>
<td>Ref. I</td>
<td>3.3</td>
<td>0</td>
<td>100</td>
<td>4.3</td>
</tr>
<tr>
<td>Comb. I</td>
<td>2.5</td>
<td>200</td>
<td>100</td>
<td>3.5</td>
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<tr>
<td>Comb. II</td>
<td>2.4</td>
<td>200</td>
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### UPCOMING EVENTS

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