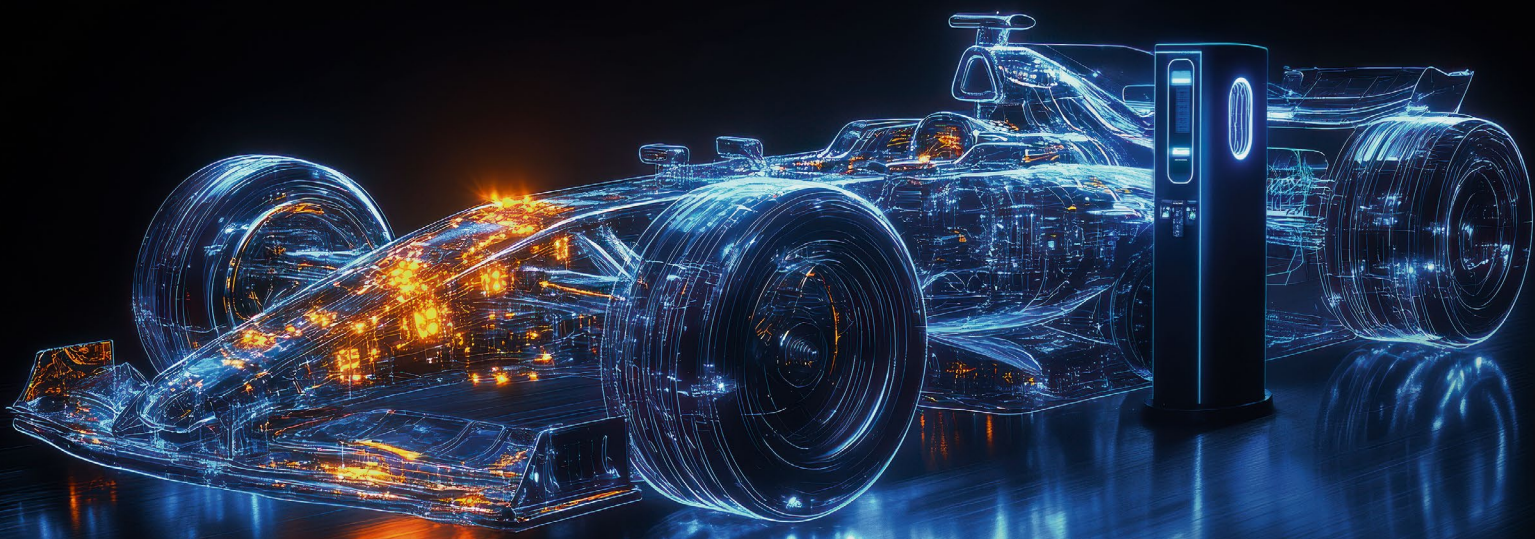


ATZ

06 June 2026 | Volume 21

electronics

Semiconductors | Electrification | Connectivity | IT



POWER ELECTRONICS

Speed up the Electrification

ATZextra
Electric Mobility

POWER SEMICONDUCTORS

Require Measures to Address
Negative Systemic Effects

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BATTERY CONCEPTS

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No Missing Pieces ...

Dear Reader,

The future of vehicles lies in real-time data, high-speed computers, and cooperative (AI) systems for connected mobility that extends beyond the individual vehicle. This requires an ever-increasing number of electronic assemblies and components for the highly specialized automotive sector. However, electronic chips are worthless without an ecosystem. In this context, the ecosystem for the semiconductor sector just alone means basic stuff like ingot production: quartz, cast as high-purity cylinders by a relatively small number of specialized companies. Among the top ten in monocrystalline silicon, three are from Taiwan, two from Japan, and one (former Wacker-)Siltronic is at least headquartered in Germany. If we want a stable European supply chain, a minimum level of manufacturing capacity must be available. In principle: check ✓.

Downside: Google states that 67 % of the silicon used comes from China, followed by Russia and Brazil. Thus check ✓ depends on the political climate of the day.

When it comes to packaging chips, SoCs, etc., there is significant capacity in Taiwan, Japan, South Korea plus China which European chip manufacturers also use, as this is currently the cheapest option despite the long transport distances. For Germany, a few companies do exist, such as PacTech, Raycics, and FhG IZM as development service provider. Meaning at least some capabilities are present. But you know: political climate. No check ✓.

Printed circuit boards (PCBs) form the basis of every electronic module. There's little to be found domestically here: less than 3 % of the world's PCBs are manufactured in Europe. Specialist suppliers like AT&S still hold their own with com-

plex multilayer or glass-core substrates. But if the PCB supply chain comes under pressure, this inevitably affects electronics manufacturers (EMS) and their customers. Semi-check ✓.

At the same time, the EMS landscape is highly fragmented in the D-A-CH region with over 600 companies: some major players like Zollner, TQ, or Rafi alongside many small companies with incredible know-how. Fail-safe electronics are essential, especially for automotive applications – SOTIF can not be achieved without this expertise. And this industry can deliver it, so absolutely check ✓.

Conclusion: The EU (and every other economic area) is right to focus on electronics with joint initiatives. But an industrial base is more than just 2-nm chip manufacturing. Materials, machinery, packaging, and assembly must also be taken into account. Without the entire value chain, even a semiconductor cluster remains limited in its effectiveness – like cars blocked in factory because of eventually missing door handles as last part of the puzzle.

Enjoy reading this issue!



Robert Unseld
Responsible Editor

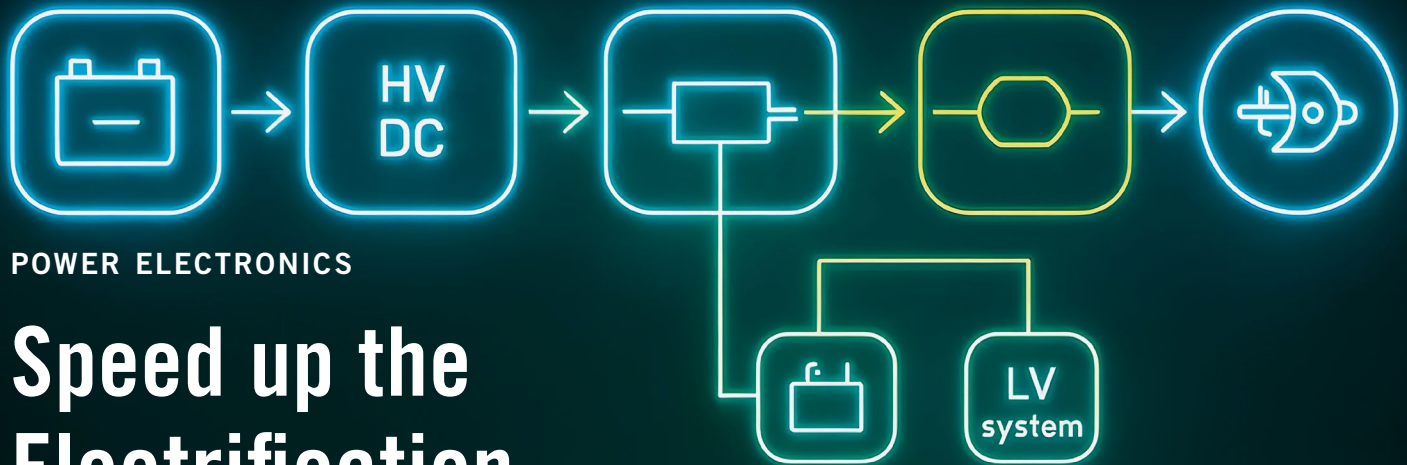


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POWER ELECTRONICS

Speed up the Electrification



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Power electronics form the backbone of modern energy and drive systems. Advanced power semiconductors increase efficiency, switching speed, and power density. Multi-domain simulation frameworks enable the comprehensive modeling of electrical, thermal, and mechanical interactions. In addition, high-voltage electrical system emulation enables realistic testing, accelerates development cycles, and reduces risks when designing future systems.

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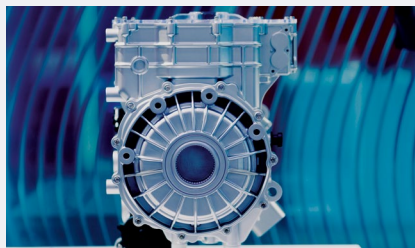
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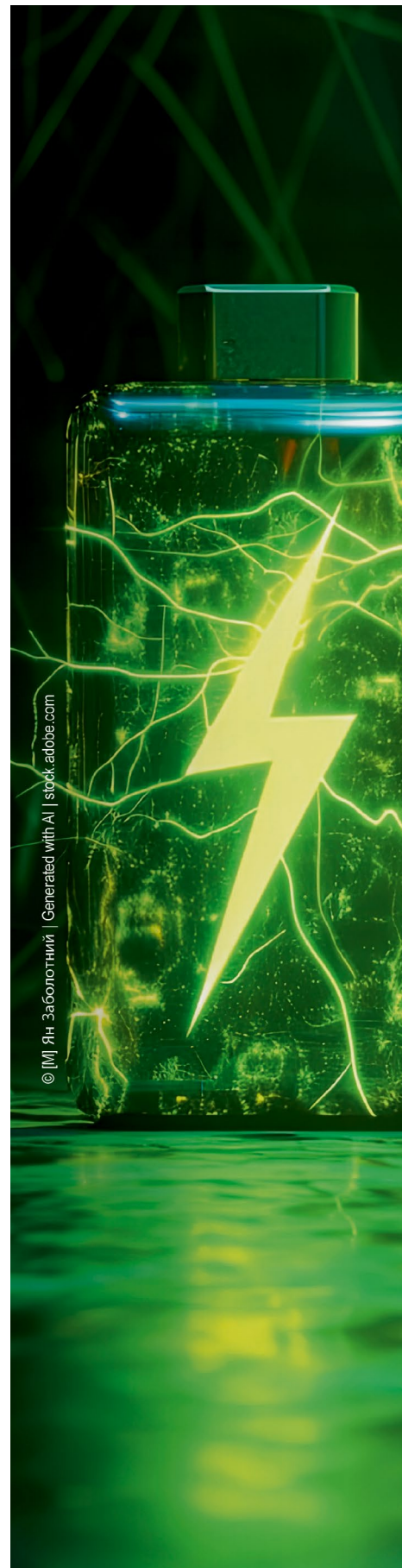


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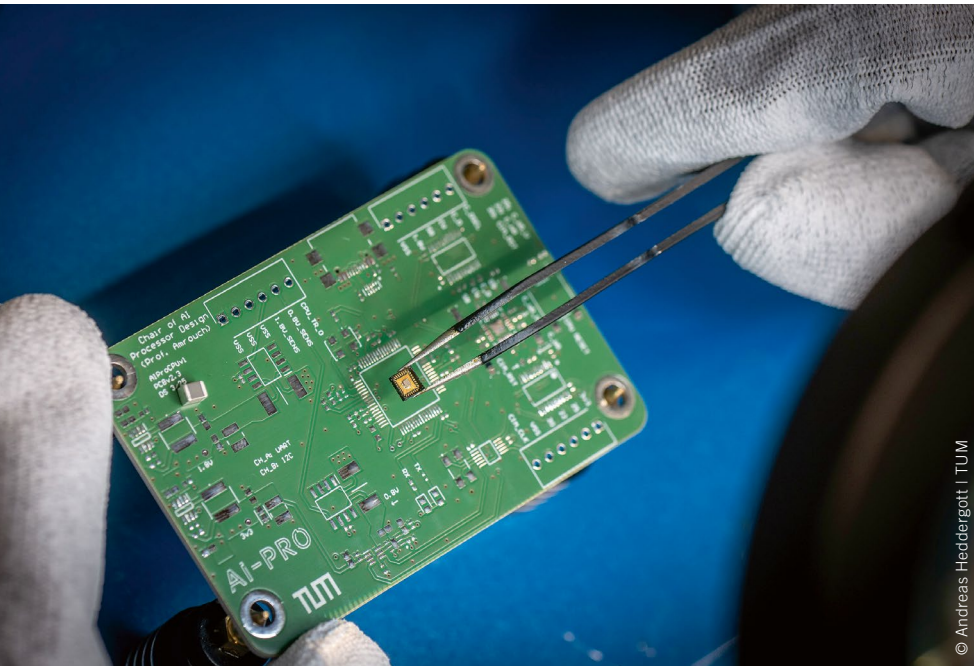
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[Arrow Electronics]



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Top News of the Month | TUM Builds AI Chip Using 7-nm Technology

The EU's first AI chip with modern 7-nanometer technology has been developed at TUM. It could be manufactured in Dresden starting in 2028.

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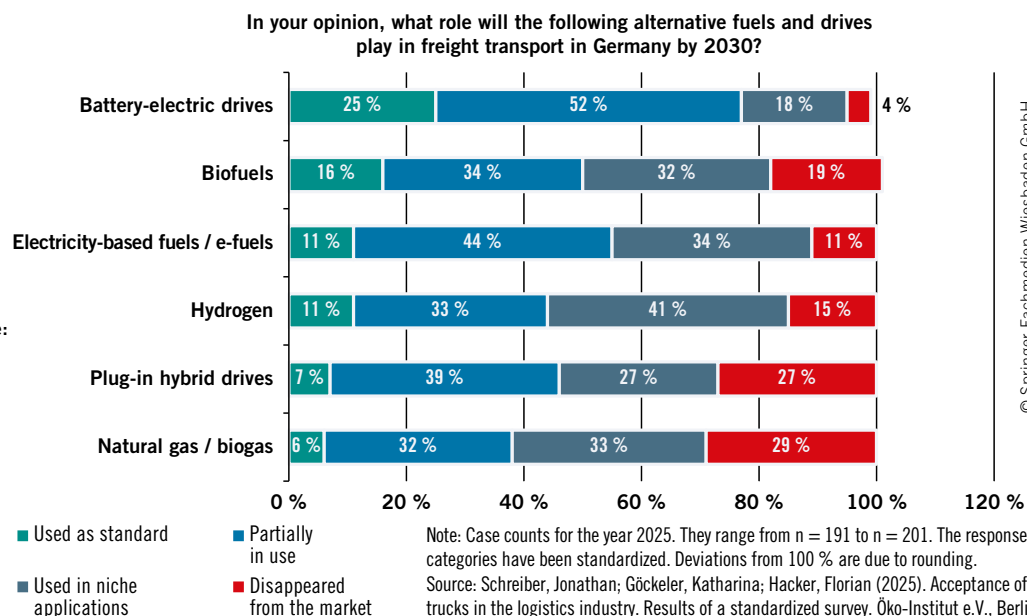
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Infographic of the Month | Acceptance of Electric Trucks in the Logistics Industry Is Growing

Among all alternative drives, the logistics industry sees battery-electric trucks as the future. However, gaps in knowledge continue to slow down market adoption. Hydrogen trucks have lost ground.

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Review | Plenty of Space and Fast Charging in the Kia EV3

With the EV3, Kia has entered the compact SUV segment. The electric vehicle, equipped with a 400-V system, impresses in many ways.



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In the Spotlight | How Physical AI Is Redefining Industry

AI is making its way into the real world: So-called Physical AI combines AI with physical systems such as self-driving cars. By 2030, this transformation is expected to open up a global market potential of around 430 billion euros.



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IMPULSES



Dr. Alexander Heintzel
Editor-in-Chief
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Game Changer

The 13th International Engine Congress held in late February 2026 once again yielded interesting and important insights. The keynote address by Shena Britzen (Rheinmetall) stood out in particular, as the strategy outlined there could have a significant impact on the future of propulsion systems. Due to the current and anticipated security situation, NATO forces in Europe must become more independent in terms of their energy supply. Military vehicle propulsion systems cannot be electrified, they rely on molecular fuels. Here, the EU's subjectively unidirectional approach clashes even more radically with reality than in the civilian sector. E-fuels therefore play a crucial role for obvious reasons.

Rheinmetall therefore aims to ensure the security of supply for European armed forces with its own e-fuels through the Giga PtX project and plans to establish a network of hundreds of decentralized production facilities for this purpose. Britzen's statement, "Building our own e-fuel capacities is a key component in strengthening our resilience," applies equally to the civilian sector. Giga PtX achieves cost minimization of the price per liter through economies of scale by "replicating many plants based on the same design." Europe could thus produce its own fuel. Fuel prices of less than 2 euros/l are therefore possible. The technology for this is mature and proven; the plans are ready to go. Britzen: "I am certain that the project will happen." It could be implemented across Europe within the next five to ten years.

In peacetime, the fuel produced in this way could be sold to meet civilian demand as well, which would also make sense for reasons of investment amortization. Demand from the defense sector could thus "trigger the industrial scaling that sustainable fuels have been waiting for for years." That would finally be a real game-changer for transportation's contribution to climate protection.



Forever and Ever

Per- and polyfluoroalkyl substances, better known as PFAS, are used in a large number of applications in automotive engineering. However, due to their unlimited life (“forever chemicals”) and their bioaccumulative properties, they pose risks to human health and the environment. Replacing all PFAS in the automotive industry seems like an unrealistic proposition at the moment. But substitutions are already possible in some applications today and research is being carried out in other areas.



igus offers a range of PFAS-tested materials

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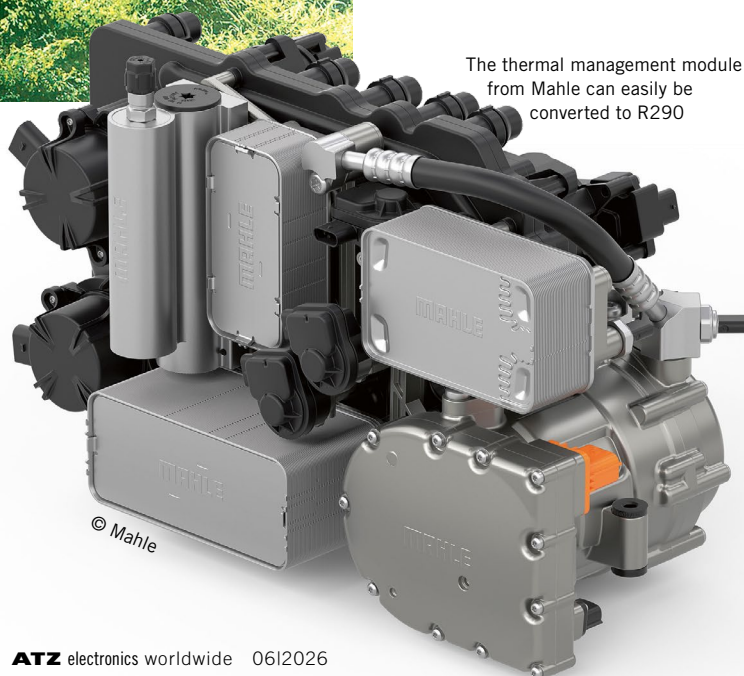
PFAS are a broad group of synthetic organic compounds that are used in numerous industrial applications. The history of PFAS goes back to the middle of the 20th century. The first fluorinated compounds were developed in the 1940s, when researchers were looking for materials with high chemical and thermal resistance for use in military and industrial applications. The discovery of polytetrafluoroethylene (PTFE, also known by the trade name Teflon) by DuPont in 1938 marked the beginning of the era of fluoropolymer chemistry [1]. Over the following decades, numerous PFAS derivatives were synthesized and these found their way into a wide range of technical products due to their surface

properties that repelled water, grease, and dirt. In the 1980s and 1990s, PFAS also became established as indispensable functional materials in high-performance applications, including the automotive, aerospace, and electronics industries [2].

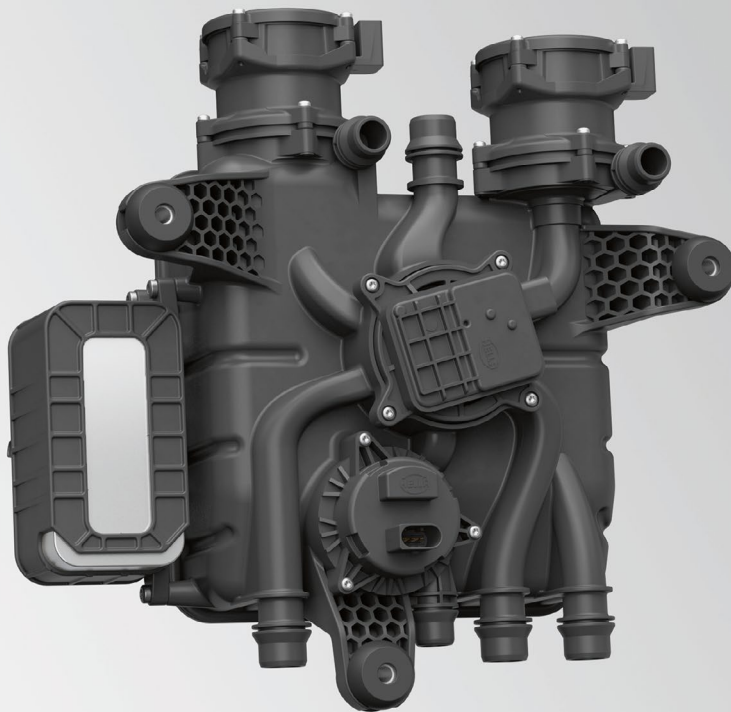
Due to their exceptional chemical stability, heat resistance, and low friction, PFAS are used particularly in those applications in which materials are exposed to extreme conditions and where conventional plastics would fail. One of the main applications in the automotive industry is elastomer seals that come into contact with aggressive media such as fuel, hydraulic fluid, or brake fluid. Fluorine rubber (FKM) and perfluoroelastomers (FFKM) have a high resistance even at temperatures above 200 °C and retain their elasticity under pressure and chemical stress. They are therefore used as sealing systems with a long service life in engines, transmissions, and exhaust systems. Fluoropolymers such as PTFE, perfluoroalkoxy polymers (PFA), and polyethylenetetrafluoroethylene (ETFE) are widely used in fuel and brake systems, hoses, coatings, and cable insulation. In fuel lines, for example, they act as a diffusion barrier for hydrocarbons.

In electric drive system components, materials containing PFAS are used for high-voltage insulation, as well as for applications such as seals for power modules and battery housings, as they have a high dielectric strength and high thermal stability. A further important area of application is surface and coating technology. Coatings that contain

The thermal management module from Mahle can easily be converted to R290



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© Forvia Hella

The Coolant Control Hub from Forvia Hella enables coolants such as R290 or R744 to be used

PFAS make components lipophobic and hydrophobic, in other words they repel oil and water. Examples include sensors, connectors, and mechanical components that need to be protected against dirt,

moisture, and corrosion. Fluorochemicals are also used in automotive textile components such as seat covers or headliners in order to provide dirt- and water-repellent properties. In addition, PFAS

can also improve energy efficiency, as lubricants that contain fluorinated additives, such as perfluorinated polyethers (PFPE), hardly change their viscosity across a wide temperature range, thus helping to minimize friction losses in bearings. These properties are particularly beneficial in electric and hybrid powertrains, in which thermal stability and low friction can have a positive effect on electric range and efficiency [3].

LIMITS TO SUBSTITUTION

For several decades now, the use of PFAS has been the focus of discussions regarding regulation and environmental protection. Due to their persistence, bioaccumulation potential, and toxicological effects, many PFAS compounds are referred to as “forever chemicals” – substances that hardly degrade in the environment and which can be detected throughout the world, even in remote regions such as the Arctic. Under the Stockholm Convention, perfluorooctanesulfonic acid (PFOS), perfluorooctanoic acid (PFOA), and perfluorohexanesulfonic acid (PFHxS) have been banned worldwide for several years now with certain exceptions, and therefore also in the EU. In addition, the EU has restricted the use of other PFAS compounds. From 2026, specific regulations will come into



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PFAS-free elastomer seals for battery modules (© Freudenberg Sealing Technologies)

force for certain PFAS in food packaging and cosmetics, for example. A more far-reaching proposal to restrict the use of all PFAS is currently being evaluated by the European Chemicals Agency (ECHA) [4]. At the moment, all indications suggest that a decision by the EU and a corresponding regulation are not to be expected before 2027 [5].

From a technical perspective, replacing PFAS poses a significant challenge and would have far-reaching consequences. Three German industrial associations, the VDA (representing the automotive industry), the ZVEI (the electrical and digital industry) and the VDMA (mechanical and plant engineering) even consider a general ban on PFAS to be a threat to the successful transformation of the energy sector. In a joint declaration in 2023, they stated that, without PFAS, the key technologies of the transformation to climate neutrality cannot be produced and thus the energy and mobility transition cannot be implemented. Their demand: substances for which there is currently no substitute and those that do not pose a risk to humans or the environment should continue to be available to industry. "In order to achieve the goal of climate-neutral mobility, the use of PFAS is and will remain indispensable. Without them, neither existing vehicles nor

future vehicle technologies are conceivable today – the planned blanket ban on PFAS threatens to become a climate protection boomerang. With a differentiated view of this huge group of substances, however, climate, environmental, and health protection can be brought together," said VDA President Hildegard Müller [6]. Studies by Freudenberg and the Thinktank IRS also show that the substitution of PFAS in the automotive industry is currently feasible only in individual cases [7, 8].

SUBSTITUTE MATERIALS FOR PFAS

Nevertheless, the industry is hard at work looking for materials that can replace PFAS. For example, air conditioning systems can be operated using CO₂ (R744) or propane (R290) instead of the current refrigerant R1234yf, which contains PFAS. Mahle and Forvia Hella are two of the companies that have presented such systems.

One product developed by Tenneco for PFAS-free plain bearings is Glycodur Neo featuring Glyco 692. Glyco 692 is a three-layer composite material consisting of a steel backing, an open-pore tin-bronze sintered matrix, and a thermoplastic-based sliding layer enriched with a filler combination. This structure offers a high level of mechanical and thermal

stability under both lubricated and dry running conditions. According to the manufacturer, other advantages include a high load capacity of up to 250 MPa (static) and 80 MPa (dynamic) and a broad operating temperature range of -50 to +260 °C. "Glyco 692 is the result of focused research and development aimed at delivering not only high-performance components, but also ones that align with evolving regulatory and environmental expectations," says Dr. Tobias Larem, Manager, R&D Material Development at Tenneco.

PTFE-free plastic plain bearings as an alternative to metal plain bearings are already being offered by the company Igus. Polymer bearings made of the material called Iglidur JPF are said to have friction and wear values that are similar to standard-series polymer plain bearings such as Iglidur J. "Since 2025, we have been able to realize around 75 % of plain-bearing applications without PTFE," explains Lars Butenschön, Head of the Iglidur Plain Bearing Technology Business Unit at Igus. The new bearing solutions were also tested for the 96 PFAS compounds considered critical for the environment and health, and they do not contain any of those substances in concentrations above 0.1 % by weight [9].

Freudenberg Sealing Technologies is offering an optimized sealing material



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Azar Mottale
Divisional Director Mobility
at ZVEI

2 QUESTIONS FOR...

What would a complete ban on PFAS in the EU mean for the European electronics industry?

MOTTALE _ PFAS combine a number of special properties and are currently indispensable for many high-tech products and processes. A comprehensive ban would massively weaken our industry. For example, it would no longer be possible to produce semiconductors in Europe. Components for power generation and transmission infrastructure would no longer be available or their development would be set back by decades. EU regulations should therefore be targeted solely at PFAS applications that have proven risks.

What implications would this have for automotive electronics and for the automotive industry as a whole?

MOTTALE _ Without PFAS, the speed of the transition to future technologies such as electric mobility and autonomous driving would fall significantly. Many components, from PCBs to cables and seals, could no longer be produced or used. Global supply chains would become weaker or would collapse altogether. Substitute materials, if they are available at all, would require a lengthy qualification process to ensure the functional safety, service life, and reliability of vehicles.

as an alternative to PFAS-containing thermoplastic and FKM seals for electric mobility applications. The new material series is processed by injection molding and is said to achieve a higher sealing performance than thermoplastics, as the elastomers react elastically and reversibly to deformation due to entropy elasticity. According to the manufacturer, the seals maintain their shape better during the cyclical volume change of the battery cells under load.

Researchers at the Fraunhofer Institute for Structural Durability and System Reliability (LBF) and the Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) are currently working on fluorine-free coated elastomers in their ongoing Hate-Fluor project. Fraunhofer LBF is concentrating on the development of high-performance elastomers as a substitute for fluoropolymers. One of the key strategies is improving the thermal and thermo-oxidative stability of the elastomers by using novel antioxidants. In addition, the focus is on developing application-opti-

mized elastomers that not only ensure maximum durability but also provide optimal adhesion for the subsequent surface treatment. Fraunhofer IFAM is also developing a coating system for the elastomers that protects the material from oxidative attack and chemical decomposition. Furthermore, it is working within the project on coatings for these elastomers to improve their friction reduction and barrier properties. A particular focus is on the development of polyimide coatings in combination with layered silicates that prevent the permeation of harmful gases and moisture. These coatings are used in particular for high-performance electronics and other demanding applications. In addition, the modification of the layered silicates is being investigated to reduce the permeation of water vapor and oxygen through the coating by up to 99 %. According to IFAM, the application of these coatings shows significantly reduced ageing and prevents dendrite growth as a result of exposure to harmful gases. The modular structure

of the system being developed within the Hate-Fluor project, which consists of paint and plasma coatings, is aimed at covering a broad spectrum in the section of fluorine-alternative seals. [10].

In their PureWaterSeal project, the Fraunhofer Institute for Laser Technology (ILT) and the Fraunhofer Institute for Mechanics of Materials (IWM) have developed special seals that are free from PFAS and suitable for water-based lubricants. To achieve this, the team developed Diamond-Like Carbon (DLC) coatings that are designed for PFAS-free plastic components. The combination of a PFAS-free coating and laser-based microstructuring allows the use of water-based lubricants. Fraunhofer ILT reports that the new development is particularly suitable for seals subject to high rotational speeds [11], such as those used in the automotive sector.

SUMMARY AND OUTLOOK

Due to their multifunctional properties, PFAS can currently be found in



Sealing ring made of a high-performance elastomer as a fluoropolymer substitute

almost all automotive subsystems, from powertrains and thermal management modules to electronics and safety systems, including interior and body components. Although research institutes and industrial companies are working on substitutes that use PFAS-free materials, replacing them poses a considerable technical challenge. Any further bans on PFAS should include exemptions, some of which could be for a limited time. At the same time, calls for recycling strategies that could help establish a PFAS circular economy are growing louder.

Richard Backhaus

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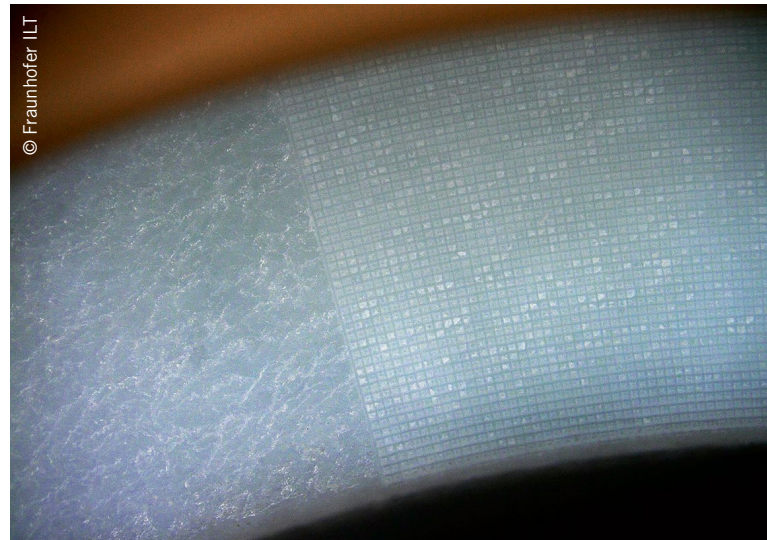
PTFE



Journal article: Johansson, P. et al.: Mechanisms behind the environmental sensitivity of carbon fiber reinforced polytetrafluoroethylene (PTFE) www.springerprofessional.de/en/link/26493860

Journal article: Tietz, D.: Sustainable Plain Bearings for the Automotive Industry www.springerprofessional.de/en/link/50692462

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The combination of a PFAS-free coating and laser-based microstructuring (right) allows the use of water-based lubricants

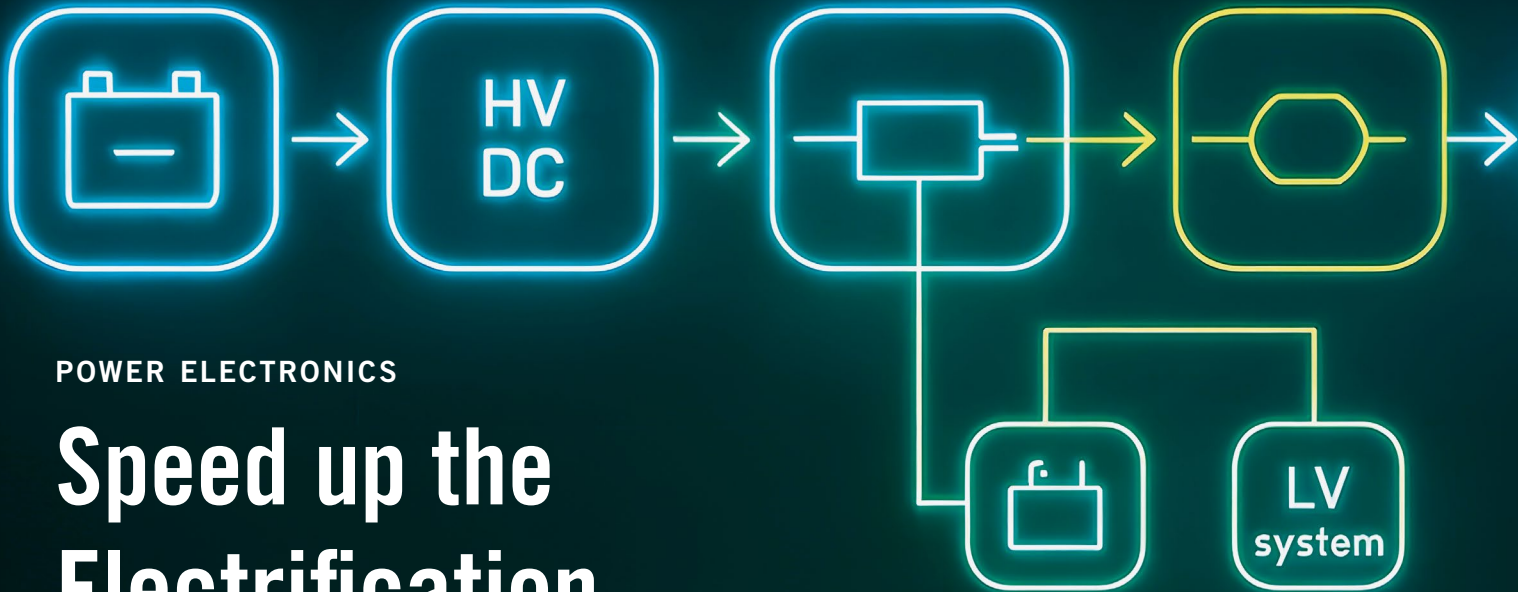


OPINION

“Regulations on PFAS are in the public interest, but fundamental change can only be achieved by an internationally coordinated campaign that involves the USA and China. Go-it-alone action by the EU will remain ineffective. That is true both for greenhouse gas emissions and bans on PFAS.”



Richard Backhaus
is Correspondent ATZ | MTZ | ATZelectronics.



POWER ELECTRONICS

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Developments in power semiconductors are driven by the growing demand for efficiency, power density, and reliability in electric mobility. Wide-bandgap technologies enable higher switching frequencies and lower losses but place greater demands on design in terms of EMC, leakage currents, and parasitic effects. Careful layout design, optimized gate drive, and tailored filtering and shielding concepts are crucial here.

In system architecture, the combination of SiC and IGBT is gaining importance. SiC devices offer advantages in terms of high switching frequencies and efficiency, while IGBTs excel in terms of cost and robustness in certain operating ranges. This involves functional and application-driven integration within power electronics.

Another important aspect is ensuring system reliability through comprehensive testing strategies. Network emulation is emerging as a key tool for simulating realistic operating conditions for traction inverters. It enables expanded test coverage, particularly for dynamic load profiles, fault scenarios, and boundary conditions. This allows development cycles to be shortened, risks to be identified early, and performance in real-world applications to be improved.

Overall, advances in power semiconductors demonstrate that a holistic interplay of components, design, system integration, and test methodology is required.

Alexander Heintzel



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Influence of Power Semiconductors on Vehicle and Environment

The integration of silicon carbide power semiconductors into the vehicle electrical system poses significant challenges at the vehicle level. Hitachi Energy highlights the key issues and outlines the measures needed to harness the benefits of silicon carbide power semiconductors without negative system effects.



WRITTEN BY



Tobias Keller

is Head of Global Product Management, Portfolio & Marketing at Hitachi Energy Semiconductors in Lenzburg (Switzerland).



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With the increasing electrification of the powertrain and the trend toward higher on-board network voltages, Silicon Carbide (SiC) power semiconductors are gaining significant importance in automotive applications. Their advantages in terms of efficiency, power density, and switching speed are

undisputed. At the same time, these very characteristics introduce new challenges at the system level, particularly with regard to Electromagnetic Compatibility (EMC), leakage and bearing currents, and insulation coordination. While conventional silicon systems based on Insulated-

Gate Bipolar Transistors (IGBTs) have exhibited comparatively well controlled EMC behavior over decades, the physical properties of SiC MOSFETs necessitate a fundamental rethinking of power electronic design, module concepts, and vehicle integration.

ALTERED EMC BEHAVIOR IN SiC SYSTEMS

The EMC challenges associated with SiC based systems can be directly derived from the specific material and device characteristics. Key features include extremely high switching speeds with correspondingly steep voltage and current slew rates, significantly reduced switching losses, higher permissible junction and operating temperatures, and comparatively low parasitic chip capacitances. While these properties contribute substantially to increased efficiency and power density, they simultaneously result in a pronounced increase in high frequency emission levels. Of particular concern are common mode disturbances caused by high dv/dt at the phase terminals, as well as differential mode disturbances arising from steep current transients. In addition, broadband emissions in the frequency range above several megahertz occur, which pose a greater challenge for compliance with vehicle specific EMC limits. In the automotive environment, characterized by long cable harnesses, complex grounding and bonding concepts, and a high density of sensitive electronic control units, these effects can quickly lead to limit violations. Early consideration of these interactions is therefore a prerequisite for robust EMC design of SiC based traction systems.

IMPACT ON INSULATION SYSTEMS AND LEAKAGE CURRENTS

A central issue in SiC based inverters is the increased electric field stress resulting from very steep voltage transitions. While conventional silicon based systems typically exhibit dv/dt values in the range of 5 to 10 $kV/\mu s$, values of 15 to 50 $kV/\mu s$ and beyond are not uncommon for SiC devices.

These high field gradients have a direct impact on capacitive coupling as well as creepage and leakage currents: Increased parasitic capacitance

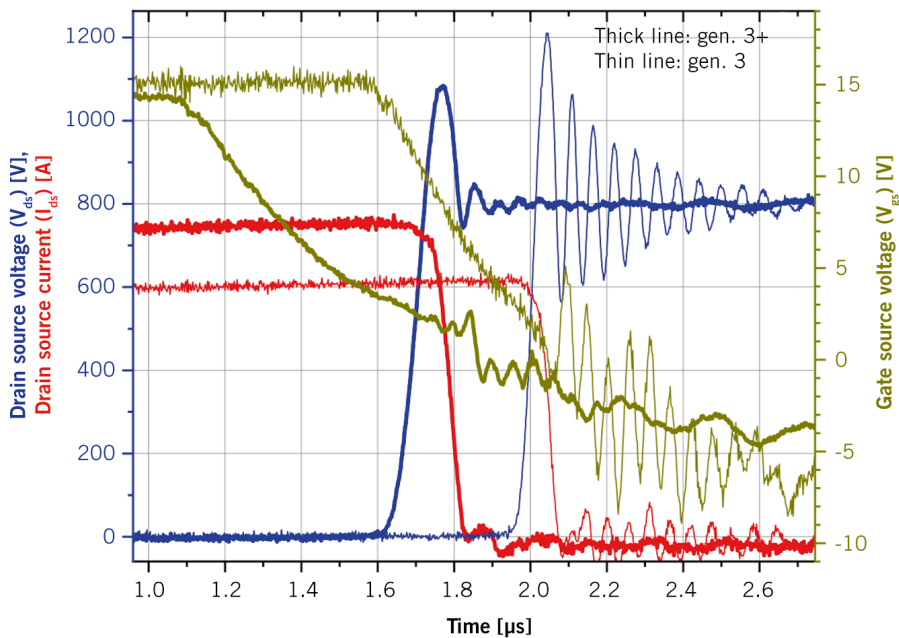


FIGURE 1 MOSFET turn off behavior of a SiC RoadPak with ten parallel chips per half bridge; generation 3 devices are unlimited, whereas generation 3+ devices include an integrated on chip gate resistor (the dv/dt exceeds 15 kV/ μ s) (© Hitachi Energy)

between power paths and the housing, as well as greater coupling in heat sinks, shields, and the vehicle chassis, result in an increase in high-frequency leakage currents. In addition, high dv/dt produces displacement current like effects that result in measurable currents even in the presence of intact galvanic isolation. Particularly affected are insulation materials within the power semiconductor module (for example epoxy mold compounds used for encapsulation or gels in gel filled modules), as well as DC link capacitors and motor windings, including associated bearing currents.

These currents are not primarily critical from a thermal or performance perspective; however, they can violate EMC limits, accelerate aging mechanisms, and trigger unintended responses in monitoring and protection systems. **FIGURE 1** shows the switching behavior of a converter SiC RoadPak from Hitachi.

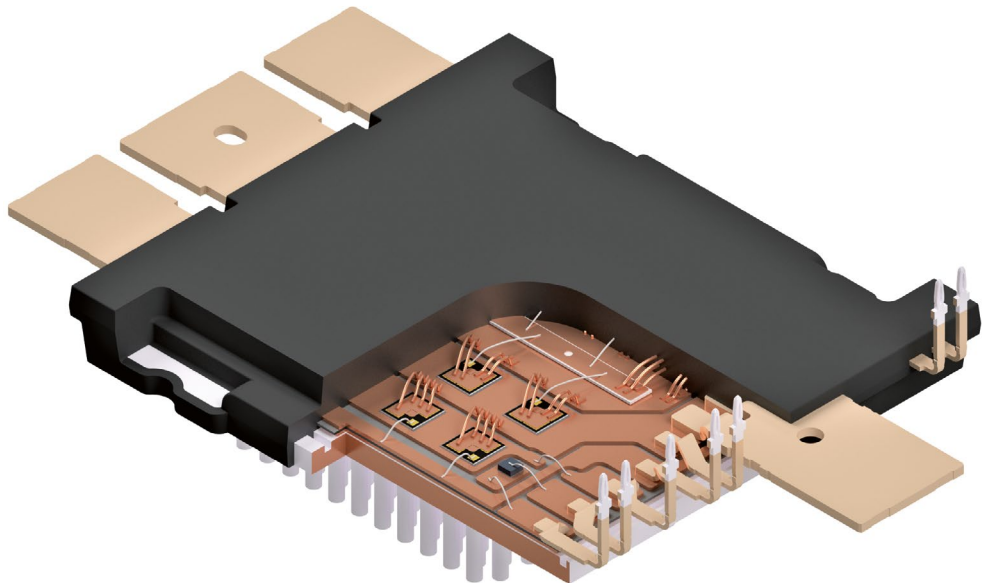
EFFECTS ON MOTOR AND PERIPHERAL COMPONENTS

The high slew rates generated by SiC inverters affect not only the power electronics but also the electric machine, particularly with respect to motor insulation and bearing currents. Regarding motor insulation, the higher voltage gradients increase stress on partial insulation systems. In particular, hairpin

motor windings experience elevated local electric field strengths, and partial discharges may occur at lower DC voltages than in conventional systems. With respect to bearing currents, increased common mode voltages promote capacitive bearing currents, raising the risk of electrical erosion and thus necessitating additional countermeasures such as insulated bearings or grounding brushes.

The risk of electrically induced bearing erosion was already a significant issue several decades ago during the introduction of IGBT inverters in railway traction systems. These problems were ultimately resolved through well defined shaft grounding concepts using capacitive grounding and grounding brushes or straps. Today, such solutions are sufficiently mature to prevent erosion even over service lifetimes of up to 40 years.

FIGURE 2 Open RoadPak module with optimized layout for low stray inductance of 5 nH at 1150 A (© Hitachi Energy)



IMPORTANCE OF POWER SEMI-CONDUCTOR MODULE DESIGN

A key lever for controlling EMC and leakage current issues lies within the power semiconductor module itself. Modern SiC modules differ fundamentally from conventional IGBT packages, as the high switching speeds and voltage slew rates impose significantly stricter requirements on internal electrical and geometric design. Critical design factors include minimized stray inductance to limit overshoot, as well as symmetrically arranged current paths to reduce common mode components. Furthermore, careful design of the internal capacitances between chip, substrate, and baseplate is essential, as these strongly influence common mode behavior. Controlled and well defined coupling to ground is also required to keep high frequency leakage currents manageable. An inadequately designed

module cannot be operated in an EMC compliant manner even with optimal gate control and will lead to increased system level stress. Conversely, a consistently optimized package concept allows high switching speeds to be maintained without destabilizing the overall system in terms of electromagnetic compatibility, insulation stress, and reliability, **FIGURE 2**.

GATE DRIVE AS KEY EMC ENABLER

Gate drive design becomes significantly more critical when applying SiC power semiconductors than in conventional silicon IGBT based systems. Whereas optimization of switching losses was the primary focus in the past, targeted control of voltage and current slew rates is now required to effectively limit EMC stress and component loading. Measures include separate gate resistors for turn on and turn off, multi stage gate driver

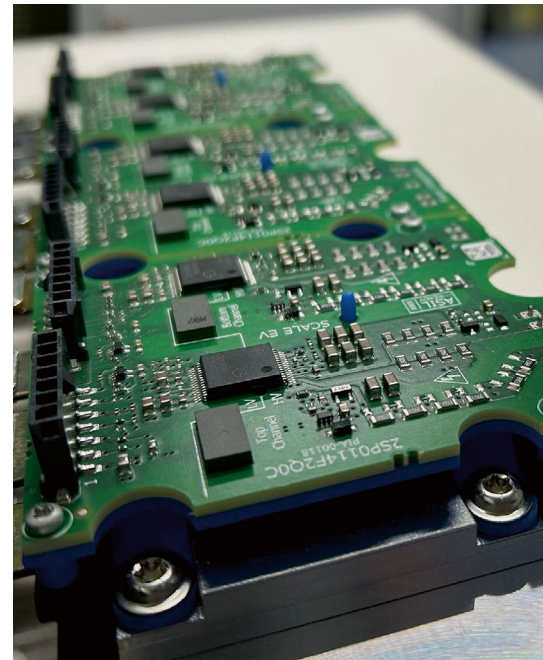


FIGURE 3 Optimized on top arrangement for RoadPak and gate unit (© Hitachi Energy)



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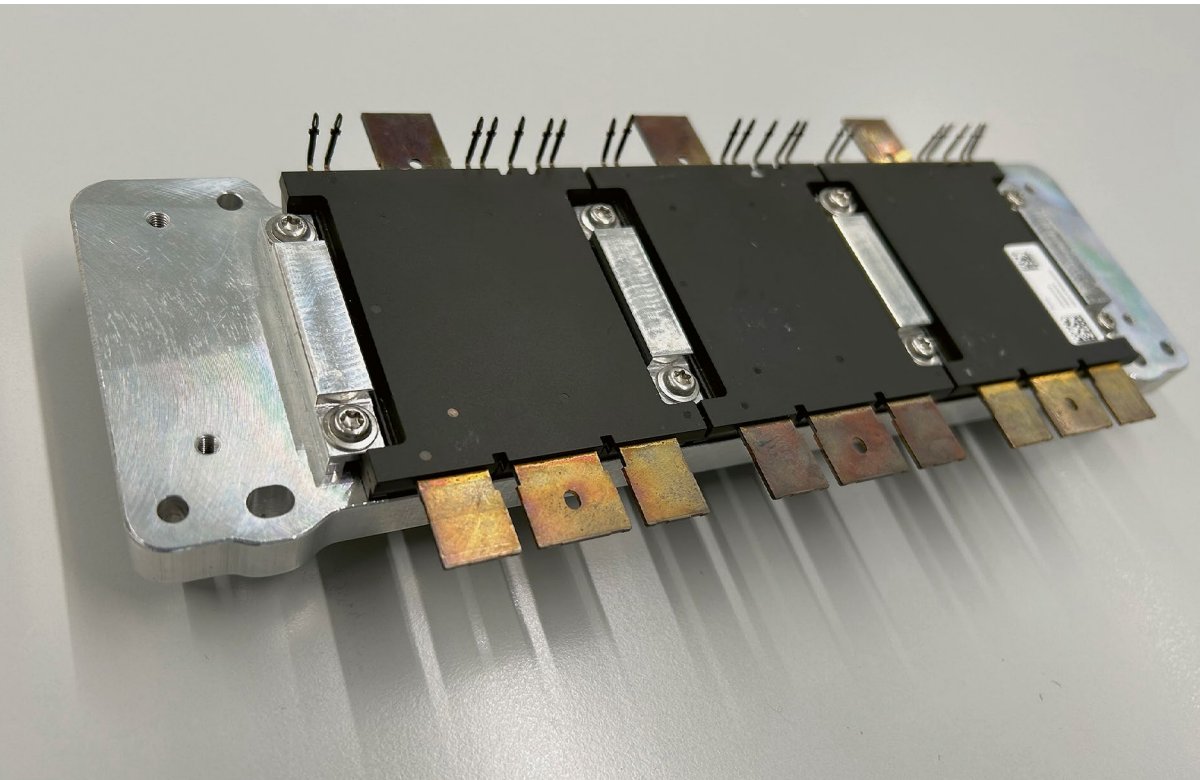


FIGURE 4 Optimized arrangement of three half bridges with heatsink and provision for laminated copper busbars (© Hitachi Energy)

concepts, so-called active Miller clamp circuits, and adapted gate voltage levels. The objective is not to maximize switching speed, but rather to establish a stable and reproducible operating point that represents a balanced compromise between efficiency, electromagnetic compatibility, and electrical and thermal device stress, **FIGURE 3**. This compromise is typically defined through extensive experimental investigations and detailed measurement campaigns under realistic system conditions.

SYSTEM LEVEL CONSIDERATIONS IN THE VEHICLE

A key difference compared with stationary applications lies in the tight functional and electrical coupling of all subsystems within the vehicle. Power electronics, the high voltage network, the vehicle body structure, and sensor systems form a highly integrated overall system in which electrical interference can propagate across multiple levels. For SiC based vehicles, this means that EMC considerations must not be addressed in isolation at the component level but must be integrated early into the over-

all development process. Cable routing, shielding concepts, and grounding architecture are integral elements of system design rather than downstream optimization steps. In addition, insulation concepts must be designed not only for static DC voltage but, in particular, for the high voltage slew rates occurring in operation. This system level perspective becomes increasingly important in 800-V architectures and future vehicle platforms with even higher voltage levels. **FIGURE 4** shows an example of how SiC power semiconductors are adapted to meet automotive requirements.

CONCLUSION AND OUTLOOK

SiC power semiconductors enable substantial efficiency and performance gains in electrified vehicles and contribute significantly to increased power density and reduced drivetrain energy losses. However, the introduction of this technology shifts the primary technical challenges from predominantly thermal and loss related aspects toward electromagnetic compatibility, insulation coordination, and system level interactions

within the vehicle. The high switching speeds and voltage slew rates of SiC devices lead to increased electromagnetic emissions, enhanced capacitive coupling, and pronounced creepage and leakage current effects that must be addressed at both component and vehicle level. Reliable deployment of SiC technology therefore requires a deep understanding of the underlying physical mechanisms and a consistent optimization of module and package concepts.

Appropriate gate drive design plays a central role, as it strongly influences dv/dt and di/dt behavior and thus contributes decisively to controlling EMC and insulation stress. In addition, a holistic vehicle level approach is essential, in which power electronics, on-board network, electric machine, cabling, and grounding are designed as a tightly coupled overall system. Future developments, such as improved insulation materials, integrated EMC structures at module level, and further optimized chip topologies, will help to unlock the full potential of SiC power semiconductors without compromising reliability or electromagnetic compatibility.

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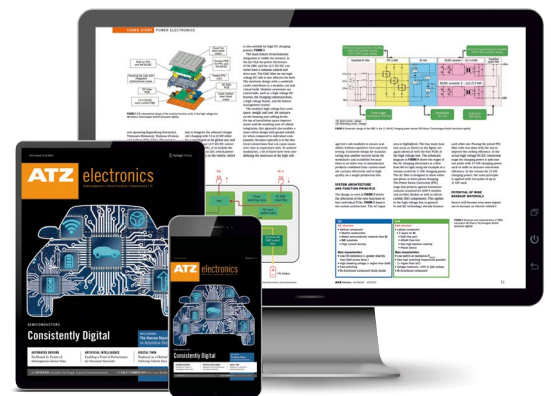
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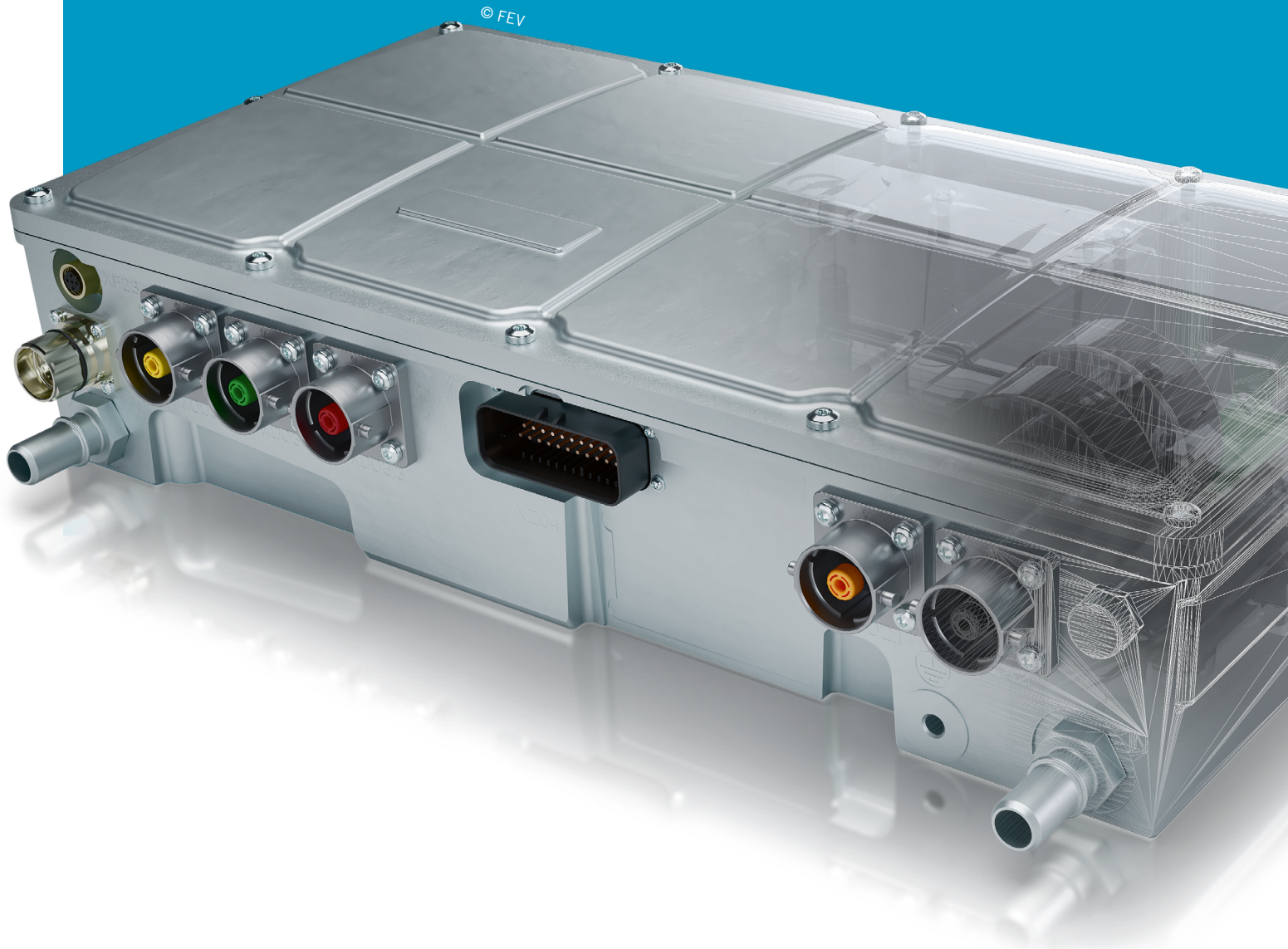
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The transition toward high-voltage electrified powertrains has created a technological environment in which traction inverters must operate across wider voltage, current, and switching-frequency ranges than ever before. Modern battery-electric vehicles increasingly adopt 800 V or higher system voltages to reduce current, improve charging performance, and enable higher continuous power operation. However, these advancements amplify engineering constraints on semiconductor devices, demanding innovations in switching materials,

gate driving strategies, control algorithms and inverter topology selection.

Simultaneously, OEMs face multifaceted challenges: achieving higher system efficiency, lowering semiconductor and cooling-system costs, ensuring electromagnetic compatibility, and mitigating thermal stresses. As physical prototyping becomes more expensive and time-consuming, simulation-driven development is essential. FEV's multi-domain framework addresses this need by providing a unified workflow capable of analyzing inverter behavior from the semiconductor physics level up to vehicle-level en-

ergy usage. It integrates benchmark databases containing representative OEM vehicle- and powertrain parameters, enabling meaningful real-world scenario simulation, **FIGURE 1**.

METHODOLOGY OF THE SIMULATION FRAMEWORK

The framework is composed of interconnected simulation layers that exchange data to form a coherent and realistic representation of inverter and drivetrain behavior. At the foundation lies a 0D vehicle simulation that

Integrated Multi-domain Simulation Framework

As voltage levels in BEV platforms increase, inverters must become more efficient, reduce losses, and be thermally optimized without compromising cost or usability. FEV presents a simulation framework that holistically evaluates system voltage, switching technologies, and topologies. Through coupled vehicle, component, and loss simulations, it enables in-depth analyses at the full-vehicle level.

determines mechanical load conditions for the electric machine across a selectable drive cycle which could be either a standardized homologation cycle or a user configured test case/scenario (such as repeated 0-100 km/h full load accelerations or a specific test track profile) or a fully composed program in order to enable the analysis of the vehicle or the powertrain under reproducible conditions. The resulting operating conditions (such as torque and speed profiles) are extracted and transferred into a 2D finite-element e-machine model, enabling accurate calculation of copper losses, iron losses, flux linkages and determining an optimal d- and q-axis current operating-strategy.

The inverter subsystem employs a 1D physics-based switching-loss model that incorporates semiconductor-level conduction behavior, turn-on and turn-off energies, and reverse-recovery effects. Temperature dependencies, switching-frequency constraints and modulation strategies are reflected through integration with MathWorks

Simscape and FEV's Powertrain Designer. This multi-domain interoperability ensures consistency of component behavior across mechanical, electrical, and thermal dimensions while maintaining computational efficiency.

FIGURE 2 shows one of the many configuration options of the tool chain. In the example shown, existing vehicle data, electric machine parameters and test bench results were used to investigate the impact of different inverter switching types on the efficiency and therefore the range of a particular application [3].

SEMICONDUCTOR TECHNOLOGIES AND TOPOLOGIES

The framework supports a comprehensive evaluation of semiconductor technologies. While Silicon (Si) devices, traditionally used in traction inverters, offer cost advantages but suffer from high switching losses at elevated voltages. Silicon carbide (SiC) devices provide superior high-voltage performance,

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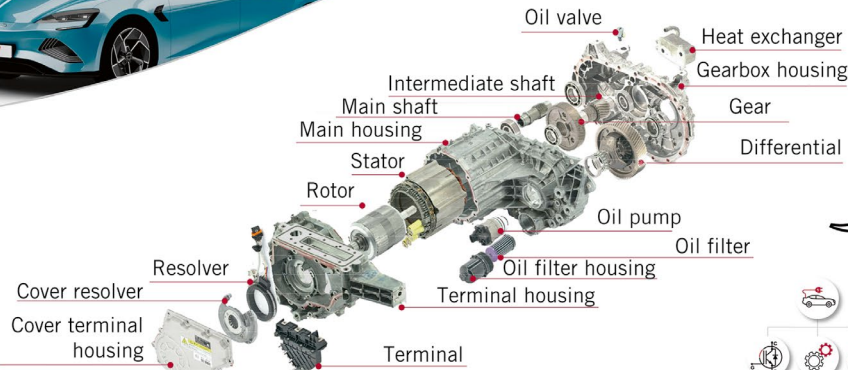


Dipl.-Ing. (FH) Dave Werry is Team Leader at FEV Europe GmbH in Aachen (Germany).



Dr.-Ing. Annegret Wörndle is Department Manager at FEV Europe GmbH in Aachen (Germany).

Global benchmark database



Powertrain Designer Tool



FIGURE 1 Collaboration between FEV's benchmark database and Powertrain Designer Tool (© FEV)

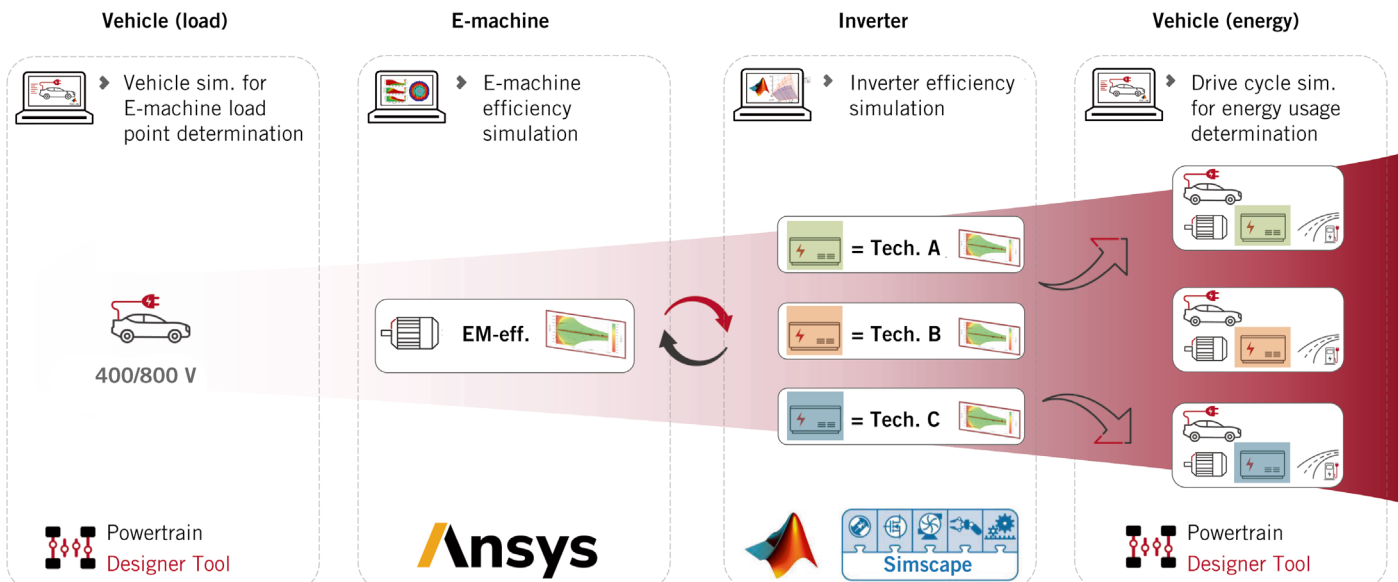
reduced switching losses, reduced conduction loss under partial load, and improved thermal characteristics, making them a preferred choice for modern 800 to 1000 V systems. Gallium nitride (GaN) devices exhibit an extremely low conduction resistance and excellent high-frequency switching capability, but challenges include limited current and voltage capability, high input capacitance and susceptibility to parasitic turn-on, **FIGURE 3**. Hybrid fusion

modules combine Si and SiC dies to achieve up to 70 % partial-load efficiency improvements at a reduced SiC semiconductor area.

As electric powertrains transition to higher system voltage levels, the range of suitable power semiconductor devices narrows, making it increasingly challenging to achieve the same magnitude of efficiency improvements previously enabled by hybrid Si/SiC fusion switch technologies used in

400 V applications. Moreover, when considering the overall energy balance of the vehicle, inverter losses constitute only a relatively small portion of total powertrain losses compared to those originating from the electric machine, gearbox and vehicle-level mechanical and aerodynamic effects. Consequently, while efficiency optimization remains important, cost optimization becomes an equally critical factor in determining the most appropriate inverter design

FIGURE 2 Multi-domain toolchain for automotive traction inverters analysis (© FEV)



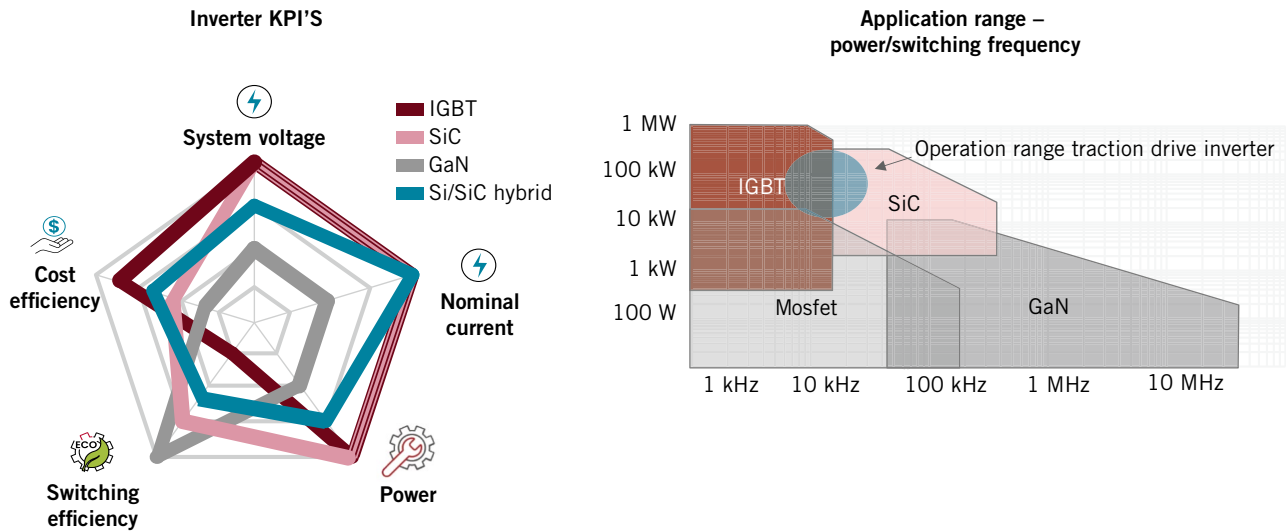


FIGURE 3 Automotive traction inverter KPI's and application range (© FEV)

strategy for next generation high voltage traction systems [2].

To expand the design space and enable the use of a wider range of semiconductor switch technologies, each offering distinct performance characteristics and tradeoffs, conventional two-level inverter topologies are increasingly being replaced by multilevel converter architectures, which inherently provide additional degrees of freedom in device selection and system optimization.

To expand the design space and enable the use of a wider range of semiconductor switch technologies, each offering distinct performance characteristics and tradeoffs, conventional two-level inverter topologies are increasingly

being replaced by multilevel converter architectures. Among these, the Active Neutral Point Clamped (ANPC) and T-Type Neutral Point Clamped (TNPC) topologies have emerged as particularly promising candidates for high voltage traction applications.

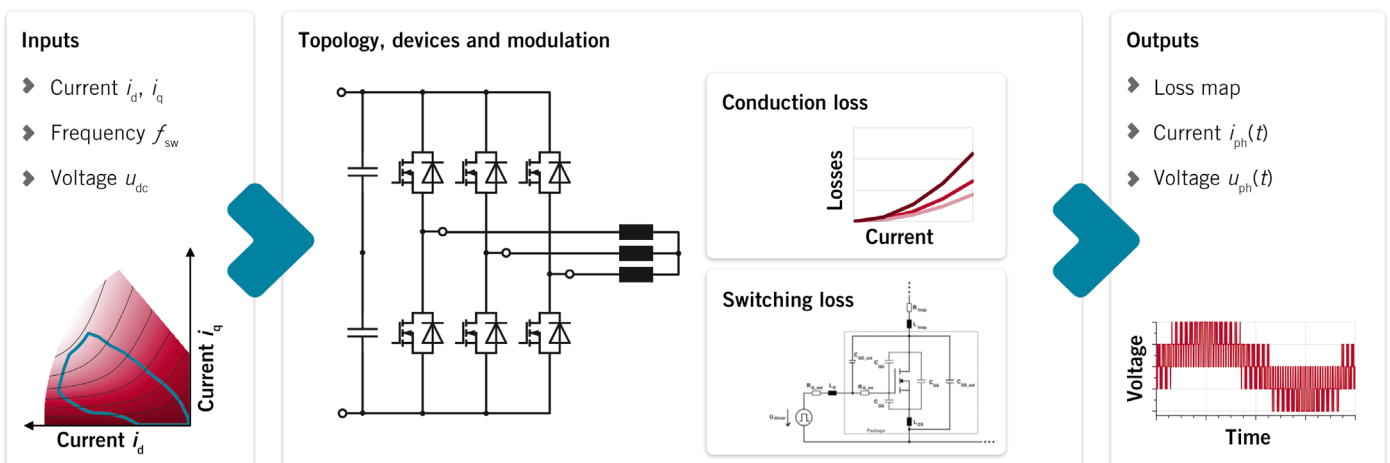
The ANPC structure provides enhanced flexibility in distributing semiconductor stress and allows the integration of hybrid switch configurations (such as combinations of Si, SiC, and GaN devices), thereby improving efficiency and thermal performance across a wide operating range. Similarly, the TNPC topology, characterized by reduced device count and optimized current paths, offers high partial load efficiency and

improved waveform quality at elevated DC link voltages. These characteristics make both ANPC and TNPC attractive, cost-effective multilevel solutions for next generation electric powertrain [1].

INVERTER MODELLING APPROACH

FEV's in-house inverter simulation tool provides a highly accurate and computationally efficient framework for assessing inverter behavior under real-world operating conditions. The model structure is shown in **FIGURE 4**. The model uses the electric drive control parameters d- and q- current references, switching frequency and DC-link voltage as direct inputs, enabling seamless inte-

FIGURE 4 Visualization of inverter modelling approach (© FEV)



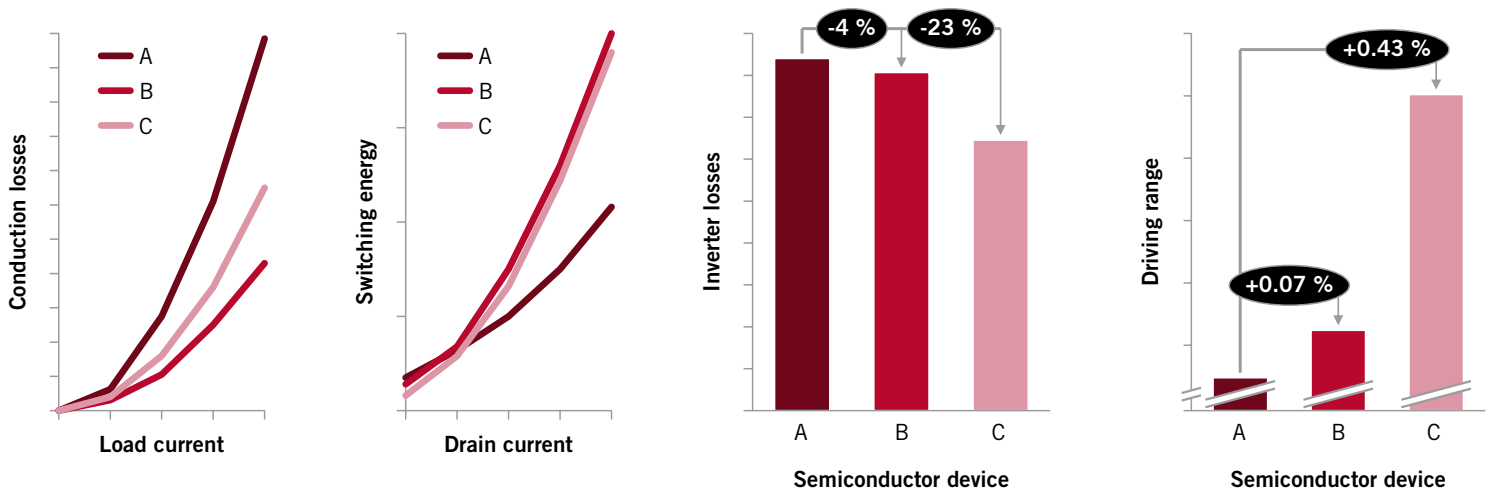


FIGURE 5 Exemplary inverter simulation results (© FEV)

gration with standard electric-drive development workflows.

A key strength of the tool is its ability to represent a broad range of inverter topologies, including conventional two-level inverters as well as advanced multi-level architectures. In addition, the simulation environment supports multiple semiconductor technologies. This flexibility allows precise comparison and optimization of different inverter configurations at an early development stage. The model calculates both conduction and switching losses with high fidelity. For switching losses in particular, the tool offers an advanced capability to model the dynamic switching behavior based on the parasitic elements of the semiconductor device. This enables a realistic representation of transient effects and switching-energy dependencies across a wide operating range.

As output, the simulation provides an operating-point-dependent loss map, supporting the evaluation of system efficiency under various load conditions. Furthermore, the tool generates the detailed current and voltage waveforms required for downstream electric-machine investigation such as loss calculations or noise vibration harshness (NVH) analysis. Modelling the inverter in the context of the surrounding system enables a more effective analysis of mutual interactions, such as considering the own inverter engineering choices, the control algorithms and the electric machine design, ensuring these effects are considered in an early concept phase. This holistic

approach significantly enhances the accuracy and reliability of virtual prototyping in the development process of electrified powertrains.

SIMULATION EXAMPLE

FIGURE 5 shows exemplary simulation results of three different semiconductor devices. The vehicle reference is an Audi SQ6 e-tron, a state-of-the-art premium segment car. The electric machine is simulated based on benchmark data and test bench measurements. The presented simulation results are the inverter conduction loss and the switching energy as function of rms phase current, the total inverter loss over one WLTP cycle and the resulting range improvement.

Switch A has the highest conduction losses while shows less losses during switching, especially at higher currents. Switch B shows minimal conduction losses while switch C is performing mostly between A and B. Nevertheless, in the driving cycle simulation, switch C presents lowest overall losses which results in the highest driving range.

CONCLUSION AND OUTLOOK

FEV's integrated simulation framework provides a powerful methodology for analyzing semiconductor devices and inverter configurations in full system context. By linking semiconductor switching behavior with drivetrain and vehicle-level simu-

lations, engineers obtain a realistic understanding of efficiency trade-offs, cost implications, and performance impacts. Future development directions will incorporate advanced thermal modeling, EMI-aware switching optimization, expanded evaluation of >1000 V systems, enabling further advancements in sustainable e-mobility engineering.

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THANKS

The authors would like to thank their colleagues Dr. Christoph Neuhaus, Paul Kämpken und Marco Korr.



Spotlight on Powertrain and Vehicle Engineering

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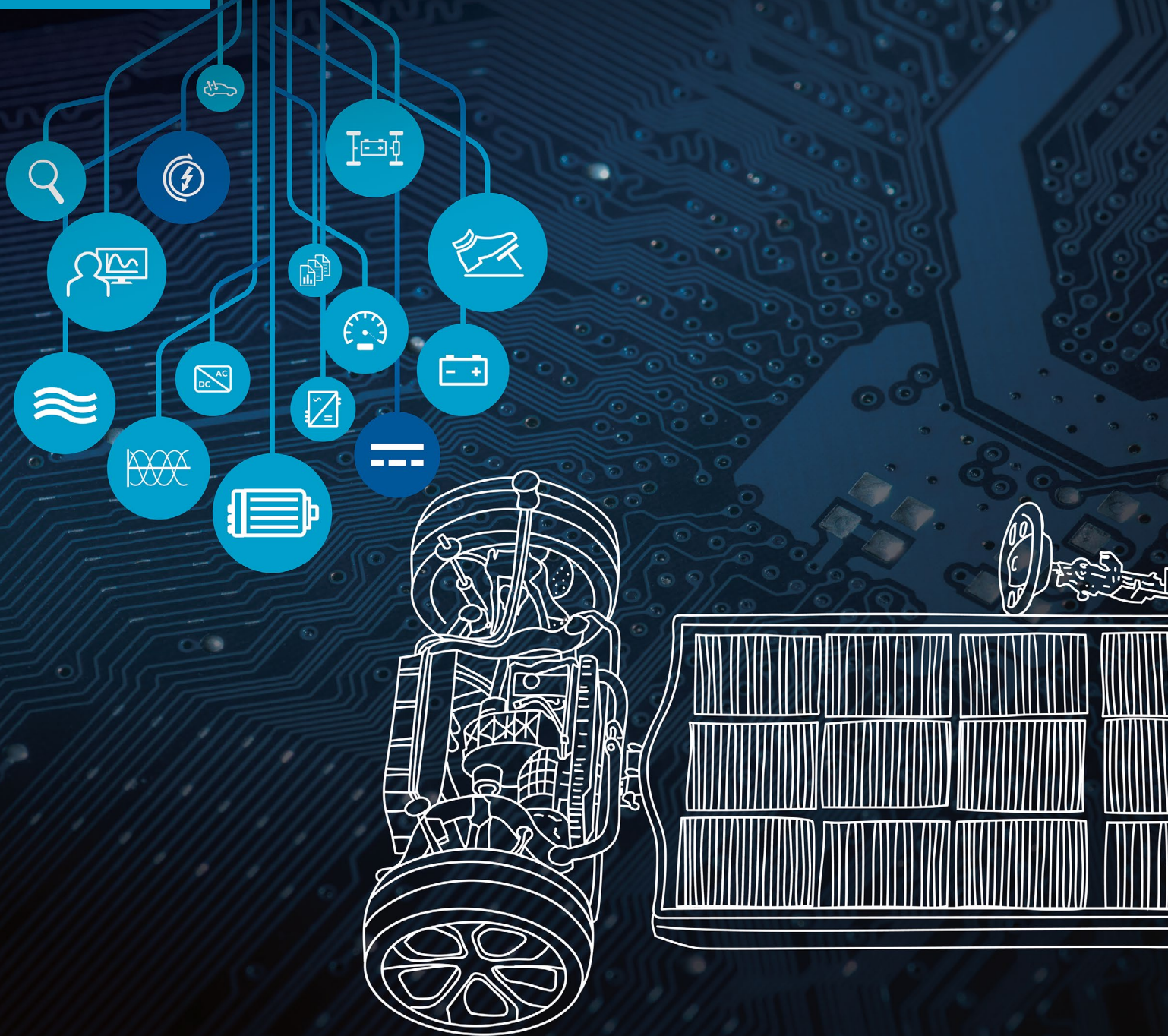
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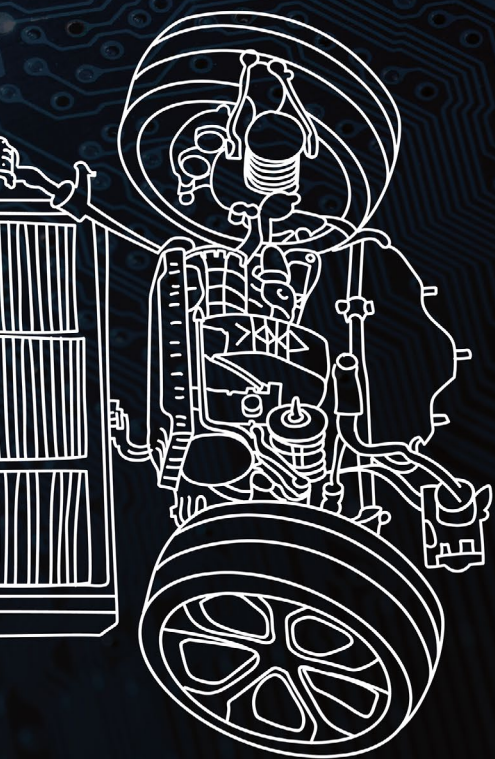
is industrial PhD student at AVL SET GmbH in Wangen im Allgäu (Germany) in cooperation with the Institute of Powertrain and Automotive Technology (IFA) at Technical University of Vienna (Austria).

Electrical systems of today's electric vehicles consist of a wide variety of components, not just the battery, inverter, and electric motor. Since these components are connected to the same High-Voltage (HV) bus, interactions occur between them which can lead to undesired effects such as voltage ripple, resonances, or the overloading of individual components. Such effects are often detected very late in the development process – typically during system integration tests on vehicle level.

Modern traction inverter testing is conducted using Power-Hardware-in-the-Loop (P-HiL) systems [1], where the inverter is integrated into a test system based on emulation technology. On the Direct Current (DC) side, battery behavior is dynamically reproduced, while on the Alternating Current (AC) side, the behavior of an electric machine is emulated with high dynamics [2]. Compared to conventional test benches, this approach offers several advantages, such as reduced

HV Electrical System Emulation for Testing Inverters for Electric Drives

Vehicles from the early phase of today's electric mobility use simple high-voltage systems with a single drive unit, charger, battery, and voltage converter. However, modern vehicles integrate numerous additional high-voltage consumers such as up to four drive units, power steering, heating systems, as well as intelligent charging solutions, and other components. The increasing complexity raises the testing requirements for components and test systems. AVL SET demonstrates how these can be addressed in traction inverters through HV electrical system emulation.



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setup and testing times, since thermally induced cooldown phases are eliminated. In addition, the influence of environmental conditions such as temperature and humidity is reduced, improving the reproducibility of test runs. Another major advantage is the absence of rotating components, which significantly reduces hazards and lowers the safety requirements for the test setup. Furthermore, P-HiL systems enable increased test coverage through efficient reproduction of

varying operating states, load profiles, and fault scenarios. Integrated protection functions – such as shutdowns in the event of overcurrent, overvoltage, or overpower – contribute to protection of the device under test and operational safety.

In modern P-HiL-based inverter test systems, such as the inverter test system AVL InverterTS, numerous machine- and system-relevant effects are emulated on the AC side of the inverter. These include nonlinear effects such as magnetic core saturation and the appearance of harmonics. System-relevant effects include phase breaks, phase short circuits, and rotor-position-sensor faults. Through model-based reproduction of these effects, it is possible to test the traction inverter as a single component

under highly realistic operating conditions. This allows targeted analysis and optimization of inverter behavior and enables the fine-tuning of control algorithms, including optimization of the system efficiency.

For a holistic and realistic evaluation of the traction inverter, it is necessary to fully reproduce not only the AC side but also the dynamic behavior of the DC side. For this purpose, the previous battery emulation at the DC terminals is to be replaced by a comprehensive emulation of the vehicle's entire HV electrical system. The implementation relies on a real-time capable full simulation of the electrical vehicle system, coupled with power electronics. The expanded test system is shown in **FIGURE 1**. By incorporating measurement signals

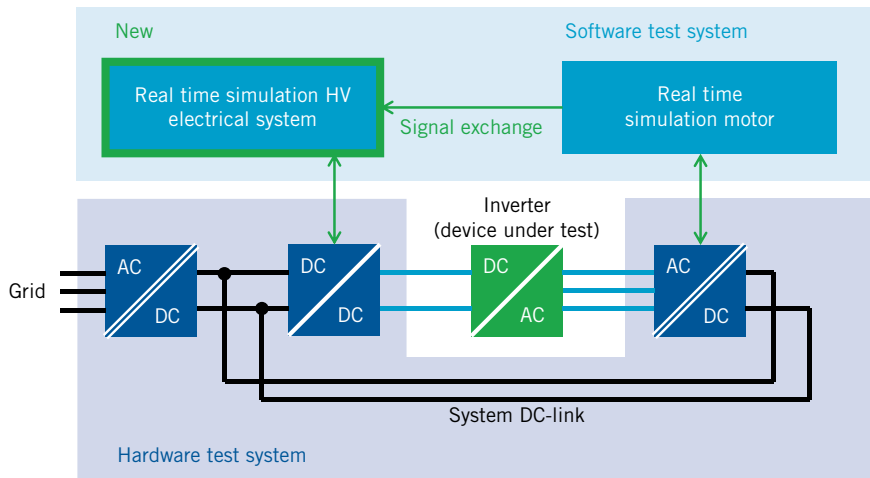


FIGURE 1 Inverter test system AVL InverterTS, expanded by HV electrical system emulation (© AVL)

such as voltages, currents, rotor position, as well as internal computational variables, the device under test can be operated and optimized within its complete electrical system context. This makes it possible to identify critical operating points and systemic interactions already in early development phases. Based on these insights, potentially problematic operating states can either be avoided or mitigated through targeted adjustments to operating and control strategies, significantly increasing system robustness and reliability.

MODELING OF HV ELECTRICAL SYSTEMS

Due to the high variety of HV electrical system configurations found in electric vehicles, the development of numerous parameterizable sub-models is required. These are combined into an overall model of the vehicle-side HV electrical system.

The complete system includes motor models of different machine topologies (induction machines, permanent magnet synchronous machines, and externally excited synchronous machines), models of various inverter topologies (two-level and three-level inverters), as well as a range of battery models. In addition, component models for HV cables, DC-link capacitors, filters, on-board chargers, and DC/DC converters are developed.

Since real-time capability is the primary requirement for the models, highly dynamic effects are implemented on the real-time computing platform of AVL SET. These effects are represented on an Field Programmable Gate Array (FPGA) basis with extremely short model time steps, while slower dynamics are offloaded to other computing units. The real-time simulation operates with simulation steps between 40 and 320 ns to accurately reproduce even transient effects. The voltage ripple

computed in simulation is intended to be actively controlled at the DC terminals of the inverter using a highly dynamic controller combined with power electronics.

The implementation of the sub-models is described in more detail in [3], along with the corresponding mathematical and physical formulations. A brief explanation of the sub-models is provided in the following sections.

The HV-battery model is based on an electrical equivalent circuit that offers simple parameterization and high computational efficiency. The model shown in **FIGURE 2** (a) can be applied at both the cell and pack levels and reproduces dynamic effects in the time domain ranging from microseconds to several seconds with sufficient accuracy. Slow effects, such as the dependence of open-circuit voltage on the state of charge, can be calculated externally and fed into the model as needed. As shown in **FIGURE 2** (b), HV cables and DC-link capacitors are combined into a single model because their coupled behavior corresponds to a second-order low-pass characteristic. While high-frequency voltage ripple above a certain cutoff frequency is damped, resonance phenomena with local peaks may occur near the natural frequency. Correctly dimensioning the combination of HV cabling and DC-link capacitors is therefore important for system design.

To model the hardware of two-level inverters, the classical B6 bridge topology with six active switches is used, as illustrated in **FIGURE 2** (c). The hardware model is coupled with the inverter software, including control structure, variable switching frequency, and different modulation methods. This enables realistic reproduction of operational behavior and ensures that the

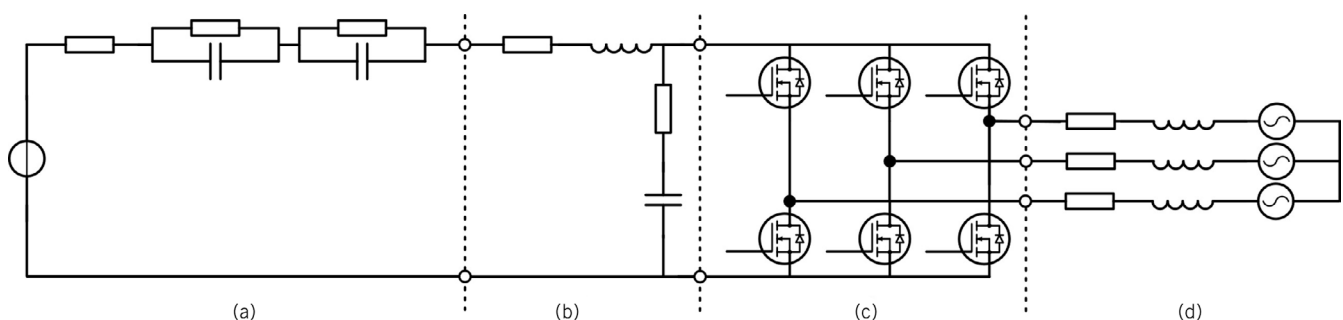
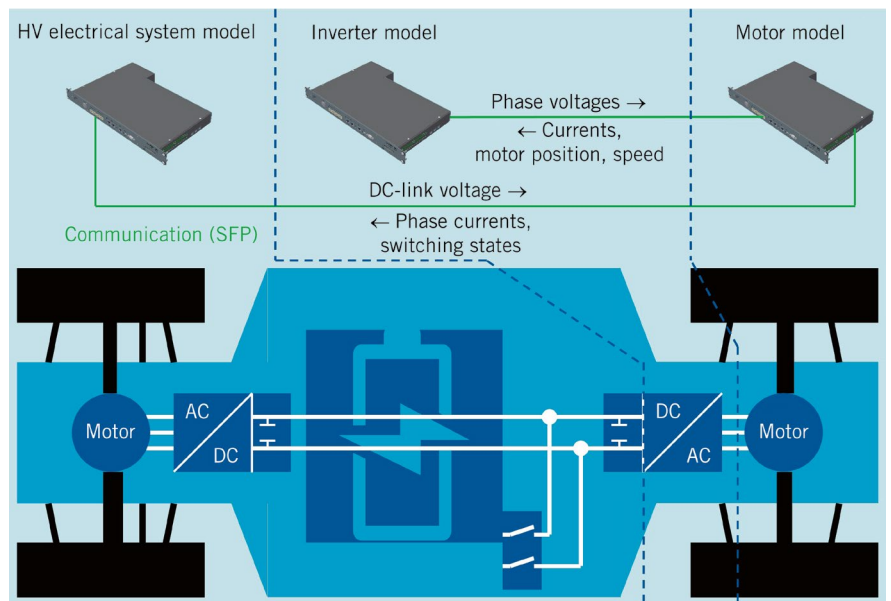


FIGURE 2 Component models of an electric drive train: HV battery (a), HV cables and DC-link capacitors (b), inverters (c), and motor (d) (© AVL)

FIGURE 3 HV electrical system of the example vehicle and distribution for HiL simulation (© AVL)



models can be applied universally across different applications.

The computation of the electrical machine models and the motor control is typically carried out in the d/q coordinate system. By applying Clarke and Park transformations, the time-dependent alternating quantities of the three-phase system are converted into quasi-stationary DC quantities [4]. This reduces the complexity of mathematical representation and simplifies current control. In **FIGURE 2** (d), the machine is shown as a three-phase system.

A key input variable for HV electrical system emulation is the bridge-input current of the real inverter, which can be calculated from the switching states of the inverter and the phase currents. For this reason, the model boundary is placed between the DC-link capacitor and the inverter power stage, enabling computation of the bridge-input current.

RESULTS OF THE REAL-TIME SIMULATION

The HV electrical system simulation is currently in the development phase, with the project scheduled for completion by the end of 2027. At present, several real-time-capable motor models of different topologies, as well as battery, inverter, and DC-link models, have been implemented. A simplified vehicle model for driving operation has been realized on a HiL system to verify the

real-time capability of the models. This model includes an HV battery and two electric drive units with permanent-magnet synchronous machines and the corresponding HV cabling, as shown in **FIGURE 3**. The selected drivetrain topology corresponds to an architecture commonly used in all-wheel-drive vehicles.

The simulation of the HV electrical system, including one drive unit, is executed on a real-time computing platform, while the inverter under test is offloaded to a separate computing platform. The emulation of the electric machine is implemented on a third computing platform. This modular distribution of components

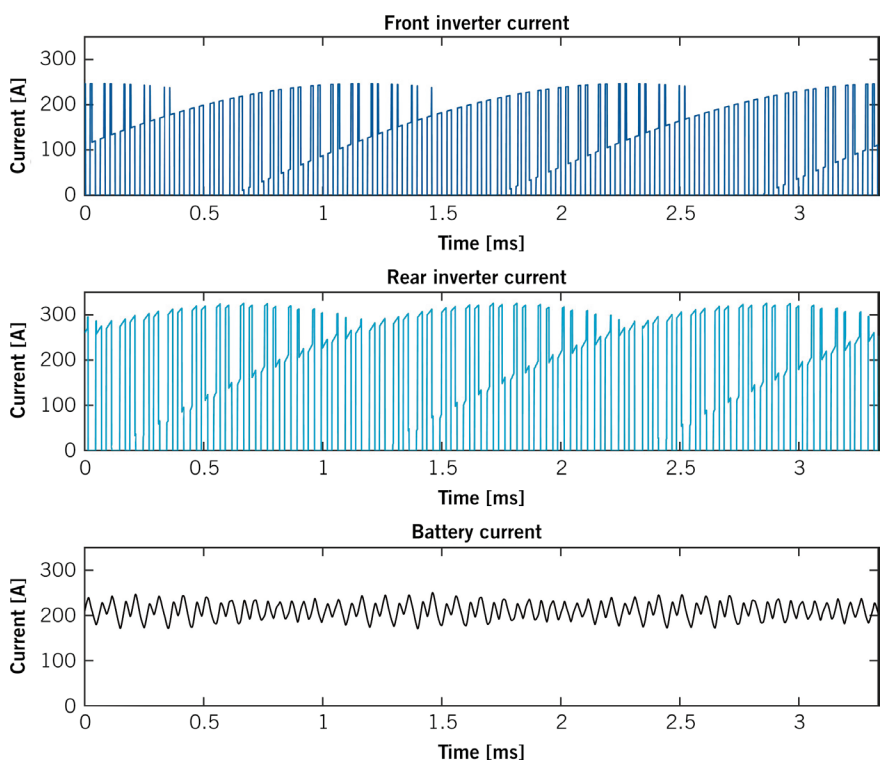


FIGURE 4 Currents from real-time HiL simulation (© AVL)

is chosen to allow later integration of the software components into various sub-systems of the AVL InverterTS. The simulation architecture and the exchanged signals are shown in **FIGURE 3**.

In the following, exemplary measurement results of the HiL setup are presented for a defined operating point. The currents and voltages at the bridge inputs of the inverters and at the battery terminals were recorded. The results in **FIGURE 4** show ripple-like bridge-input currents. The battery current is strongly damped by the HV cables and DC-link capacitors. **FIGURE 5** shows ripple-affected voltages at the DC input of the inverters as well as at the battery, which are caused by the bridge-input currents.

NEXT STEPS

In the next step, the software is to be transferred from the HiL system to the AVL InverterTS. The voltages simulated in real time, as shown in **FIGURE 5**, are to be actively controlled at the DC terminals of a real inverter. Building on this, investigations into control dynamics will be carried out to enable highly dynamic control of the DC-voltage ripple. The required dynamic performance criteria will be derived, and the feasibility of the concept will be evaluated. In parallel, an extension of the component models and the implementation of a complex drivetrain with different motor topologies and additional HV components is planned. Furthermore, an investigation of alternative inverter topologies, such as so-called open-winding concepts, will be conducted.

APPLICATION EXAMPLES OF HV ELECTRICAL SYSTEM EMULATION

HV electrical system emulation enables early evaluation of the electrical behavior of the HV system during the development process. Attention is given to the current load of DC-link capacitors and the analysis of voltage ripple at the high-voltage battery. High capacitor currents can significantly reduce the lifetime of DC-link capacitors, while pronounced voltage ripple at the battery can accelerate its degradation. After identifying critical operating points, targeted optimizations can be implemented, for example, through appropriate sizing of

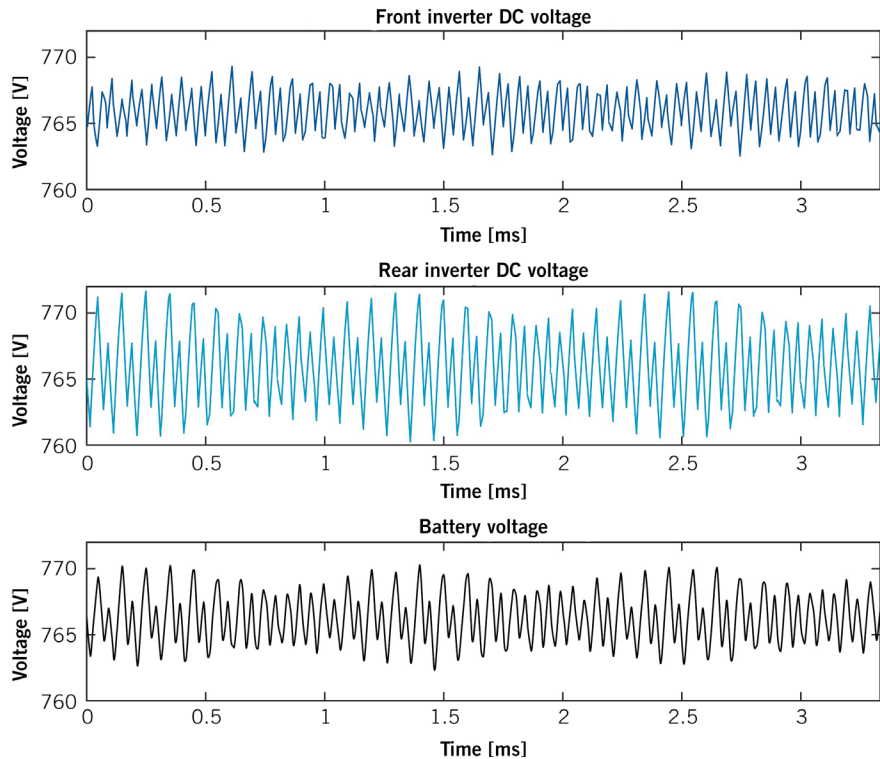


FIGURE 5 Voltages from real-time HiL simulation (© AVL)

DC-link capacitors, selecting suitable switching frequencies, or synchronizing multiple inverters to reduce interactions within the HV system.

A central goal of the developed method is the ability to test the same traction inverter across different vehicle architectures and drivetrain topologies. Automobile manufacturers are increasingly relying on modular platform strategies to use identical components across multiple vehicle platforms. By using the AVL InverterTS in combination with full emulation of the HV system, these diverse application scenarios can be tested realistically without requiring physical prototypes of all vehicle variants. This reduces vehicle-level testing effort, shortens development cycles, and enables significant cost and time savings – a key factor in improving competitiveness in a dynamic market environment.

SUMMARY

By extending the AVL InverterTS with comprehensive electrical system emulation, testing can be shifted to early development phases. This allows operating strategies, control parameters, and sys-

tem design to be optimized at an early stage, while potential integration issues can be reliably detected and avoided.

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THANKS

The author would like to thank Isabella Knauder, Zora Hansmann, and Patrick Winzer, all AVL SET GmbH, for their support in the creation of this contribution.

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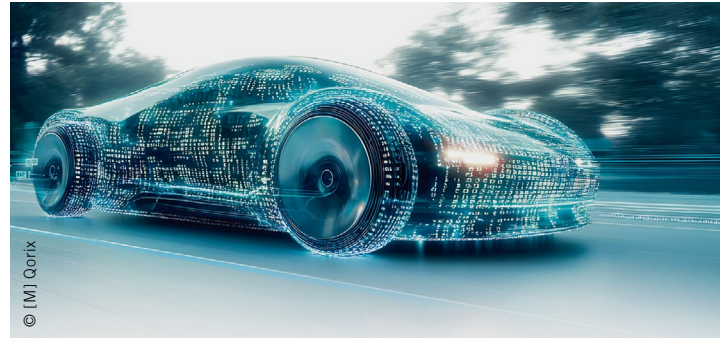
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Qorix | RN | Partnership in India

Qorix has entered into a sales partnership with RN Embedded Solutions from India, which will act as an authorized partner to distribute the middleware portfolio in India. Qorix is already active in the country with its own teams and is expanding its access to the local automotive sector through this cooperation. The portfolio includes AUTOSAR Classic and Adaptive, the proprietary Performance Stack, and the Developer with AI capabilities. RN Embedded Solutions will handle marketing, sales, and support and has close relationships with OEMs and Tier 1 suppliers. Both partners initially plan to target automotive applications and later expand into other industries. The agreement is seen as the first step in a broader partnership strategy in India.



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Stellantis | Microsoft | Collaboration on Digital Transformation



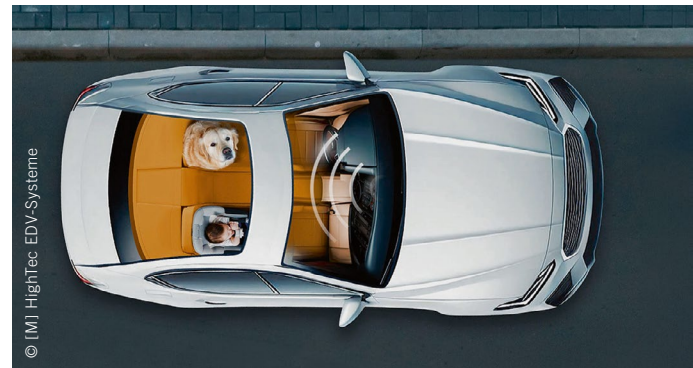
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Stellantis and Microsoft have agreed to a five-year collaboration to expand AI, cybersecurity, and engineering capabilities for the automotive company's digital transformation. The partnership aims to combine Microsoft's cloud, AI, and security capabilities with Stellantis' technical expertise to accelerate digital processes across the entire ecosystem. More than

100 AI initiatives are planned, including product-related validation, predictive maintenance, and faster rollout of digital services. In addition, an AI-powered global cyber defense center will be established to secure IT systems, connected vehicles, production facilities, and digital products, and to enhance the ability to respond to threats.

HighTec | Novelic | System for Interior Monitoring

HighTec EDV-Systeme supports Novelic's ACAM solution – a radar-based system for interior monitoring – with its development platform. The technology is designed to detect the presence and movement of occupants and enable manufacturers to meet upcoming Euro NCAP requirements for detecting the presence of children. The 2026 protocol requires that children up to six years of age be detected within 15 s of locking the vehicle and that graduated warning signals be triggered upon detection. The company uses the HighTec C/C++ compiler for Infineon Aurix TC3x for software development. ACAM also offers functions such as seat occupancy detection as well as intrusion and proximity warnings.



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Aumovio | Sale of Mechelen Site



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Aumovio plans to sell its production site in Mechelen to the Dumarey Group. The agreement stipulates that customer contracts will remain with the company, while the buyer will take over the plant and employees and continue operations. Component manufacturing is to continue at the site for a limited time, while the buyer plans to introduce new products and activities for other industrial sectors. Dumarey intends to gradually shift production to other plants within its network. The Mechelen site was founded in 1971, employs around 300 people, and manufactures solenoid valves, hydraulic and electronic control units, and wheel speed sensors for the automotive sector.

AT&S | Use of Glass Core Substrates

AT&S is driving the development of glass core substrates for industrial applications in the fields of artificial intelligence, high-performance computing, high-speed communication, and photonics. Glass is a promising alternative to conventional substrate materials because it remains flat, reduces electrical losses, and enables high-precision structures. Glass core substrates form the stable carrier layer of a chip package, on which fine copper structures are located that supply power and transmit data between the processor, memory, and the rest of the system. One advantage is the ability to integrate optical connections directly into the chip package, which allows for the transmission of enormous amounts of data with minimal latency and low energy consumption.



© Julia Trampusch | AT&S

Gentex | Antolin | Cooperation on Dimmable Sun Visors

Gentex and Antolin have agreed to collaborate on the development of dimmable sun visors for the European automotive sector. Gentex is combining electrochromic glass with the interior expertise of its partner Antolin to provide an advanced visor. The system is designed to

replace the conventional, opaque visor with transparent glass that can be darkened automatically or manually. This is intended to reduce glare without restricting the driver's view. In this way, traffic, signals, and signs remain visible, enabling a safer driving experience.



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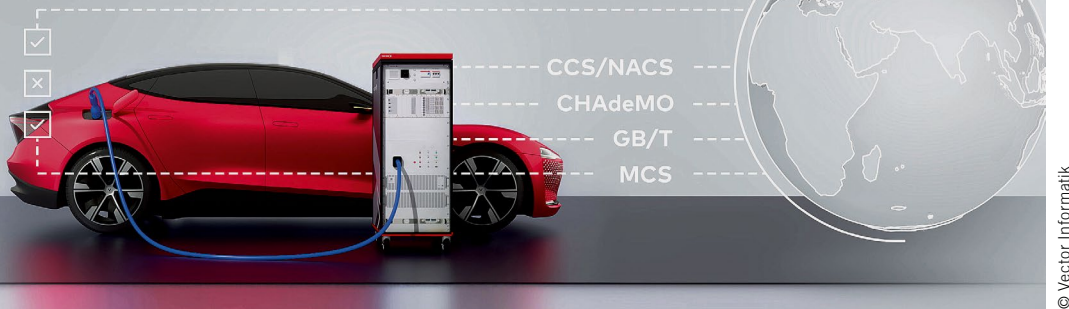
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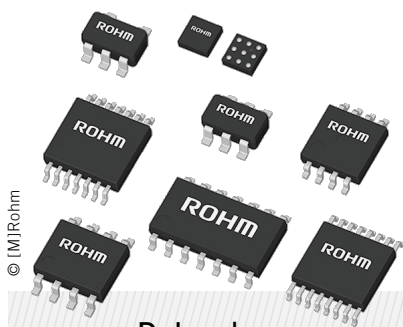


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Vector Informatik | Security Testing for Charging Communication

Vector Elektronik has expanded its CANoe Test Package EV to include security functions for charging communication. The expansion is intended to enable manufacturers and suppliers to identify vulnerabilities in implementations early on and to address regulatory requirements. Given increasing connectivity and requirements from ISO 15118 as well as TLS-based procedures, automated verification is gaining importance, as manual tests are often time-consuming and

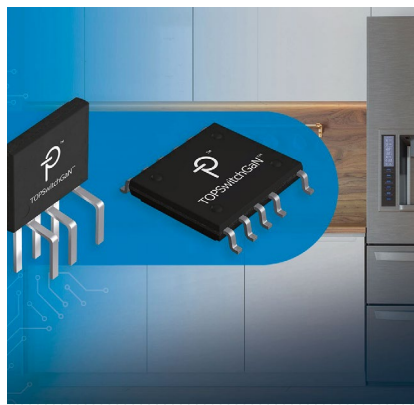
difficult to reproduce. The package offers automated testing, systematic documentation, and integration into development processes. The feature set includes V2G fuzzing, TLS fuzzing, protocol testing, and customer-specific tests. Support is provided for ISO 15118-2, ISO 15118-20, TLS 1.2, and TLS 1.3. The solution is continuously being expanded and is designed to address security aspects early in the development process.



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Rohm | 17 New OpAmps

Rohm has introduced 17 CMOS operational amplifiers from the TLRx728 and BD728x series, which are suitable for applications in the automotive, industrial, and consumer systems sectors. According to the manufacturer, the products are characterized by low input offset voltage, low noise, and high slew rate. The TLRx728 has an input offset voltage of 150 μV (typ.), while the BD728x offers 1.6 mV (typ.). Both series have a noise voltage density of 12 nV/ $\sqrt{\text{Hz}}$ at 1 kHz and a slew rate of 10 V/ μs . They are therefore suitable for a wide range of precision applications, including sensor signal processing, current sensing circuits, motor controls, and power supply monitoring systems. The rail-to-rail input/output capability enables maximum utilization of the supply voltage range and ensures a wide dynamic range.



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Power Integrations | Flyback IC up to 440 W

Power Integrations has introduced a flyback topology designed to extend the power range of such converters to 440 W. The new Top-switchgan IC family combines Powigan technology with the Topswitch architecture to reduce complexity and, in many cases, eliminate the need for heat sinks. The devices achieve up to 92 % efficiency at 10 to 100 % load and meet ErP requirements with <50 mW power consumption in standby mode. The integrated 800-V Powigan switches enable low switching losses and frequencies up to 150 kHz. The ICs are available in eSOP-12 and eSIP-7 packages and are pin-compatible with TinySwitch-5 devices.



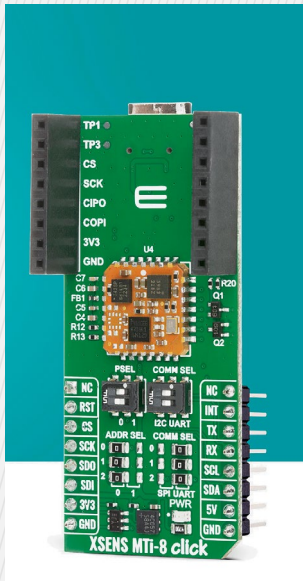
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Bosch | Third-generation SiC Chips

Bosch has begun introducing third-generation silicon carbide semiconductors and is supplying samples to the first automotive manufacturers. The components are designed to increase the efficiency of electric drives, as the specific on-resistance is specified at 4 m $\Omega\cdot\text{cm}^2$ at 175°C. Additional parameters include a maximum junction temperature of 200°C over 100 hours, a threshold voltage of 4 V, a gate-source voltage of -11 to 23 V, a chip thickness of 100 μm , a pitch of 3 μm , and trench technology with I-Sense and T-Sense options. Aluminum-free power metalization is used in the manufacturing process. The qualification complies with the extended AEC-Q101 standard.

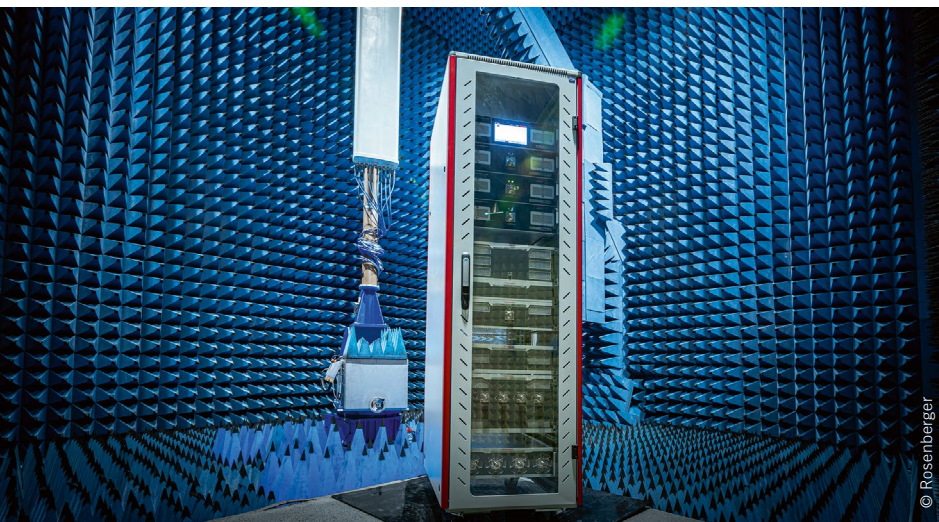


MikroE | RTK-based Positioning



With the XSENS MTi-8 Click, MikroE has introduced a Real-Time Kinematic (RTK)-based GNSS and inertial navigation system solution designed to enable precise positioning and orientation tracking in demanding outdoor embedded applications. The system is based on the MTi-8-5A, an RTK-optimized GNSS/INS module from Xsens that combines GNSS positioning with inertial measurement and real-time sensor fusion. It features a sensor fusion algorithm with output data rates of up to 100 Hz for high-speed dead reckoning and delivers roll and pitch accuracy of 0.5° RMS, yaw accuracy of 1° RMS (with GNSS support), and position accuracy of up to 1 cm + 1 ppm CEP in RTK mode (Real-Time Kinematic). The module integrates a wide-range gyroscope, an accelerometer, and a magnetometer.

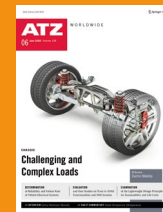
Rosenberger | New Generation of the PIM Rack Analyzer



Rosenberger is expanding its portfolio in the field of passive intermodulation measurement technology with a new generation of the PIM Rack Analyzer. The modular system is designed for users in laboratory and production environments who require fast, precise, and reproducible PIM measurements across all relevant mobile communication frequency bands. The system design is based on cascaded filter units: Up to six filters for different frequency bands can be connected per

base unit. Thanks to automatic switching, the solution is particularly well-suited for production environments with frequent frequency band changes. The integrated Distance-to-PIM (DTP) function allows interference sources to be located quickly and reliably, significantly speeding up troubleshooting. Optionally, broadband VNA functionality is available directly at the same test port, enabling high-precision localization of VSWR mismatches.

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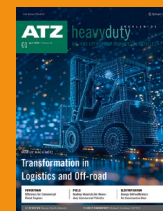


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Open Source over Software Silos

The automotive industry is undergoing a deep transformation. Software is now the central driver of innovation, enabling advanced vehicle functions, intelligent systems, and connected services. Notably this paradigm shift demands new development approaches that balance safety, efficiency, and innovation. Etas describes how the Eclipse Safe-Open-Vehicle-Core (S-CORE) approach lays the groundwork for this.

For vehicle manufacturers (OEMs), the shift towards software-defined vehicles (SDVs) brings with it a level of complexity that is hardly manageable with traditional development models. Automotive software must not only be innovative, but also cyber-secure, functionally reliable, and maintainable for decades. At the same time, it requires the

rapid and continuous deployment of new features – and thus more efficient, cost-effective development processes with short time-to-market. While this is the expectation, the reality for OEMs is characterized by fragmented software architectures, potential vendor lock-in, and stringent safety and cybersecurity requirements.

HIGH EFFORT, LOW ADDED VALUE

The enormous fragmentation of the software landscape contributes significantly to high development costs and long development cycles. To put this in perspective: While essentially two operating systems have become dominant for billions of smartphones,

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the relatively small automotive ecosystem has between 20 and 30 different platform software variants. This fragmentation leads to massive duplication of effort: Development, integration, and qualification processes for safety and security are repeatedly performed on countless software and hardware platforms. As a result, a large portion of the effort is channelled into non-differentiating basic software like middleware and core functions that every OEM needs, but which offer no brand differentiation or discernible added value to the customer, **FIGURE 1**.

Proprietary solutions from individual suppliers only offer superficial relief, as they often lead to excessive vendor lock-in. This not only weakens OEMs' negotiating position regarding prices and licensing models, but also stifles their innovative capacity, as they are bound to the development cycles and technological specifications of the respective supplier. Technology changes become uneconomical or even impossible, and strategic flexibility is severely impaired.

In addition, there are stringent requirements for functional safety and cybersecurity; compliance with standards such as ISO 26262 and ISO/SAE 21434 is, after all, non-negotiable. However, the immense effort required for the rigorous validation

of safety-critical systems, for comprehensive testing, for the integration of security controls, and for secure update mechanisms, sometimes across multiple vehicle lines, further increases cost and development time.

OVERCOMING PROPRIETARY SILOS

All these complex requirements and uncertainties of SDV development call for a more agile and collaborative development approach. Until now, collaboration in the industry has mostly been based on defining standards. However, this has resulted in countless different and proprietary implementations that, while functioning for a manageable number of platforms, no longer scale with the shift to SDV. Frequent updates, short release cycles, and rapid feature rollouts are hardly manageable with this approach. Each isolated solution generates new interfaces, variants, and dependencies, which massively increases project risk and complicates the transfer of functions across model series and vehicle generations.

True innovation, however, is most likely to emerge when the industry collaborates on the issue itself and open-source software (OSS) is the crucial enabler for this. It provides a common foundation for legally compliant collaboration, accelerates development,

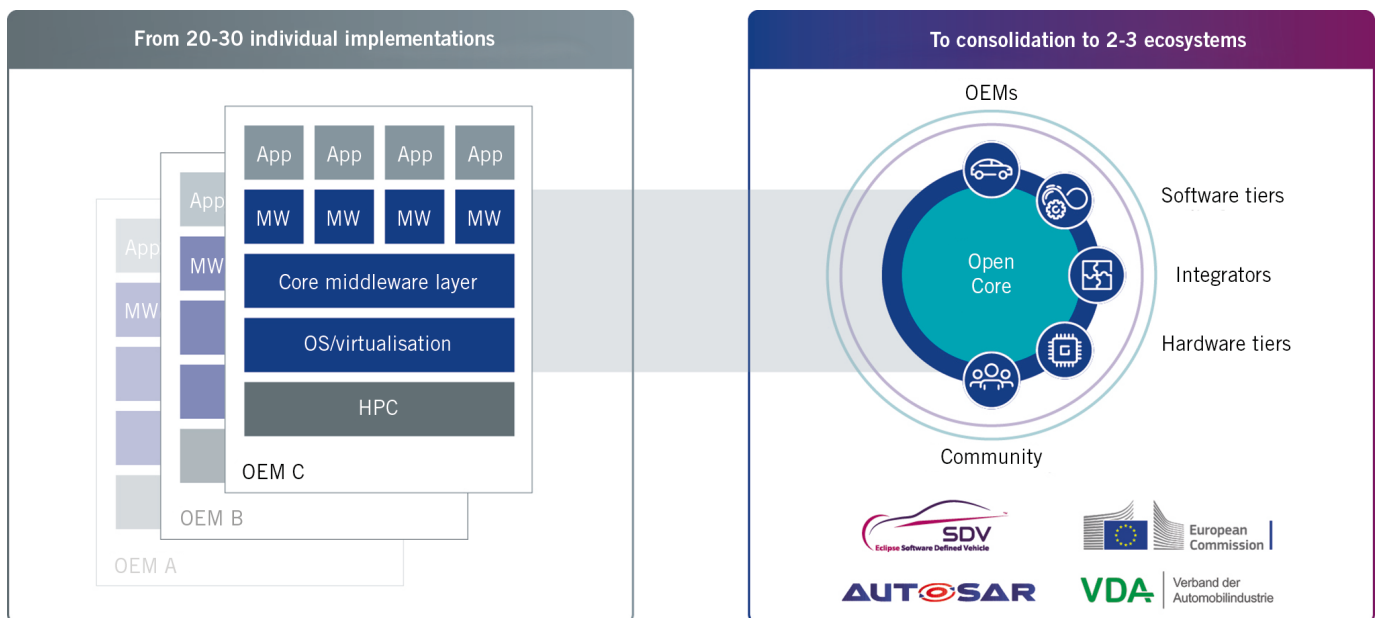


FIGURE 1 There are currently 20 to 30 different platform software variants in the automotive sector. For efficient software development, consolidation into a few systems is essential (© Etas)

and ensures transparency. By overcoming their proprietary silos, OEMs and suppliers can focus on developing genuine unique selling propositions instead of constantly reinventing the wheel.

MIDDLEWARE BASIS FOR MICROPROCESSOR SYSTEMS

The Safe Open Vehicle Core (S-CORE) project within the Eclipse SDV Working Group embodies this new approach. It provides a standardized, open software stack that serves as a common platform for all stakeholders in the automotive ecosystem. S-CORE's focus is clearly on the software below the application layer: It is an open, modular middleware base for microprocessor systems. It provides non-differentiating functions and components with standardized APIs that all market participants can use. As a safety- and security-oriented open-source platform for POSIX-compliant operating systems such as QNX or Linux, it is specifically designed for ASIL-B applications and engineered to meet the highest standards of safety and real-time capability, **FIGURE 2**.

The goal is to facilitate the integration and reuse of software across vehicle lines and generations. The open-source solution addresses the stated requirements for SDV-compliant software platform development: S-CORE, as a common foundation, reduces industry-wide fragmentation, facilitates the inte-

gration of software components, and supports compliance with critical security and cyber protection standards.

DIFFERENTIATION DESPITE SHARED BASE

Open collaboration during development allows the entire industry to benefit from collective intelligence, faster problem-solving, and ultimately higher code quality. The open-core model ensures that the software foundation remains robust, scalable, and future-proof, while enabling all stakeholders to actively participate in its development. At the same time, everything that manufacturers use to differentiate themselves in the market remains outside the scope of S-CORE. The platform creates a reliable, jointly maintained foundation on which companies can then develop their own brand-specific innovations. Manufacturer-specific applications, the individual brand experience, and vehicle functions at the application level are explicitly not part of S-CORE, because that is precisely where competition and differentiation should continue to take place.

NEW KEY FEATURES

Within this clearly defined framework, S-CORE, as a modular, service-oriented software layer, provides

key technical performance features for modern vehicle architectures:

- The platform enables the dynamic deployment of applications, standardized inter-process communication, and lifecycle management of in-vehicle software components.
- S-CORE supports service discovery, secure communication between processes, and centralized resource management.
- The platform enables the integration of software across different domains (multi-domain integration) and provides robust update mechanisms.
- Features such as application isolation, health monitoring and policy-based execution control ensure that system integrity is maintained throughout the entire lifecycle of the vehicle.

These features allow OEMs and suppliers to develop complex software functions – for example in the area of driver assistance – on a common, safety-compliant and stable basis and to make them available for future vehicle generations.

LESS DEVELOPMENT EFFORT

Primary advantage for OEMs: Using S-CORE significantly reduces the total cost of ownership (TCO). While manufacturers previously developed and maintained redundant basic software, the shared platform now enables massive component reuse. This is measurable through a

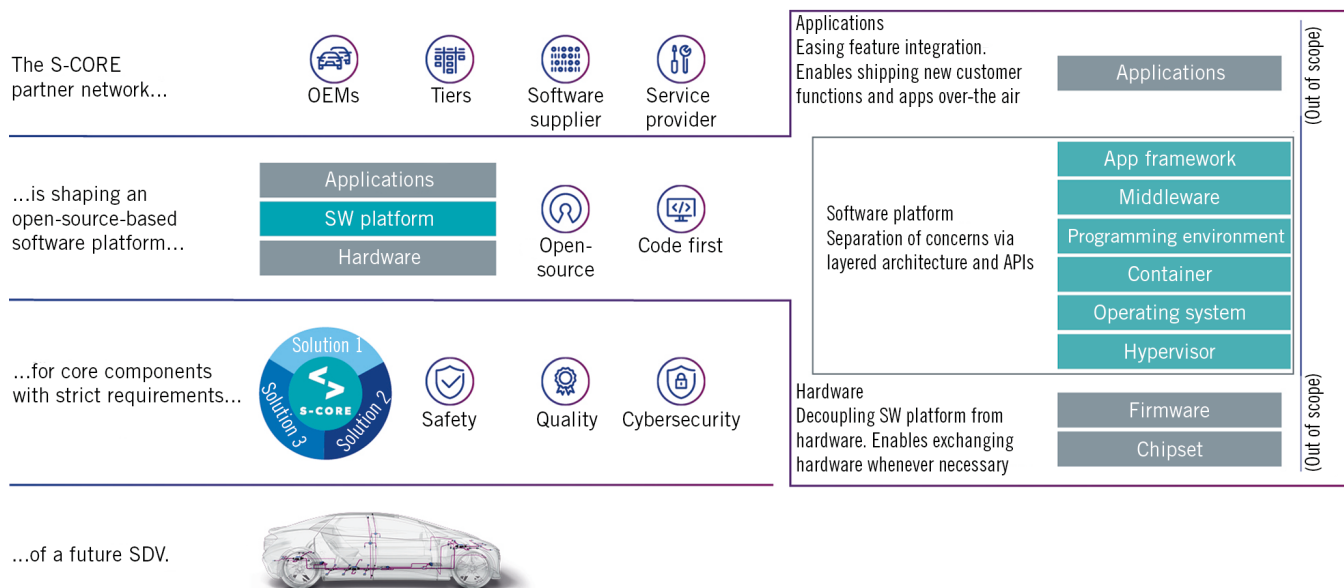
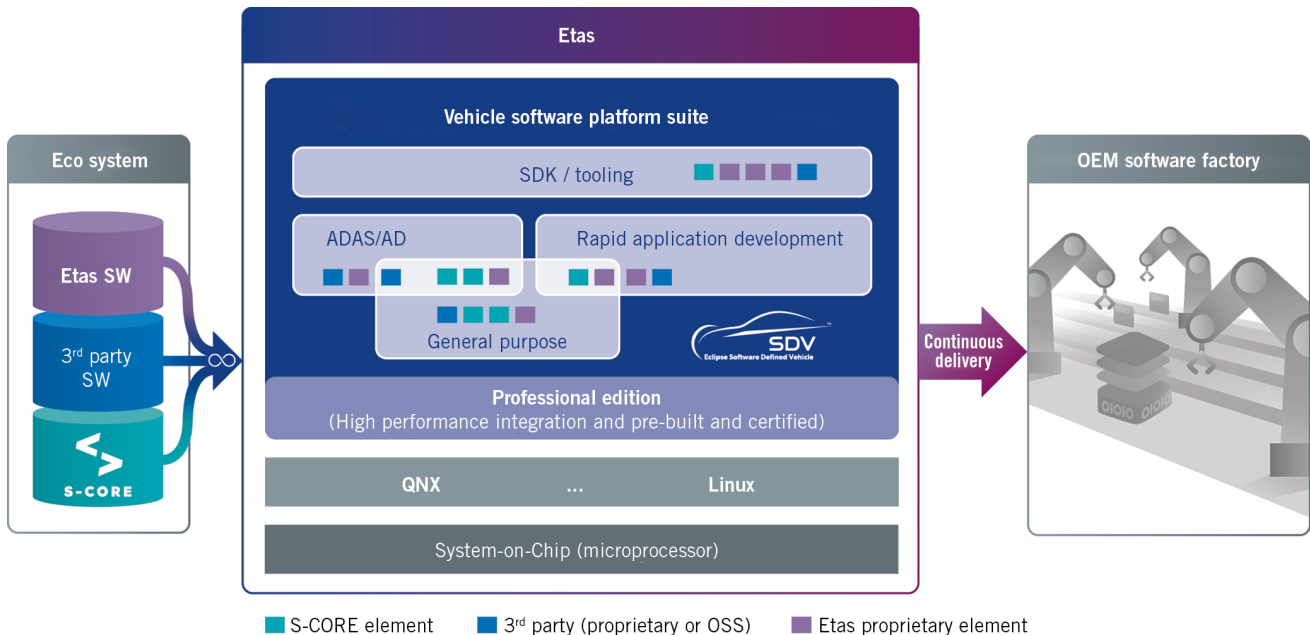


FIGURE 2 Eclipse S-CORE is an open-source stack developed collaboratively by stakeholders from across the automotive value chain, serving as a middleware base below the application layer (© Etas)

FIGURE 3 Distributors refine the open S-CORE source code into production-ready middleware that can be seamlessly integrated into OEMs' development processes (© Etas)



decreasing number of interface variants and reduced development, re-validation, and – in the medium term – maintenance costs across multiple product cycles.

Accordingly, S-CORE significantly reduces time-to-market. A standardized foundation with clear, stable interfaces immediately reduces integration effort and makes software updates more predictable. Faster software integration and a higher release frequency subsequently enable new vehicle functions to be made available to customers more quickly. The companies participating in the S-CORE initiative expect up to 40 % less effort for the development, integration, and maintenance of non-differentiating software, as well as up to 30 % faster time-to-market through shared, automotive-quality components [1].

Furthermore, S-CORE reduces dependency on individual suppliers and mitigates the strategic risk of vendor lock-in. The resulting flexibility and increasing negotiating leverage represent a decisive advantage for future platform and sourcing decisions.

FROM SOURCE CODE TO SERIES PRODUCTION

However, it's also true that while Eclipse S-CORE, with its open-source code, provides the technological foundation for

the vehicle's software platform, it's not directly usable in series production. This is where S-CORE contributors like Etas also act as expert distributors. They transform the open-source stack into a production-ready, S-CORE-based middleware, which is then provided to OEMs as a production-ready distribution. This distribution is specifically tailored to the requirements of automotive software developers: consistently pre-configured, version-traceable, and prepared for efficient integration into series development processes. Ideally, it also integrates other selected open-source components from the Eclipse SDV ecosystem, supports industry-standard toolchains, and is consistently aligned with modern CI/CD workflows.

The S-CORE distributor also handles quality assurance and hardening: Through systematic testing, continuous updates and fixes, and preparation for safety and security certifications, the software itself is transformed into a product that OEMs can reliably use. The result is a dependable, expandable platform (e.g., Etas Vehicle Software Platform Suite) that accelerates innovation while ensuring compliance with functional safety and cybersecurity requirements, as well as maintainability throughout the vehicle's entire lifecycle, **FIGURE 3**.

CONCLUSION

The transformation to software-defined vehicles (SDVs) can hardly be managed with traditional development models anymore. For OEMs, it's time to break free from proprietary silos and concentrate their innovative power where it directly impacts the customer experience. Here, the S-CORE initiative paves the way: by sharing responsibility for the secure and robust software foundation, the industry frees up significant resources. And while qualified S-CORE distributors prepare the middleware for series production, the OEM can focus on its core competencies: creating unique brand experiences and innovative customer features. The shared S-CORE foundation thus becomes a catalyst for genuine, individualized innovation and a competitive advantage in the SDV era.

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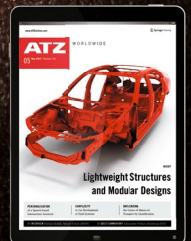
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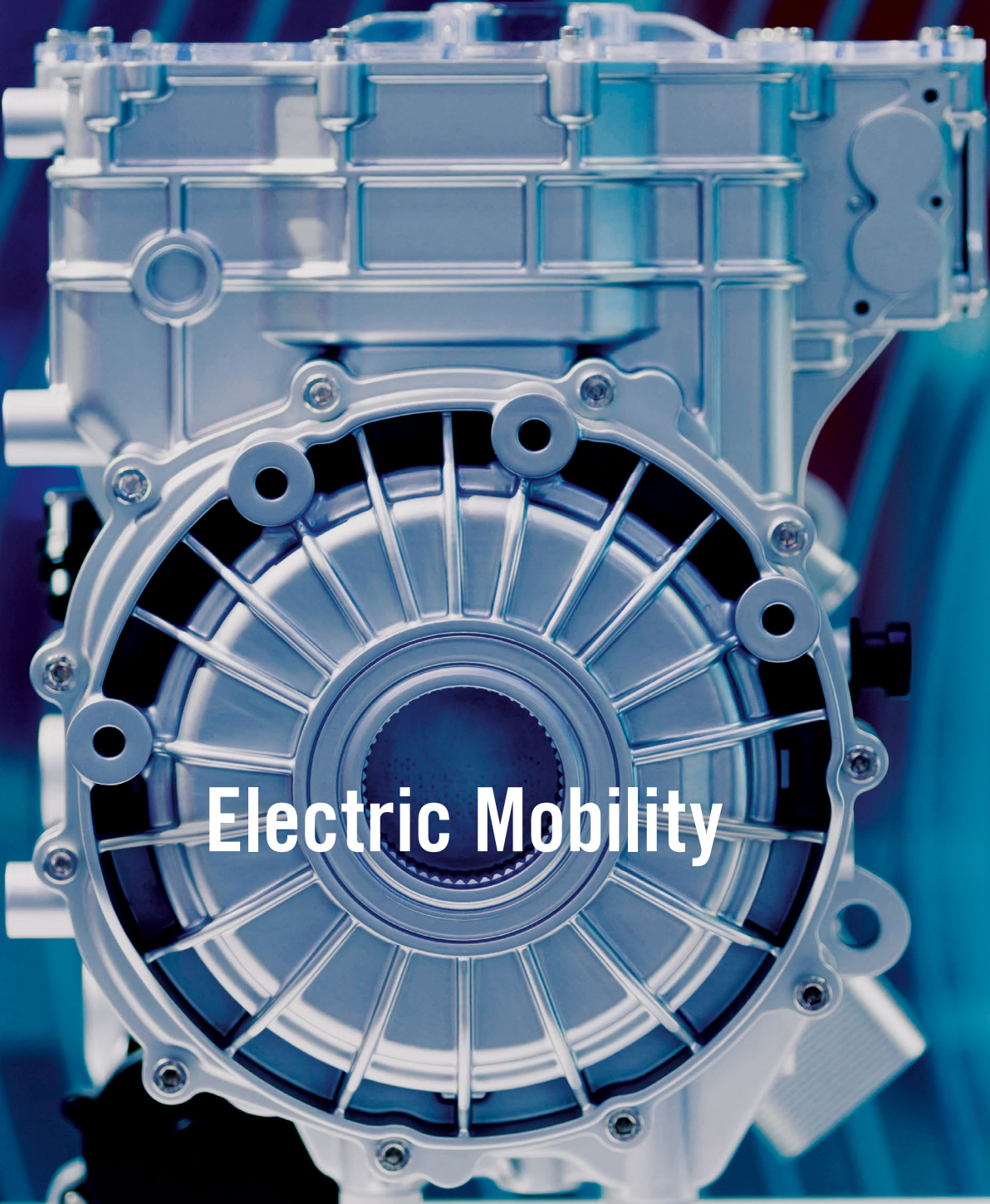


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Electric Mobility



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Disruptive changes are placing pressure on the automotive industry, requiring new skills, more flexible work methods, and faster innovation processes. Electrification now calls for more than just optimizing performance, costs, and installation space. Given future regulatory requirements, other key figures such as the cradle-to-gate approach are gaining importance. It allows for the capture of environmental impacts along the entire upstream value chain and the comparison of product life-cycle assessments. Range-extender and plug-in hybrid vehicles offer both high electric driving ratios and the range flexibility of conventional powertrains. This means they can bridge a gap, particularly in the commercial vehicle sector, during the transition to electric mobility until the charging infrastructure is fully established. At the other end of the scale, limited installation space complicates the powertrain design of small electric vehicles. Here, air-cooled wheel-hub motors with cooling fins can serve as a compact alternative. Parallel to this, new vehicle architectures place high demands on safety and system integration. Composite shields designed to protect high-voltage batteries from fire and underbody damage can combine functional, economic, and ecological advantages.

Caroline Behle

 Springer Professional

Electric Mobility



Magazine article: Ziegler, M.: "Range anxiety is no longer a concern". Interview mit Christoph Menne, FEV.
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Magazine article: Arnold, P. et al.: The MEB Drive APP350 from Volkswagen.
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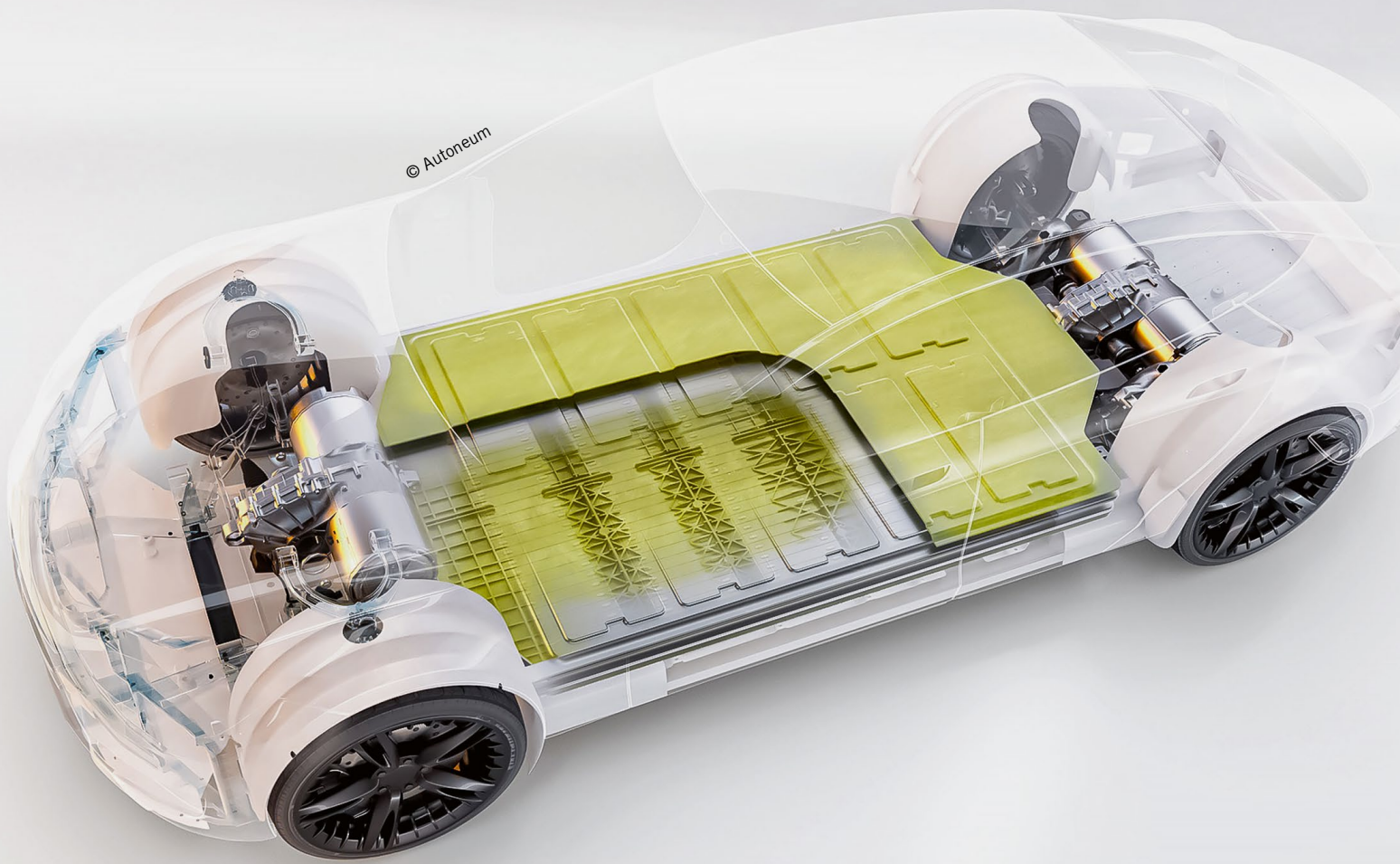


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Guest Commentary
by Lea Schwarz [Audi]



Composite Shields for Battery Protection in Electric Vehicles

In modern electric vehicles, specially designed shielding elements are integrated into high-voltage batteries to provide fire resistance and underbody impact protection. Autoneum has developed powerful shield systems using composite materials. These offer advantages in terms of function, cost, and sustainability over conventional materials like mica, aluminum, or steel plates.

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As Battery Electric Vehicles (BEVs) become more popular, concerns about the safety of high-voltage batteries and their protection from damage are growing. Although lithium-ion batteries in BEVs rarely incur ignition, fires that do occur can spread rapidly and present significant challenges to extinguish. To address this, effective shielding is required between the high-voltage battery and passenger compartment, allowing enough time for occupants to exit safely during a thermal-runaway event. Robust underbody shields also provide battery protection against mechanical damage, like impacts from driving over obstacles, by absorbing and dampening shocks.

FLAME PROTECTION SYSTEM

Most flame protection components for BEVs are made from mica-based materials. In countries such as India and Madagascar, the mining of the mineral mica sometimes takes place under inhumane conditions. For example, child labor is widespread in mica mines, while the lack of occupational safety and protection against heat and dust leads to health hazards and serious accidents at work. Wages are extremely low even by local standards, and illegal mining causes substantial environmental damage [1, 2]. Overall, the use of mica materials is not aligned with the sustainability and ethical standards demanded by society, customers, and policymakers. For automotive manufacturers, identifying and validating suppliers for such products is a complex, time-consuming, and costly process: Ensuring compliance with human rights, environmental and sustainability standards is essential, along with meeting requirements for quality, reliability, and traceability.

From a technical perspective, mica materials also have disadvantages. In BEVs, flame-retardant shields are used as covers for batteries, electrical modules, and busbars. Mica is brittle and not very malleable, making it cumbersome to process and install. To replicate the complex contours of modern battery systems, the flame protection shields must be assembled using many individual segments, driving up production costs.

As an alternative to mica, Autoneum has developed a flame protection shield based on glass-fiber composite materials. This concept offers numerous benefits: The components are cost-efficient, strong, and lightweight, making them ideal for large-area applications, **FIGURE 1**. Thanks to their formability, complex geometries such as lids with embossments and recesses, as well as intricate modules or busbar covers, can be easily replicated. Exhaust ducts for venting hot gases and particles away from critical areas in the event of thermal runaway can also be integrated into the design, **FIGURE 2**. If battery components explode during a thermal-runaway event, the flexible yet robust composite structure provides effective protection against flying debris. The material also offers high electrical breakdown strength at over 3 kV/mm and can incorporate highly effective Electromagnetic Compatibility (EMC) shielding.

Autoneum has validated the glass-fiber flame protection concept through extensive testing, including verification of thermal, mechanical, and electrical properties. In the so-called pyro test, a flat specimen is exposed to the particle jet of a firework for more than 20 s. The high output of around 9 kW produces temperatures exceeding 1400 °C, while a particle mass flow of 1.5 g/s applies pressure loads to the specimen. While the glass-fiber shield showed no perforation even after the test, the mica specimen failed after 14 s, and an aluminum sheet failed after just 10 s, **FIGURE 3** (left).



FIGURE 1 Flame protection shield demonstrator made of glass-fiber-based composite material, showing the feasibility of complex shapes (© Autoneum)

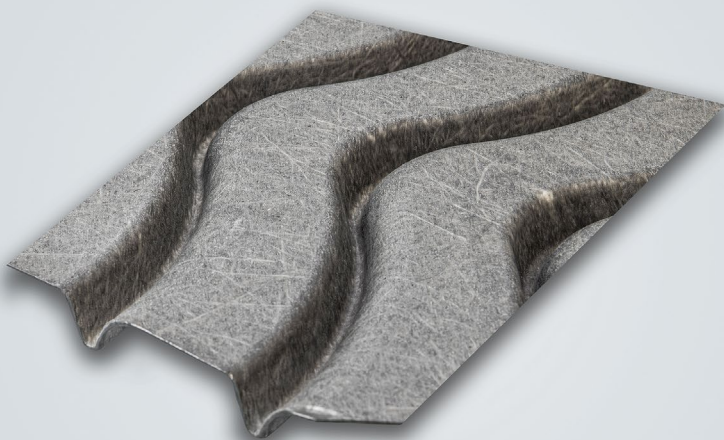


FIGURE 2 Flexible design options for the flame protection shield contour (© Autoneum)

Another series of evaluations, known as the torch test, involves exposing the specimen to a high-performance flame (temperature over 1300 °C, power up to 13 kW) for 10 min. The glass-fiber material passed these tests without perforation, **FIGURE 3** (right). The temperature on the non-exposed side of the specimen remained below 400 °C throughout the test, demonstrating the composite material's superior thermal insulation compared to mica. In practice, this means that occupants are effectively protected from both flames and heat in the event of a battery fire.

Due to the high flame-protection effect and the material composition that can be adapted as required, the thickness of a glass-fiber composite shield can be reduced to as little as 1 mm, resulting in a 30-% weight reduction

compared to mica components that offer similar protection. System-wide cost savings of up to 20 % are achieved thanks to easier and more flexible manufacturing, reduced transport efforts, and easier handling during vehicle assembly as fewer attachment points are needed due to the material properties of the glass fiber composite. Another advantage is the flexible adaptation of the shield geometry to the battery system. For example, the shield's shape can be quickly and easily adjusted if a vehicle platform is designed for various battery sizes or new battery technologies. Moreover, manufacturing and processing glass-fiber composite materials pose no safety concerns, and the certification requirements for procurement and traceability, which are mandatory for mica products to ensure

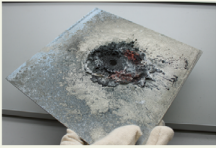
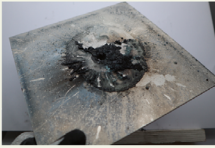
European Union (EU) compliance, do not apply. The glass-fiber flame protection shield has been successfully validated by multiple automotive manufacturers through full battery-pack tests under real-world conditions.

UNDERBODY PROTECTION

In modern BEV platforms, the traction battery is mounted as a flat component on the vehicle's underbody, saving interior space and offering effective crash protection. However, this means the battery is exposed to potential damage from below. To mechanically protect the high-voltage battery against collisions, impacts, stones, water and corrosion, most BEVs today incorporate a shielding element within the underbody.

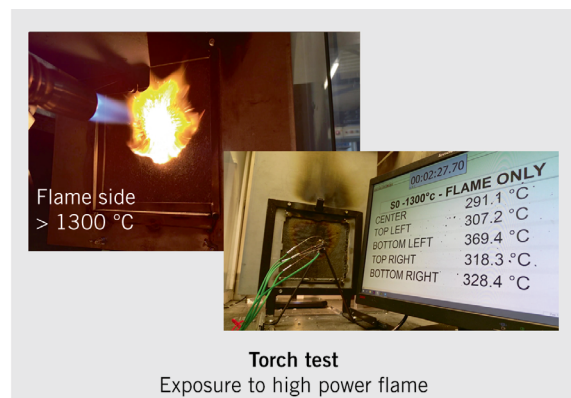
Autoneum uses Uni-Directional tapes reinforced Long Fiber Thermoplastics (UD-LFT) made from Polypropylene (PP) for underbody shielding. This material mix ensures high strength, stiffness, impact resistance, and dimensional stability with low weight. Simulation-optimized reinforcement ribs further stiffen the structure and provide additional stability, **FIGURE 4**. The new impact protection plate offers effective battery protection due to its high energy absorption capacity while being elastic enough to return to its original shape even after strong impacts. In contrast, plastic deformation can be observed in conventional underbody protection components made of aluminum or sheet steel upon impact or intrusion. This can lead to the transfer of load to the battery and cause consequential damage. Furthermore, the initial pro-

FIGURE 3 Pyro test (left) and torch test (right) (© Autoneum)

Autoneum flame shield 2 mm	Mica 2 mm	Aluminum 3 mm
		
No perforation	Perforation after 14 s	Perforation after 10 s

Pyro test

Exposure to temperature above 1400 °C with particle blast and pressure load



Torch test

Exposure to high power flame

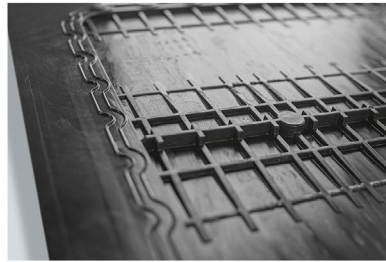
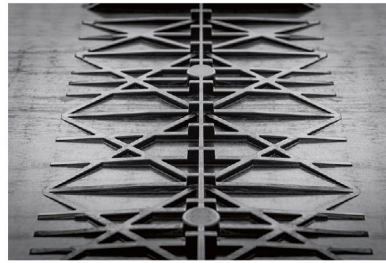
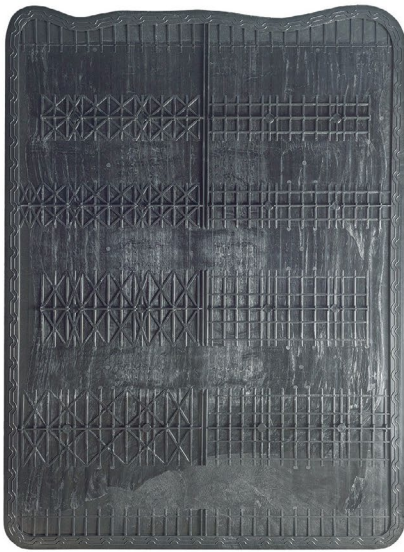


FIGURE 4 Underbody plate made of fiber-reinforced plastic (left) and rib structure (right)
(© Autoneum)

tection may be compromised by the plastic deformation of the metal plate, so that in the event of a subsequent

impact at the same location, the force is no longer absorbed but transferred to the battery.

Another major advantage of the UD-LFT component over conventional metal sheets is its very good thermal insulation. This enables better battery system temperature management, contributing to an increased electric range, **FIGURE 5**.

Simulations with a correlated battery model show potential energy savings of about 1 kWh. This calculation was based on a cycle developed in collaboration with an automotive manufacturer, consisting of 3 h of highway, country road and city driving, an outside temperature of 0 °C, and a total battery capacity of 90 kWh.

Additionally, improved thermal insulation provides extra protection in the event of an external fire under the vehicle. In corresponding tests in which the underbody was exposed to temperatures of up to 1000 °C, temperatures around the battery remained at 200 °C compared to 400 °C measured with conventional shields.



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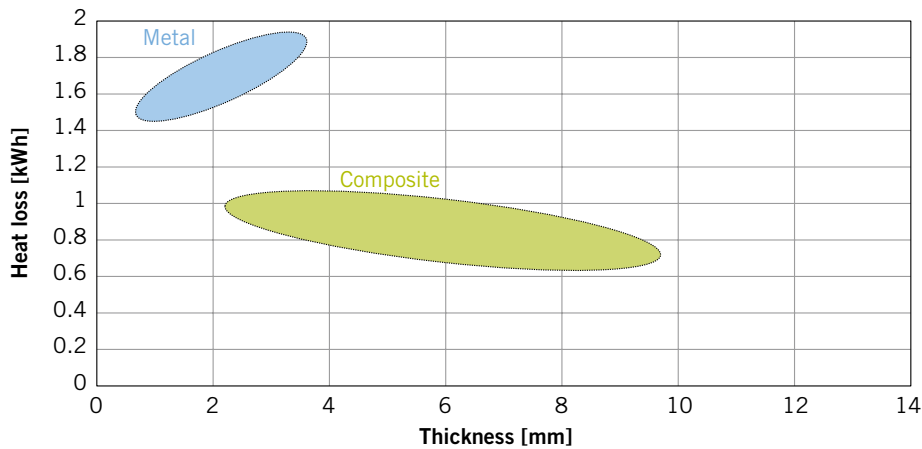


FIGURE 5 Reduced heat loss during cycle operation with a composite underbody shield compared to metal (© Autoneum)

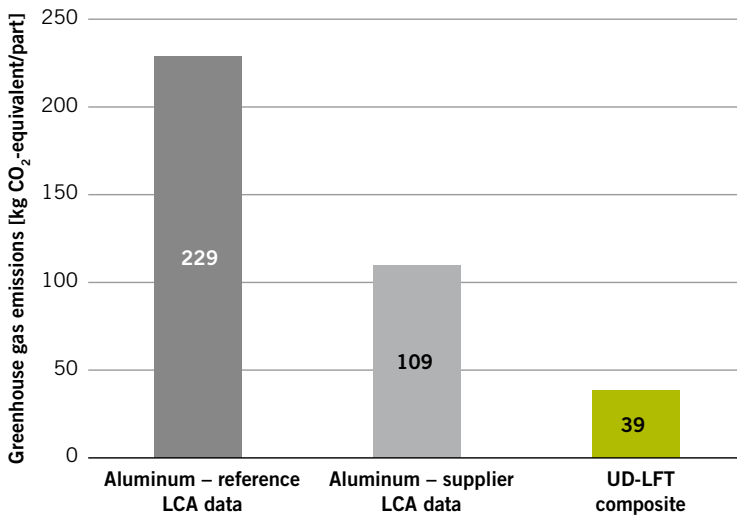


FIGURE 6 Sustainability analysis and comparison of shielding alternatives (LCA: Life-Cycle Analysis, UD-LFT: Uni-Directional tapes reinforced Long Fiber Thermoplastics) (© Autoneum)

Beyond thermal performance, the fiber-reinforced plastic component also excels acoustically, offering improved noise protection, for example from stone chips. It is corrosion-resistant even under extreme operating conditions (including impacts and scratches) and thus has a long service life. The significantly lower weight compared to metal sheets and elastic behavior also makes installation and removal, such as battery maintenance or repair, considerably easier.

The UD-LFT material has a positive ecological balance over the vehicle's lifetime. **FIGURE 6** presents the results of a so-called cradle-to-supplier-gate CO₂ analysis. As shown, the UD-LFT shields generate significantly less green-

house gas emissions than aluminum components, with a maximum of 39 kg CO₂ equivalent per part and a weight of 22.0 kg. In comparison, the reference aluminum part with a weight of 22.5 kg produces greenhouse gas emissions ranging between 109 kg CO₂ equivalent based on best identified aluminum supplier data and 229 kg CO₂ equivalent based on reference Life Cycle Assessment (LCA) data. In addition to reducing CO₂ emissions, 22 % of the proposed UD-LFT solution is composed of recycled content from the end-of-life recycling of Polypropylene polymers. At the end of its life, the composite material is also recyclable, as the fibers and matrix can be efficiently reprocessed and reused.

SUMMARY AND OUTLOOK

To protect vehicle occupants and batteries, automakers equip BEV batteries with multilayer shielding systems. Key elements include a flame-resistant shield between the battery and the passenger cabin, and a robust shield on the underbody of the vehicle. Current structures use mica-based materials for flame protection and aluminum or steel for underbody protection. The shield systems developed by Autoneum for both requirements, made from specially adapted composite materials, offer not only improved protection, but also functional advantages such as lower weight and costs and enhanced sustainability compared to existing solutions. Furthermore, the omission of mica minerals ensures the demanded product compliance.

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THANKS

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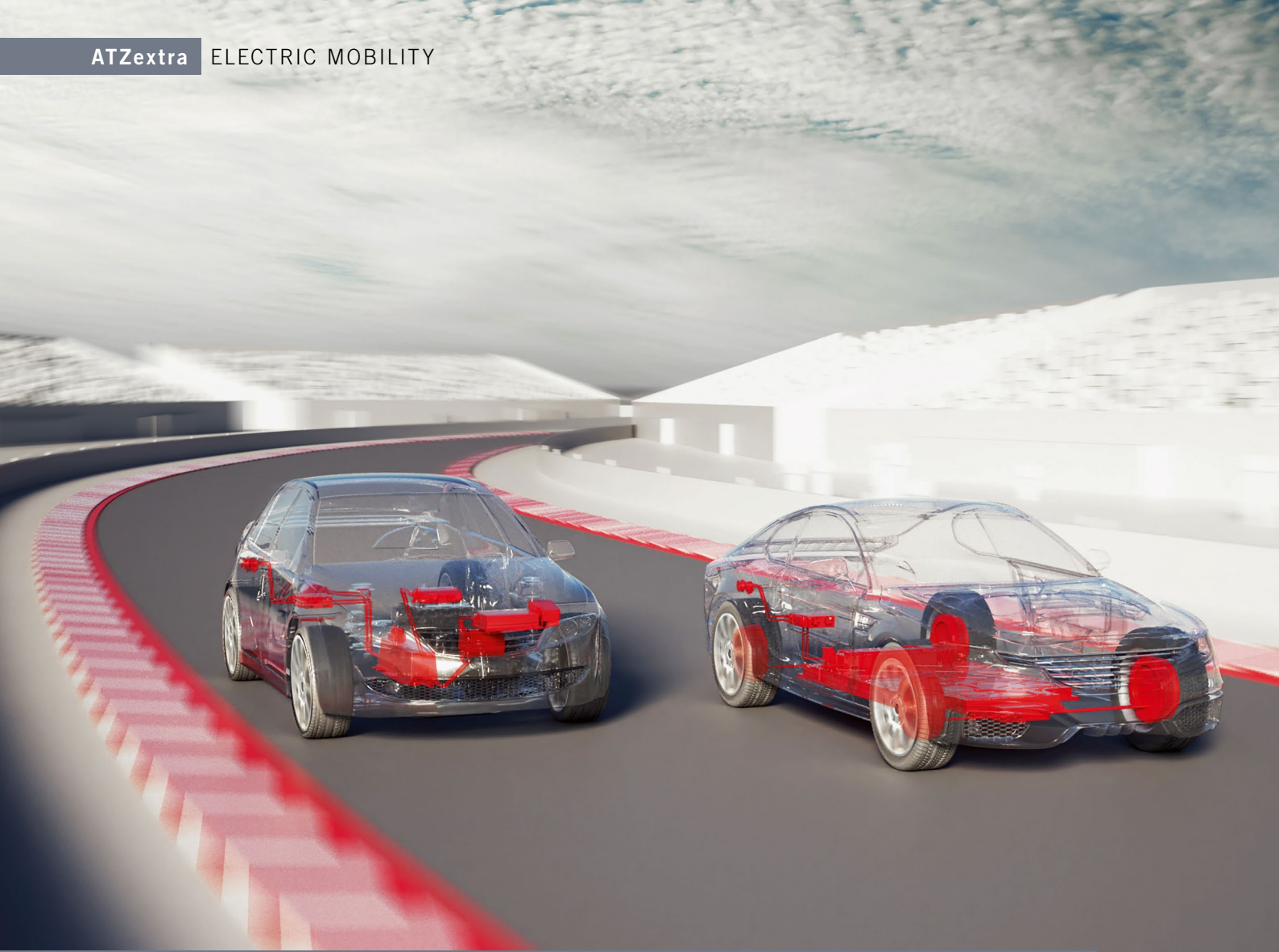


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BORGWARNER



Deriving Battery Concepts for Hybrid and Range-extended Vehicles

Range-extended and plug-in hybrid vehicles are becoming an increasingly significant commodity in the electrification of powertrains. These concepts bridge the gap between the current landscape in terms of charging infrastructure, energy prices, and user behavior on the one hand, and fully battery-electric mobility on the other. FEV shows how battery concepts for these two types can be derived from purely battery-electric drive platforms and how an optimal architecture can be determined.



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The strong market growth of Range-extended Electric Vehicles (REEVs) in China can be attributed to the fact that so-called New Energy Vehicles (NEVs), that is, vehicles with an all-electric range of more than 100 km, are benefiting from strong government incentives. Europe is also seeing an increased interest in these vehicles, despite the regulatory hurdles which currently prevent them from being classified as Zero-emission Vehicles (ZEVs). At present, this only includes purely Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs).

It is expected that Plug-in Hybrid Electric Vehicles (PHEVs) and REEVs will become increasingly important, particularly in commercial-vehicle applications, where they can be compared to ZEVs. Furthermore, the ability to combine a high share of electric driving with the range flexibility of conventional powertrains makes range-extender concepts increasingly relevant for next-generation vehicles. In the case

of Light-duty Vehicles (LDVs), EU regulations for PHEVs consider battery capacity, charging capability, and typical usage profiles to determine the Utility Factor (UF), which represents the real-world share of electric driving. At high UF values, an REEV can approach the regulatory characteristics of a BEV, as weighted CO₂ emissions are calculated using the electric driving share and the charge-sustaining operation as a function of UF.

For Heavy-duty Vehicles (HDVs), the Vecto simulation tool is used to determine CO₂-relevant emissions, based on emission-specific driving cycles such as long-haul, regional delivery, or bus duty cycles. That means battery sizes must be matched to the power and energy demands of the respective duty cycles to optimize fleet-level emissions.

BATTERY TYPES FOR ELECTRIFIED ARCHITECTURES

The chosen battery technology depends strongly on the vehicle type and the target application as different electrified architectures (xEV) require the correct balance between energy density, charging power, and cycle life, as well as cost and safety. Depending on the powertrain architecture used, the typical Key Performance Indicator (KPI) values of traction batteries can vary significantly, **TABLE 1**. For REEVs, the following KPIs are particularly relevant:

- electric range: greater than 150 km (entry segment) to approximately 200 km (premium segment) as indicative thresholds for eligibility in incentive schemes and for everyday usability
- specific energy (Wh/kg): a key driver of weight and packaging efficiency
- cycle life: frequent charging with minimal degradation
- thermal behavior: safety across the entire temperature and load range
- cost per kWh: directly influencing vehicle price and market competitiveness
- charging power: 400/800 V DC fast-charging with more than 350 kW increasingly expected
- power and system-voltage requirements: in the same range as that of BEVs built on the same platform, particularly in charge-sustaining operation.

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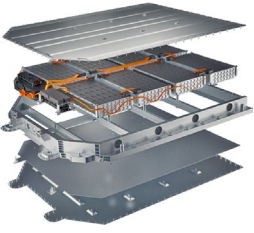
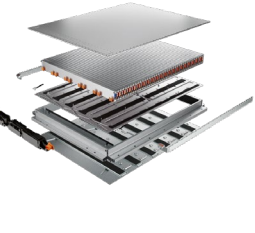
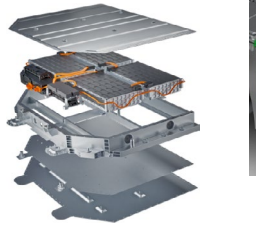
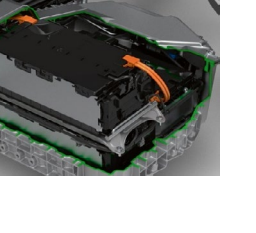
	Premium, long-range BEV	Cost-optimized, mid-range BEV	REEV / long-range PHEV	Mid-/short-range PHEV
Visualization				
Vehicle platform	BEV	BEV	BEV/ICE	ICE
Cell chemistry	High energy, mid power: for example NMC, NMx, (A)SSB	Mid energy, mid power: for example LMFP, LFP, Sodium-Ion	Mid energy, mid/high power: LFP, Sodium-Ion, (NMC)	Mid/low energy, high power: for example LFP, Sodium-Ion
Charging strategy	Fast DC and AC	Fast DC and AC	(Fast) DC and AC	Often AC, no fast-charging
Discharge C-rate	2:1-3:1	2:1-4:1	3:1-6:1	> 6:1
Cell energy density	800-1000 Wh/l	300-500 Wh/l	250-400 Wh/l	250-350 Wh/l
Pack voltage (max.)	800-1000 V	400/800 V	400/800 V	300-400 V
Pack energy	100-180 kWh	60-100 kWh	25-60 kWh	8-20 kWh
Pack energy density	350-450 Wh/l	280-330Wh/l	200-250 Wh/l	150-200 Wh/l
Pack weight	450-700 kg	400-600 kg	200-400 kg	120-200 kg
Electric driving range ¹	650-1200 km	400-650 km	160-400 km	100-160 km
Cycle lifetime ²	750-1500 EFC	1000-2000 EFC	2000-4000 EFC	4000-6000 EFC
Cost prediction 2030+	80-120 €/kWh	55-65 €/kWh	65-75 €/kWh	75-100 €/kWh

TABLE 1 Relevant performance metrics for xEV-architectures (BEV: Battery Electric Vehicle, REEV: Range-extended Electric Vehicle, PHEV: Plug-in Hybrid Electric Vehicle, ICE: Internal Combustion Engine, NMC: Nickel Manganese Cobalt, ASSB: All-solid-state Battery, LMFP: Lithium Manganese Iron Phosphate, LFP: Lithium Iron Phosphate), ¹ estimation based on a consumption of about 15 kWh/100 km, ² Equivalent Full Cycle (EFC) – total charge throughput expressed as full charge/discharge cycle equivalents) (source and © FEV)

Despite the disparity in the KPIs, there are substantial commonalities between BEV and REEV/long-range PHEV batteries, which forms the basis for a unified platform strategy across different xEV battery systems.

COMMON BATTERY PLATFORM

When choosing the correct strategy for a common battery platform, a number of factors need to be considered. These include the gross energy content and the discharge C-rate (power factor) of battery packs, with the C-rate being the ratio of discharge current to battery capacity. Both factors are illustrated across various vehicle platforms (PHEV, REEV, BEV) in **TABLE 1** and can be used to draw the following conclusions:

- The type of application influences the power-to-energy ratio and thus the appropriate cell selection.
- A distinction between energy-oriented applications (such as BEVs) and power-oriented applications

(such as short-range PHEVs and HEVs) can be made.

- REEV and long-range PHEV batteries fall between PHEVs and BEVs; some BEV packs already meet typical REEV requirements.
- Within a battery family, a dedicated REEV pack is required to create synergies with existing BEV architectures facilitating development and integration.
- Lithium Iron Phosphate (LFP) batteries generally offer lower energy density than Nickel Manganese Cobalt (NMC) batteries, but in some cases achieve even higher discharge C-rates.

Other key parameters for battery configurations include the number of series-connected cells to achieve the target system voltage (ySxP) and the number of parallel strings to meet the target energy (ySxP). The available installation space, charging and inverter voltage windows, and the State-of-Charge (SoC) operating window (upper/lower limits) also play a role. In addition, the power-management strategy within the drivetrain (for example serial/

parallel PHEV/REEV configuration, SoC and power-distribution strategy) [1], and the 400/800-V architecture, including the charging strategy, are also relevant.

In high-volume production, reducing the number of cells and cell variants has many advantages. On the one hand, the overall number of components is minimized, which simplifies assembly. On the other hand, the packing density increases and integration, interconnection, and monitoring become less complex. With this in mind, the following options are available for a common battery family:

- a single cell type for all applications, with scaling achieved through parallel strings (for example 125S1P for an REEV, 125S2P for a BEV)
- multiple cell types with scalable geometries, while maintaining a consistent ySxP configuration across all xEV batteries
- a hybrid approach, combining both strategies to balance flexibility and manufacturing efficiency.

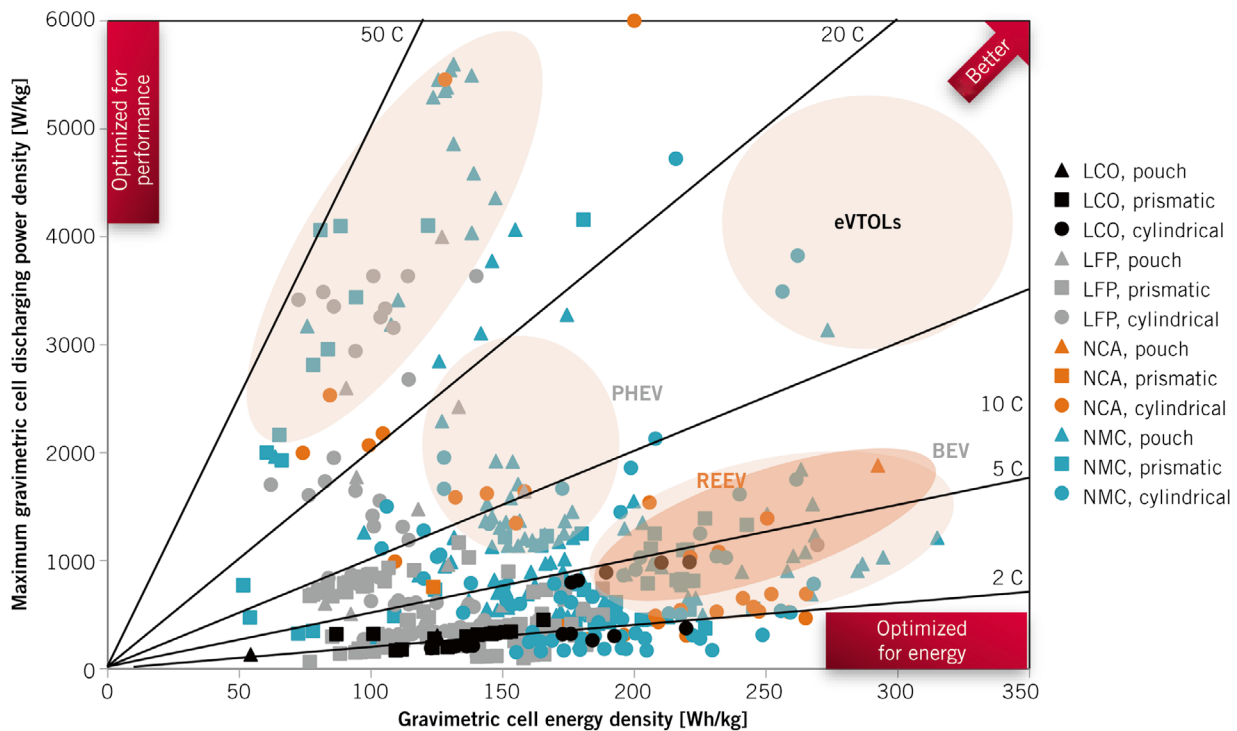


FIGURE 1 Energy density and calculated discharge power density of various cells (eVTOLs: electric Vertical Take-off and Landing aircraft) (© FEV)

Choosing the optimal strategy is a multi-dimensional challenge as beyond the technical requirements and constraints, economic factors, as well as the implications for redundancy and serviceability, must be considered. At lower production volumes, a unified cell type may offer the best overall compromise, whereas at higher volumes, application-specific cell designs can become economically advantageous. With BATT.Code, FEV has developed a tool that is suited for this purpose.

CELL SELECTION FOR OPTIMUM SYSTEM DESIGN

The battery cell defines essential system attributes such as power capability, safety, cost, driving range, and overall scalability. Therefore, a broad set of criteria needs to be evaluated to select the optimal cell technology, such as the form factor, the chemistry, and the operating window, as well as the supply chain and costs.

In terms of form factor, cylindrical cells provide the highest packaging flexibility, while large prismatic cells enable highly efficient use of space when suitable installation volume is available. Pouch cells occupy an inter-

mediate position in terms of packaging efficiency and structural requirements. From a chemical perspective, LFP offers strong intrinsic safety at lower cost, NMC supports compact high-performance applications, and Lithium Titanium Oxide (LTO) anodes provide exceptional cycle life – even

at low temperatures. The charging and discharging performance across relevant temperature and SoC ranges must be compatible with the intended duty cycle and use case. In addition, local cell manufacturing, long-term strategic partnerships, and circular economy concepts are becoming increasingly

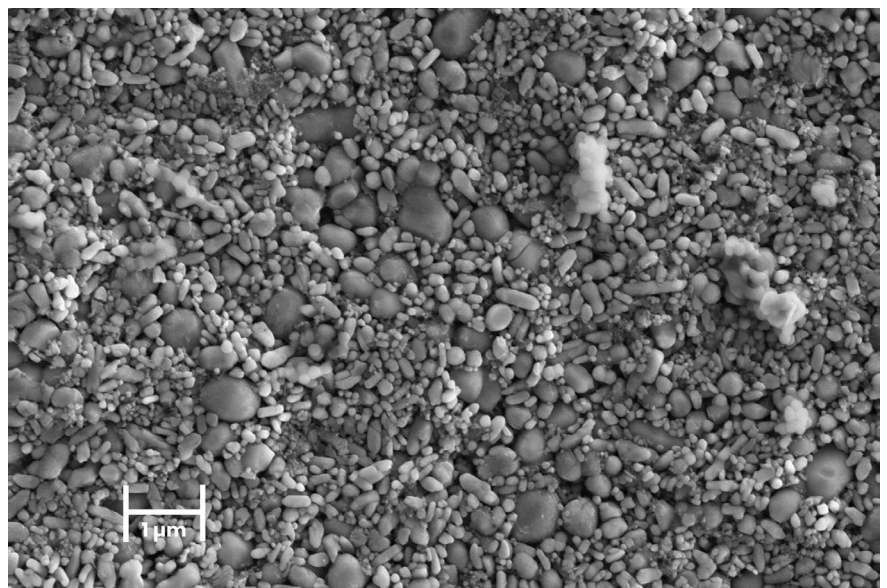


FIGURE 2 Cathode top view of the LFP battery cell in the Xiaopeng G9; source: FEV benchmarking (© FEV)

Modular architecture

- Scalability for energy and power
- Common interfaces
- Adaptable thermal management and performance

Voltage flexibility

- Charging interface 800/400 V
- Operation voltage of electric motor
- Voltage adaptation via string switching or DC/DC converter

FIGURE 3 Design criteria for cross-platform xEV batteries (SoC: State-of-Charge) (© FEV)

Packaging

- Floor-mounted packs (BEV + REEV)
- Compact packs in engine bay, tunnel or under seats (PHEV + REEV)
- Crash safety zones and serviceability and thermal-propagation reaction

Cell selection

- Power/energy ratio
- Power limits over SoC, especially discharging at low SoC
- Cell swelling and cycling stability
- Heat dissipation
- Thermal stability

important factors in technology selection. Finally, in terms of costs, LFP is generally more cost-effective than NMC, but the competitive pricing depends strongly on high production volumes whereas at lower volumes, unit costs tend to be significantly higher.

The discharging power density and energy density at cell level are illustrated in **FIGURE 1**. There is a clear distinction between power-optimized cells, which have high power, high specific power density in W/kg or high C-rates, and energy-optimized cells which have high energy, high specific energy density in Wh/kg. For REEVs and long-range PHEVs, the required power-to-

energy ratio is similar to that of BEVs. As electric range and pack energy increase, the required power-to-energy ratio typically decreases; peak discharge rates of up to 5 C are sufficient for acceleration and gradeability. For LCVs in particular, both BEV and REEV batteries can be realized using identical cells based on modern LFP technology [2]. It is essential, however, that power limits – especially at low SoC – are coordinated with vehicle-level energy-management strategies to ensure adequate performance across the full electric operating range.

It can be seen in FEV's ongoing cell-benchmarking studies that there is still substantial development potential in

battery-cell technology. For future PHEVs and REEVs, further improvements in the relationship between driving range, power capability, and cost can be expected. These advancements arise from both electrochemical innovations and improvements in the thermomechanical design of battery cells.

Electrochemical performance improvements are primarily driven by three technological developments: On the one hand, particle-surface coatings and functional additives enable cycle life and power capability to be increased. On the other hand, tailored particle morphology – for example, structural modifications that reduce lithium-ion diffusion paths –

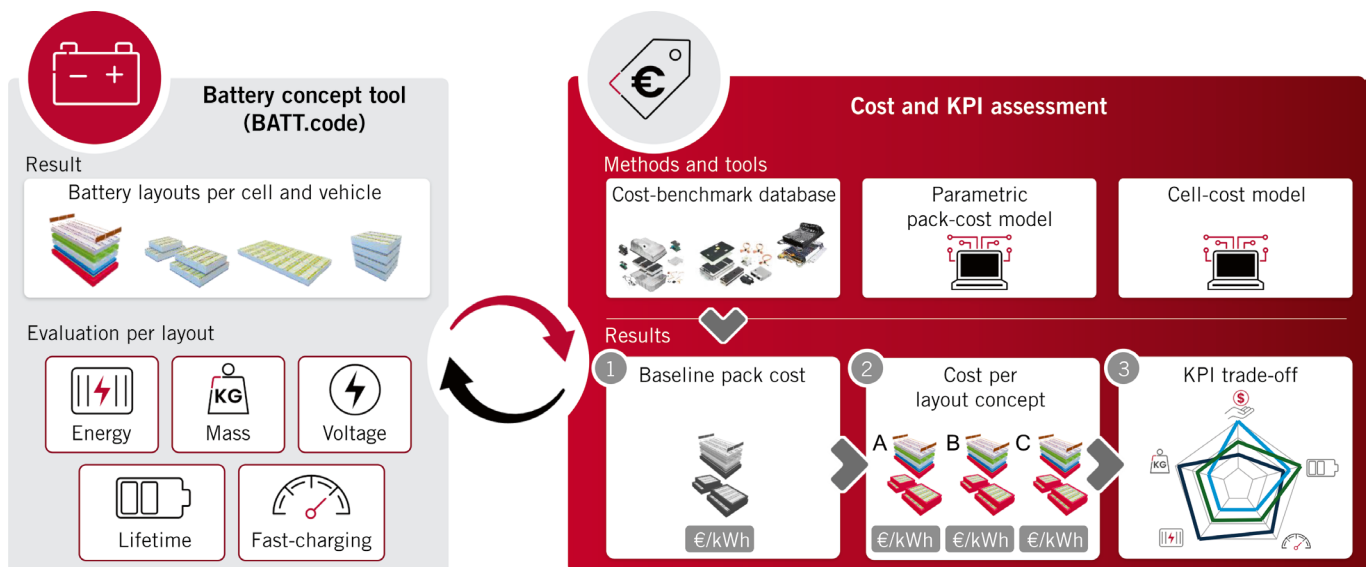


FIGURE 4 Determination of the optimal architecture for an xEV battery platform (KPI: Key Performance Indicator) (© FEV)

results in significantly improved power density. What is more, optimization of electrolyte additives enhances cyclability, lifetime, and thermal stability of the system.

A recent example of performance-enhancing particle morphology which was revealed by FEV's benchmarking, is found in the LFP cell of the Xiaopeng G9. This cell uses exceptionally small, rod-shaped LFP primary particles instead of spherical structures to significantly reduce effective diffusion pathways and thereby increase cell power capability, **FIGURE 2**.

A lithium-ion cell is a highly coupled, nonlinear electrochemical system, therefore optimizations in one design domain must always be evaluated for potential impacts on other functional areas. Nevertheless, in the field of power enhancing measures in particular, a wide spectrum of technological approaches is available that can increase power capability while maintaining – or even improving – energy density.

Mechanical and thermomechanical optimization strategies typically involve the use of thinner current collectors, separators which introduce higher porosity while preserving safety performance, and design measures that promote more uniform current distribution. These improvements help reduce overall operating temperatures and achieve a more homogeneous temperature profile within the cell. In turn, they slow electrochemical aging and enhance overall system performance.

TRANSITION FROM BEV TO REEV

Efficient battery engineering begins with selecting the right base architecture, **FIGURE 3**. REEV platforms are often derived from existing BEV architectures, while long-range PHEV batteries frequently evolve from short-range PHEV designs originally developed for ICE platforms. These transitions pose specific engineering challenges. Two common derivative transition scenarios either increase the energy content of an existing PHEV pack while maintaining the same installation space to form a long-range PHEV battery, or reduce the installation space of a BEV pack while simultaneously maximizing energy and

power density to form a REEV battery.

Using a common cell type across multiple configurations can simplify development, validation, quality assurance, manufacturing, and supply-chain management. However, it may also restrict design flexibility and limit KPIs. As power density increases and high-load phases become longer, efficient cooling and thermal management become more critical for ensuring safety and durability. This includes the controlled handling of vent gases in the event of thermal propagation [3]. In addition, cell swelling and the required cell-to-cell spacing influence the achievable energy and power density at pack level and increase packaging requirements – these are all factors that must be addressed early in the development process.

Automation and the use of artificial-intelligence-based methods accelerate concept development and evaluation against critical target metrics, **FIGURE 4**. Automated generation of system concepts and module configurations based on real cell data supports the definition of the baseline architecture. Concept-level cost assessment enables the identification of the most technically and economically suitable solution.

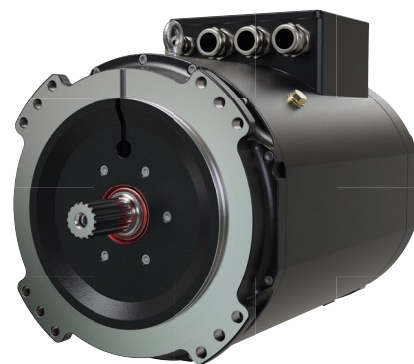
CONCLUSION

REEVs and long-range-capable PHEVs represent an important intermediate step on the pathway toward full electrification of both passenger and heavy-duty transportation. They provide a practical solution for users who cannot – or do not yet wish to – transition fully to battery-electric propulsion, while still enabling significant CO₂ reductions. Early definition of the battery family and underlying battery architecture is essential to finding the right balance between technical targets, cost, environmental regulations, and supply-chain constraints.

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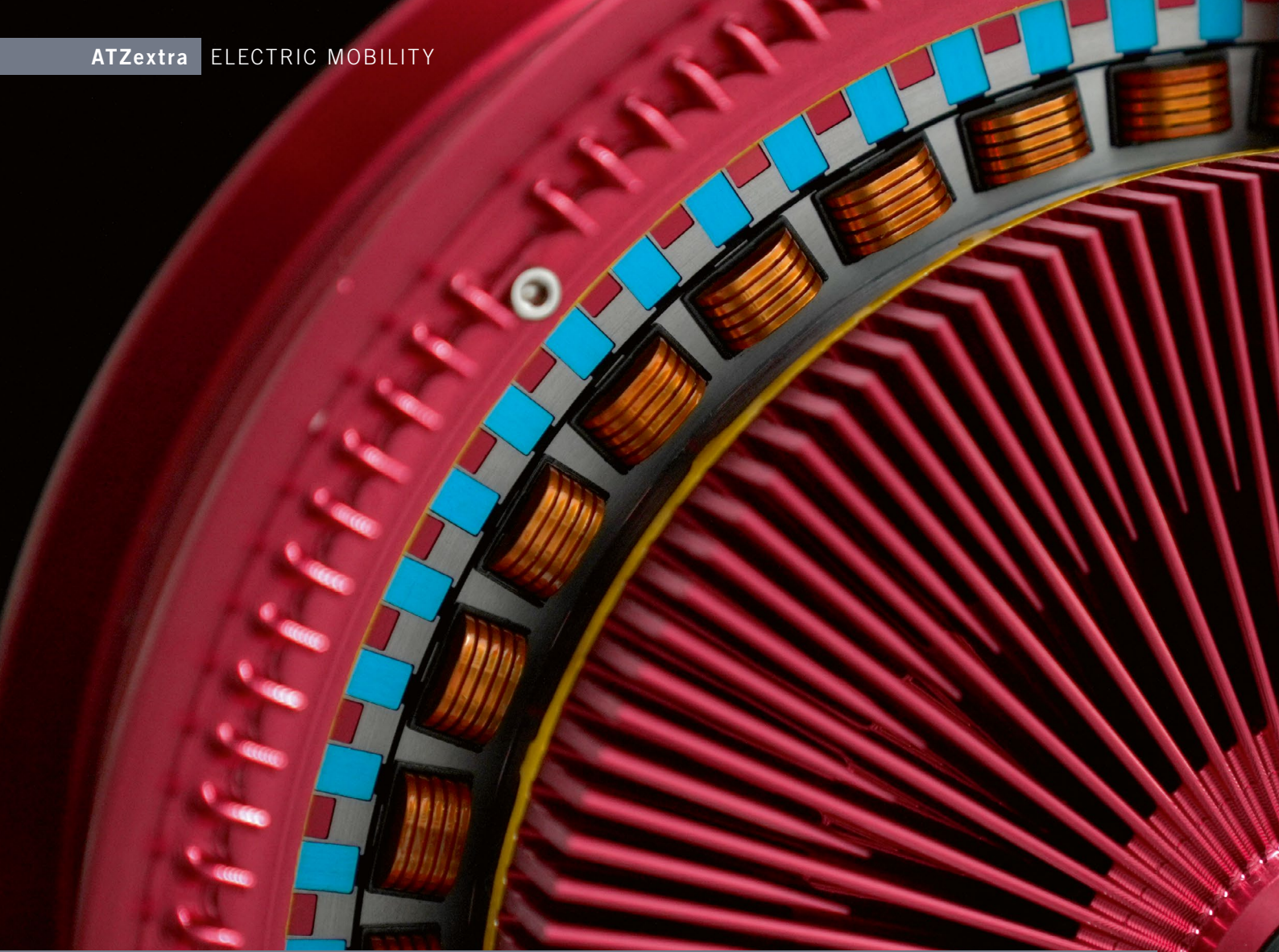
100 - 1000 kW



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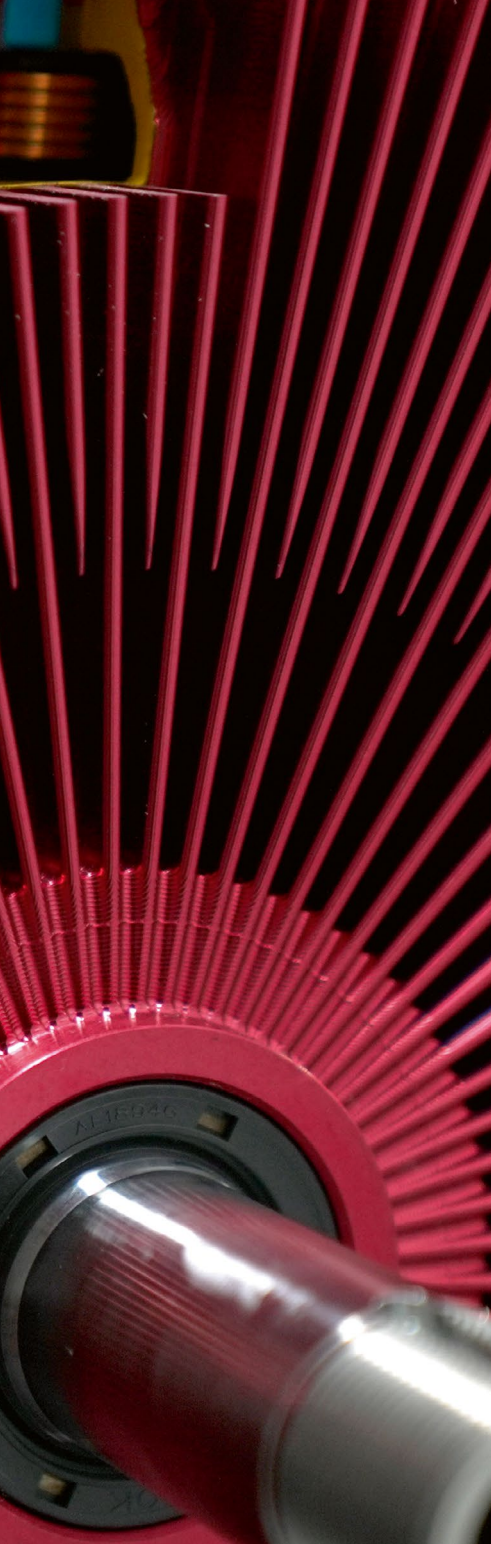
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A detailed close-up photograph of an air-cooled in-wheel motor. The image shows a curved section of the motor's rotor assembly. On the left, a red-painted metal housing features a series of radial cooling fins. Adjacent to this is a black stator core with several copper-colored electromagnetic coils wound around it. Blue and red rectangular markers are visible on the stator core. To the right, a yellow-painted component is partially visible. The background shows more of the red cooling fins, creating a sense of depth and rotation.

Air-cooled In-wheel Motors for Small Electric Vehicles

Small vehicles and motorcycles place strict demands on electric drive systems due to limited installation space and allowable system cost. Applying in-wheel motors remains challenging, especially when it comes to cooling performance. Astemo's direct-drive system provides a rotary-fin cooling concept, where radial cooling fins are integrated into the side surfaces of the rotor housing, enabling heat to be directly dissipated into the surrounding air by utilizing the motor's own rotation.



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From a drivetrain layout perspec-
tive, Electric Vehicles (EVs) can be
broadly classified into two categories.
The first is the central-drive type, in

which the combustion engine is replaced
by a centrally mounted electric motor
within an existing vehicle platform.
The second is the in-wheel type, where
the motor is integrated directly into the
wheel. Most EVs currently on the mar-
ket adopt the central-drive configura-
tion. However, in-wheel motors offer
several inherent advantages, includ-
ing reduced mechanical losses through
direct wheel drive, enhanced control
freedom, and increased layout flexibil-
ity by relocating the drivetrain into the
wheel, thereby enabling greater cabin
space utilization. To make use of these
advantages, a research and development
team of Astemo has previously developed
a 19-inch oil-cooled in-wheel motor for
passenger-car applications.

When applying in-wheel motor tech-
nology to small vehicles, significantly
stricter constraints on packaging space
and system cost must be considered. In
such applications, oil-cooling systems
become problematic due to the need
for additional piping and auxiliary com-
ponents. Conversely, adopting air cool-
ing introduces a different challenge:
The limited wheel size of small vehicles
makes it difficult to secure sufficient
heat-dissipation surface area to main-
tain acceptable thermal performance.
A novel rotary-fin cooling structure ad-
dresses this challenge. By integrating
cooling fins into the rotor housing and
utilizing the motor's own rotation, heat
is directly dissipated into the surround-
ing air without relying on oil- or water-
based cooling systems.

This article presents the cooling
concept based on the rotary-fin struc-
ture, investigates approaches for maxi-
mizing fin surface area, discusses fin-
shape optimization through thermal-
fluid analysis, and outlines the results
of heat-run tests conducted using a
prototype motor.

TABLE 1 Specifications of the air-cooled in-wheel motor (© Astemo)

Item	Unit	Value
Size	inch	12
Maximum output	kW	13
Continuous output	kW	5.5
Maximum torque	Nm	370
Supply voltage	V _{dc}	400

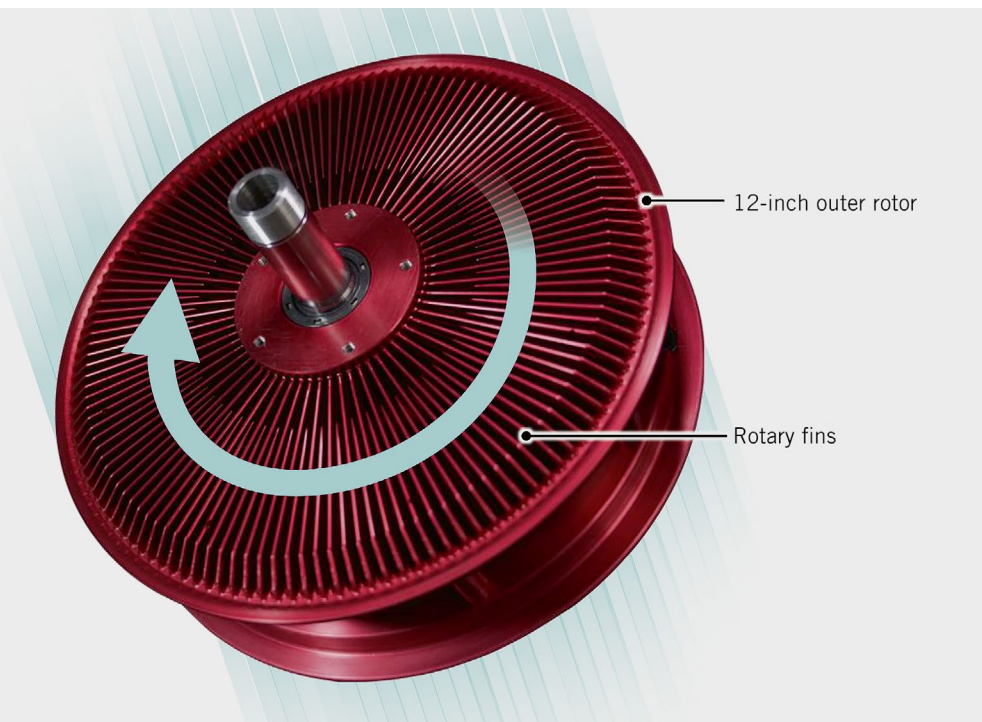


FIGURE 1 Side view with outer rotor and radial fins (© Astemo)

MOTOR CHARACTERISTICS

The air-cooled in-wheel motor adopts an outer-rotor direct-drive configuration and is designed as a 12-inch unit suitable for installation in small vehicles and motorcycles. Despite employing air cooling, the motor provides the driv-

ing performance required for electric mini vehicles, achieving a maximum output of 13 kW or 52 kw with four-wheel drive. The continuous output per wheel amounts to 5.5 kW, **TABLE 1**. Radial rotary fins are arranged on the side surface of the rotor housing, **FIGURE 1**. During rotation, radial airflow gener-

ated by centrifugal forces between the fins, together with circumferential shear flow near the fin tips, effectively dissipates heat from the fins into the surrounding air.

ROTARY-FIN COOLING CONCEPT AND DESIGN

In the proposed cooling structure, more than 1 kW of heat losses must be dissipated using air cooling alone. At the initial design stage, it was therefore assumed that a relatively large number of fins would be required to secure sufficient heat-dissipation area. When radial heat-dissipation fins are arranged on the rotor housing, the circumferential fin spacing becomes narrower toward the inner circumference and wider toward the outer circumference. To increase the total fin surface area under this geometric constraint, Astemo has adopted a configuration in which the number of outer fins exceeds that of inner fins. As the fins also act as ribs to ensure sufficient housing rigidity, each inner fin is mechanically connected to a corresponding outer fin. Fin spacing was determined with consideration of manufacturing constraints, and changes in fin surface area were evaluated by varying the inner-fin outer diameter d_f .

FIGURE 2 summarizes the calculation results. For the inner fins, the mini-

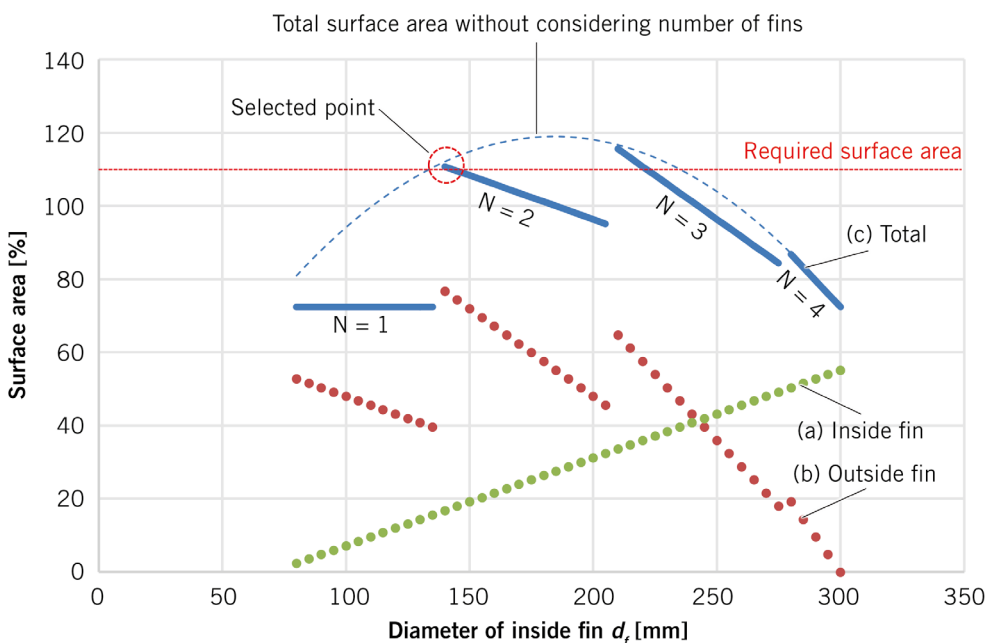


FIGURE 2 Calculation of the housing outer surface area (© Astemo)

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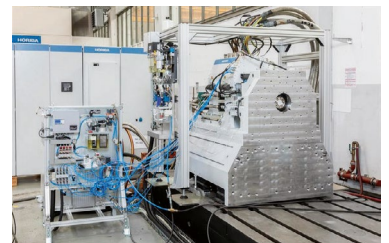
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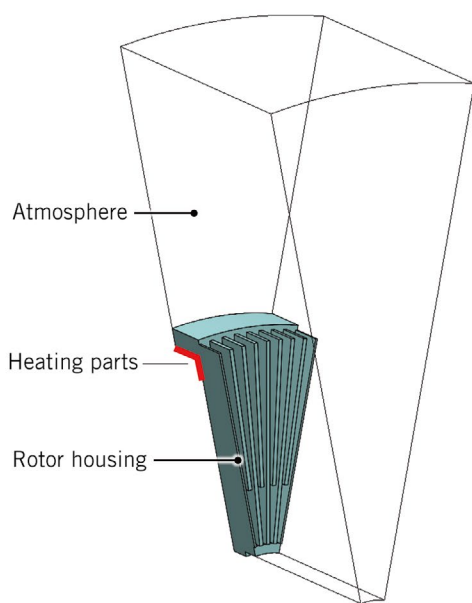
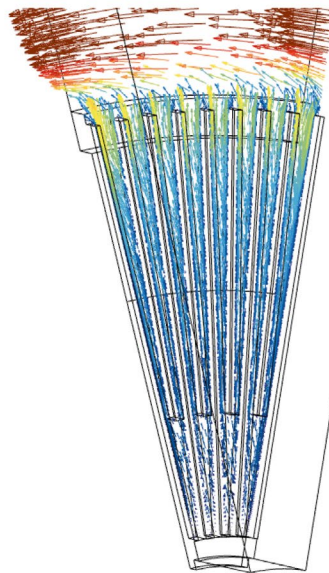


FIGURE 3 Steady-state thermal-fluid analysis: analysis model (left) and airflow vectors (right) (© Astemo)



and the surrounding air region were modeled, and the total motor loss was applied to the region corresponding to the magnetic circuit. **FIGURE 3** (right) shows the airflow vectors at the fin roots in a rotating coordinate system. A distinct radially outward flow induced by centrifugal force can be observed. Since the centrifugal force is proportional to the square of the rotational speed, higher rotational speeds significantly enhance the radial airflow component.

THERMAL-FLUID ANALYSIS

For the fin geometries investigated in the previous section, Astemo conducted thermal-fluid analyses. The results are shown in **FIGURE 4**. Compared with model 1, model 2 extends the fins into the cylindrical section and introduces a chamfer between the cylindrical and disc surfaces. This design modification reduced the maximum temperature by 13 °C, demonstrating a clear improvement in cooling performance.

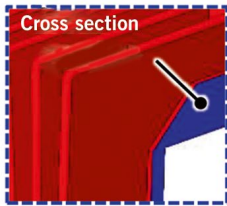
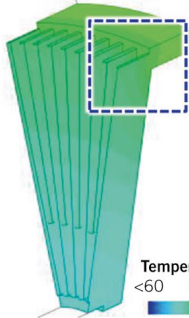
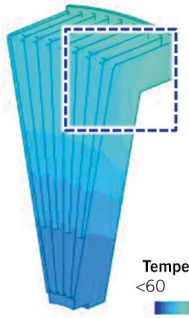
FIGURE 5 illustrates the distribution of the heat-transfer coefficient for the two fin configurations. In model 1, the air confined between adjacent fins is driven radially outward by centrifugal

force. The minimum fin spacing remains constant as d_f changes, resulting in an inner-fin surface area that is proportional to d_f . For the outer fins, increasing d_f shortens the radial fin length. However, increasing the ratio N of outer fins to inner fins enlarges the minimum outer-fin spacing, allowing a greater number of outer fins to be arranged. Consequently, the outer-fin surface area increases with larger N but decreases with increasing d_f for a fixed N . The total fin surface area, obtained as the sum of the inner- and outer-fin areas, therefore exhibits a parabolic trend with respect to d_f . Based on these considerations, the final design parameters were set to $N = 2$ and $d_f = 140$ mm, which provide the required heat-dissipation surface area while keeping the total number of fins relatively small.

In order to optimize the fin shape, consideration must be given to the fact that the rotating tire wheel is exposed to a relative airflow of approximately $2v$ at the top, 0 at the bottom, and v at the front when the vehicle is traveling at a speed of v , resulting in an average relative airflow of v around the wheel perimeter. Since the temperature distribution on the rotor housing can be assumed to be circumferentially uniform, the flow field was approximated as axisymmetric. In this

simplified model, translational airflow due to vehicle motion was neglected, and only the rotational speed corresponding to v was considered. The thermal-fluid analysis model is shown in **FIGURE 3** (left). The rotor housing

FIGURE 4 Temperature distribution of model 1 (initial) and model 2 (improved) (© Astemo)

Item	Model 1	Model 2
Enlarged view		
Temperature distribution	 Temperature [°C] <60 85 >110	 Temperature [°C] <60 85 >110
Maximum temperature	88 °C	75 °C

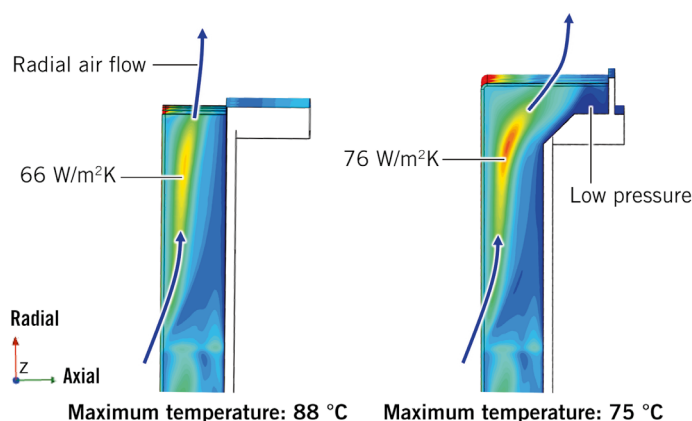
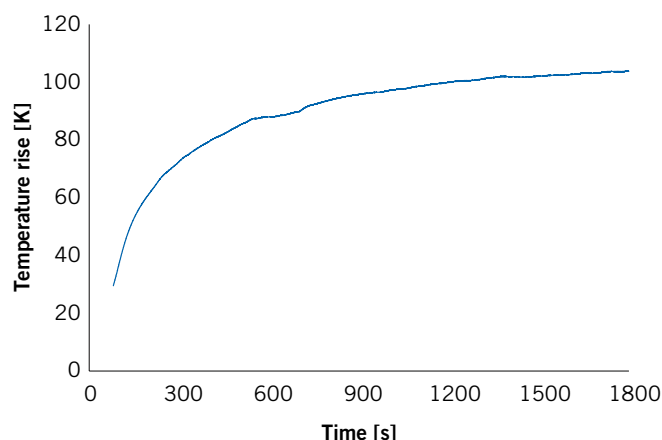


FIGURE 5 Illustration of air flows between the fins of model 1 (left) and model 2 (right) (© Astemo)

FIGURE 6 Temperature rise of the coil during heat-run test (© Astemo)



force, entering near the rotation axis and exiting from the outermost fin edge. In model 2, the centrifugal air-flow generates a low-pressure region in the vicinity of the cylindrical section and the chamfered surface. As a result, the radial airflow between the fins is guided along the chamfer, leading to an extended flow path and a broader region exhibiting high heat-transfer coefficients. Consequently, the introduction of the chamfer increases both the effective flow-path length and the heat-transfer area, thereby enhancing the overall heat-transfer performance.

PROTOTYPE TESTING

To evaluate the cooling performance of the rotary-fin structure, a prototype in-wheel motor was manufactured and subjected to a heat-run test

on a bench setup. Under continuous-rating conditions, the test focused on verifying whether the coil temperature remained within the allowable limit at a continuous output of 5.5 kW. The coil temperature was measured using thermistors attached to the coil ends.

FIGURE 6 presents the measured temperature rise during the heat-run test. During 30 min of continuous operation – corresponding to the continuous rating – the coil temperature rise reached 104 K, remaining below the specified upper limit of 120 K. These results confirm that the proposed rotary-fin air-cooling structure provides sufficient cooling performance for continuous operation.

CONCLUSION

This study aimed to realize an air-cooled in-wheel motor suitable for

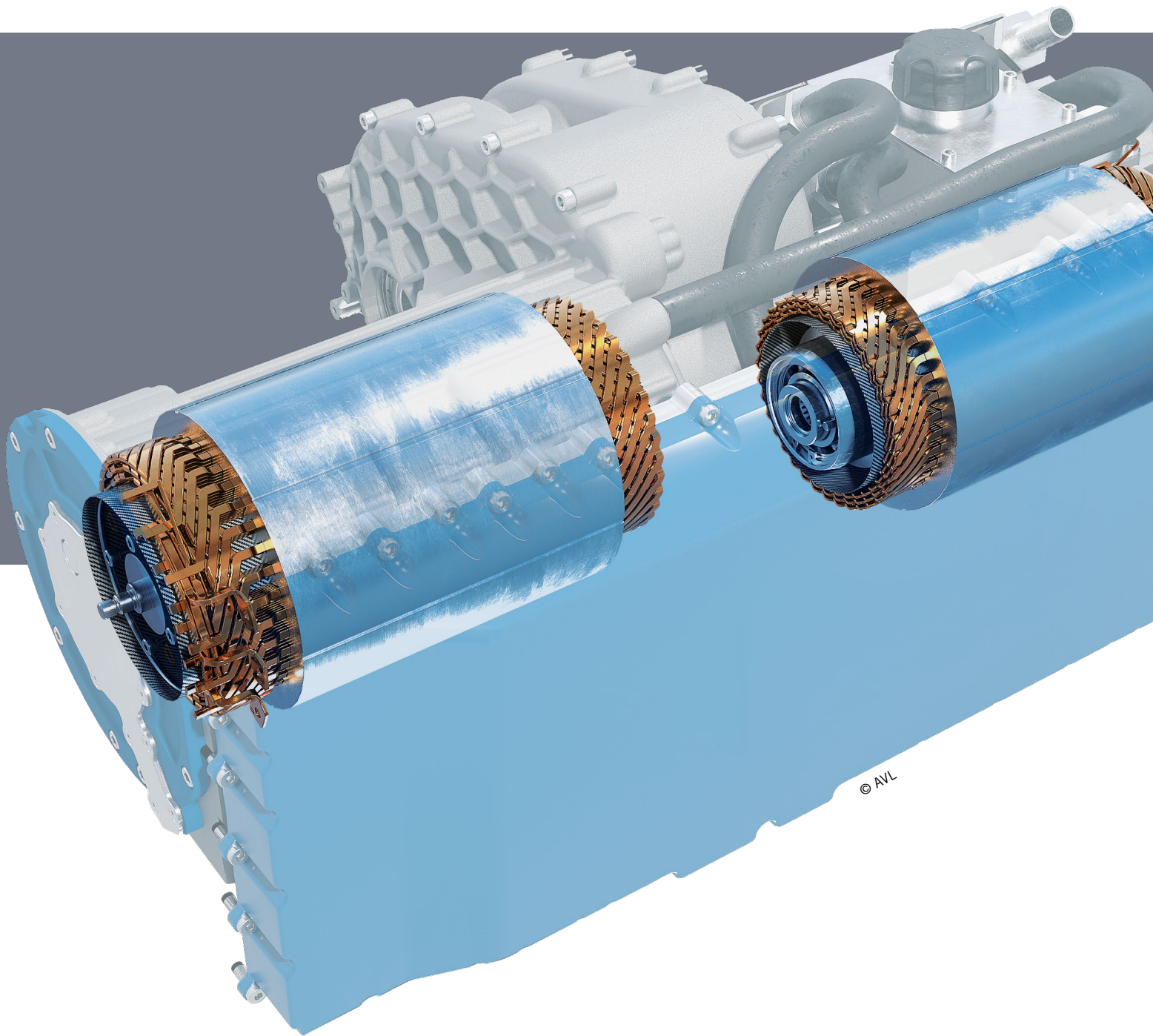
small vehicles, which are subject to stringent constraints in packaging space and system cost, by proposing a rotary-fin structure that dissipates heat into the atmosphere through radial fins integrated into the rotor housing. Thermal-fluid analyses and prototype testing showed that by combining inner and outer fins, both manufacturability and maximization of the total fin surface area could be considered, and an optimal fin configuration that maximizes surface area be determined. Thermal-fluid analyses comparing different fin geometries demonstrated that introducing a chamfer between the disc surface and the cylindrical surface increases the heat-transfer coefficient by approximately 15 %, enabling dissipation of the maximum loss at a continuous output of 5.5 kW. Heat-run tests using a prototype motor confirmed that the proposed cooling structure satisfies the continuous-rating requirement of 5.5 kW. Based on these results, it can be concluded that the proposed rotary-fin structure enables an air-cooled in-wheel motor with sufficient thermal performance for application in small vehicles.

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Manufacturing-related CO₂ emissions are increasingly becoming the key criteria in drivetrain sustainability. As global Electric-vehicle (EV) volumes ramp up, both regulators are tightening their standards and customers and investors are raising their expectations around circular-economy performance, supply-chain due diligence, and transparent product footprints. In parallel,

decarbonization of the energy system reduces the relative relevance of operational emissions, shifting attention toward upstream “embedded” impacts such as the environmentally damaging extraction of raw materials – for example, rare earths –, energy-intensive processing, and transportation impacts. This raises a practical engineering question: If usage-based CO₂ emissions continue to decline, where

are the remaining drivetrain hotspots – and what factors can be influenced realistically by development teams? Against this backdrop, this article compares standardized traction-motor topologies and quantifies the impact on the CO₂ equivalent (CO₂e) when recycled materials are used, considering the entire process from raw material extraction to leaving the factory (cradle-to-gate).



CO₂ Equivalent Influencing Factors for Electric Motors

Looking into upcoming regulations, another parameter will be added to the development of electric motors in addition to performance, weight, manufacturing, and cost targets: the so-called cradle-to-gate emissions. In order to help evaluate different technologies in an early design stage, AVL has developed a method for comparing the CO₂ equivalent footprint.

STANDARDIZED COMPARISON OF MOTOR TYPES

In current EV drivetrains, three motor concepts dominate engineering discussions: the Permanent-magnet Synchronous Machine (PMSM) is still the prevailing choice in applications with high power density requirements and high production volumes, while the Electrically Excited Synchronous Machine (EESM) is gaining traction as manufacturers seek magnet-free alternatives. The Induction Machine (IM), however, is frequently deployed as a secondary machine, for example in all-wheel-drive applications. Published sustainability comparisons between these topologies often point in different directions. The reason is rarely the assessment method alone; more commonly, results diverge because boundary conditions are not aligned. Design assumptions, material selections, operating requirements, and, critically, power and torque levels vary across studies [1].

In order to isolate the effects of topology from design artefacts, a controlled and standardized comparison is required. This involves using Representative Comparable Machines (RCMs) that are de-

signed to the same set of requirements. They are evaluated at a continuous power level that reflects the reality of today's market, **FIGURE 1**. Specifically, a study derived a representative continuous-output power rating for model year 2023 based on EV market data [2]: The power of the single-motor drive unit is aggregated across vehicle segments, evaluated both as an unweighted average and as sales- and model-weighted averages (based on production forecast model data and sales figures), resulting in values of approximately 150 kW [3, 4.] For ease of calculation and communication, a nominal 150-kW continuous rating is therefore selected as the reference point – high enough to be representative across the dominant passenger-car segments. At the same time, the ambiguity and scatter that typically accompany peak-power specifications is avoided.

MATERIAL HOTSPOTS IN TRACTION MOTORS

Across the assessed traction-motor designs, the material contribution is concentrated in four dominant mass and impact drivers: aluminum (primarily housing and structural parts), copper

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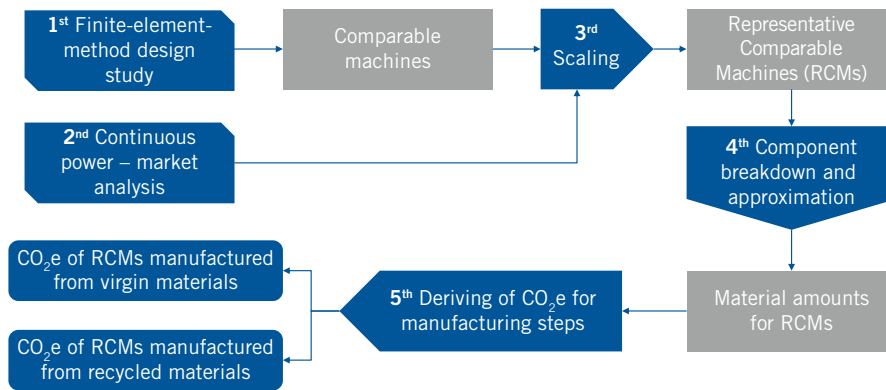


FIGURE 1 Approach of standardization and scaling of motor models (CO₂e: CO₂ equivalent) (© AVL)

(winding system and electrical connections), electrical steel (laminations in stator and rotor), and – specific to PMSM – Neodymium-iron-boron (NdFeB) permanent magnets, **FIGURE 2**. Minor components with low mass share and limited influence on cradle-to-gate CO₂e are treated as secondary and are therefore excluded from the hotspot discussion to keep the analysis decision-relevant. From an engineering perspective, this concentration is intuitive: Housing and magnetic core elements are typically the main factors influencing the overall motor mass, while the magnet system (despite comparatively small mass) can dominate footprint intensity and supply-chain risk due to energy- and process-intensive upstream steps as well as concentrated sourcing.

METHOD BASELINE

The approach to determining the CO₂ equivalent product balance is based on a design comparison of RCMs evaluated at two voltage levels (400 and 800 V). Key design targets, such as diameter and speed, are kept consistent across topologies. The design comparison uses the Finite Element Method (FEM). The resulting FEM motor models are high-speed machines. **FIGURE 3** shows a PMSM optimized for maximum power density within the manufacturing constraints. At the same time, passive material masses were reduced to a technically “minimum viable” level using aligned thermal assumptions, ensuring that no differences arise due to oversized housings or conservative cooling margins. All designs are then scaled to a representative market-standard continuous power of about 150 kW explained

at the outset to reflect typical traction-motor sizing in current EV segments. For the sustainability assessment, the system boundary is cradle-to-gate, using primary-material emission factors from databases such as Ecoinvent [5]. Factors for recycled materials are derived from literature-based secondary routes that assume optimal material recycling in order to quantify an optimistic but technically sound circular economy scenario.

RESULTS

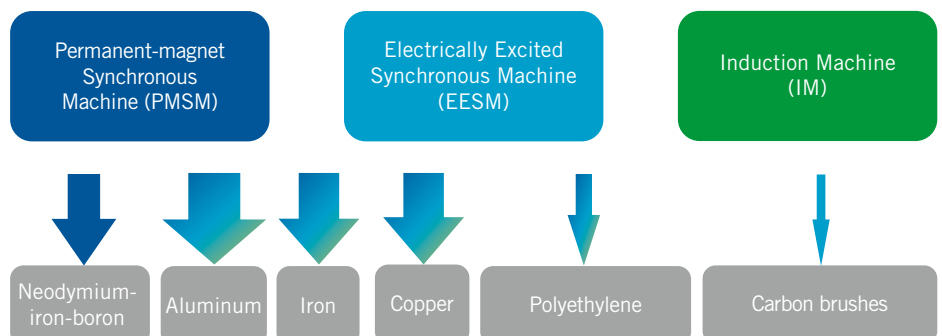
The key finding is that topology differences are measurable, but recycling is the dominant lever for cradle-to-gate CO₂e in the defined 150-kW class. In the virgin-material scenario, the induction machine exhibits the highest footprint at exemplary 271 kg CO₂e, while the high-speed PMSM lies in the range of about 235 to 263 kg CO₂e and the EESM at around 234 kg CO₂e. When switching to recycled-material supply routes, all three concepts converge to approximately 50 to 66 kg CO₂e, corresponding to an overall reduction of

about 75 to 79 %. The underlying driver is material-specific: In the virgin case, the aluminum housing is usually the largest single contributor, whereas in the recycled case, the relative share shifts. Eelectrical steel becomes more dominant in machines that are not excited by permanent magnets, and in PMSMs, the proportion of NdFeB is significant when compared, **FIGURE 4**, reflecting that magnet recycling remains more CO₂e-intensive than the best-case secondary routes for aluminum and copper.

TECHNOLOGICAL IMPACTS

For electric-motor engineering and industrialization, the implications are straightforward: Machine topology selection matters, but it is not the primary manufacturing CO₂e lever. The larger opportunity sits in a design that is suited to a circular economy (design-for-circularity) and in proactively shaping material pathways. Designs should facilitate disassembly, clean alloy separation, and viable recovery methods for high-impact subcomponents, such as NdFeB

FIGURE 2 Dominant materials in traction motors: the color gradient in the arrows indicates which materials are required, and the arrow thickness represents their contribution to the total footprint (© AVL)



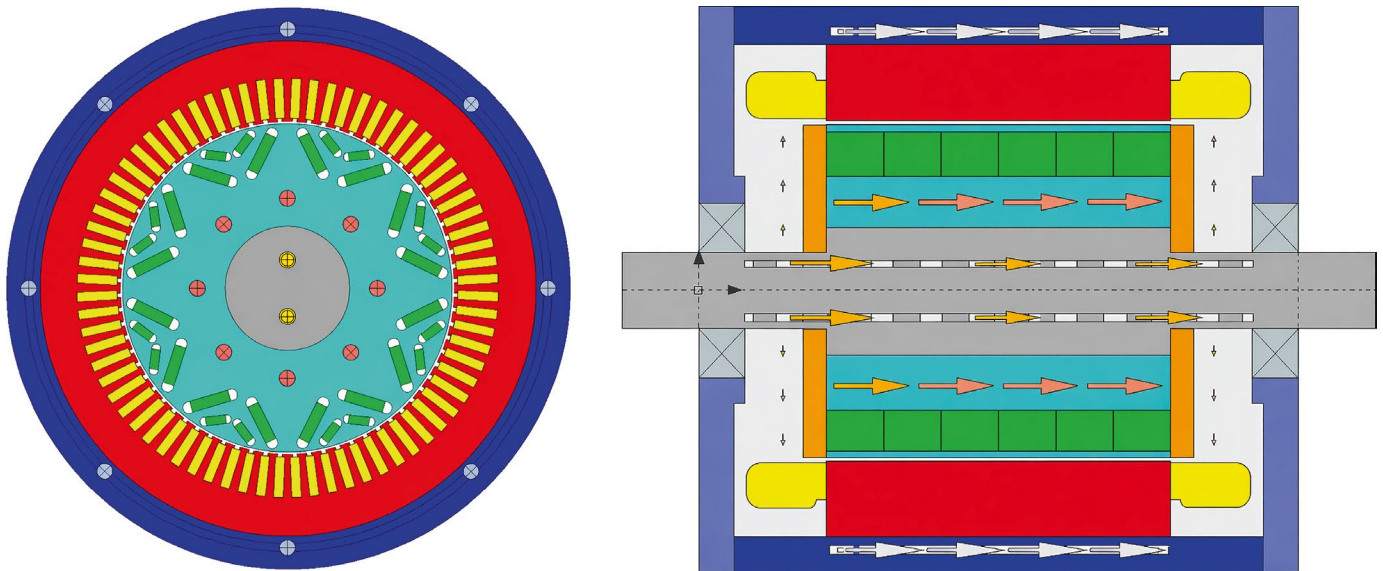


FIGURE 3 Ansys motor CAD drawing of a permanent-magnet synchronous machine with 800 V DC and a structure of 72 slots and eight poles (© AVL)

magnets [6]. At AVL, these future requirements are already covered by new design guidelines and by making use of advanced simulation tools. For the housing system, this translates into securing recycled-aluminum supply, optimizing casting and finishing routes, and avoiding structural over-dimensioning in areas where the thermal concept and load paths allow. For copper, the central lever is enabling high-grade scrap loops (winding-to-winding where feasible); once recycled, con-

tent is available at scale, and downstream process choices typically have a second-order effect compared to the avoided primary production [7]. Recycling is also beneficial for electrical steel, but rolling and processing remain energy-intensive, making supplier engagement essential – particularly with regard to the use of electricity generated with low CO₂ emissions as well as the overall energy efficiency of the processes [8]. Consequently, topology should be chosen primarily

based on efficiency, cost, and a strategy focused on CO₂ equivalents, while low-carbon material sourcing and circular design can be treated as a parallel – and often larger – CO₂ lever that should already be integrated into the early stages of industrialization.

Machine design directly impacts lifetime emissions, from material selection during production and efficiency during operation, to recyclability at end-of-life. The designs modelled here were built

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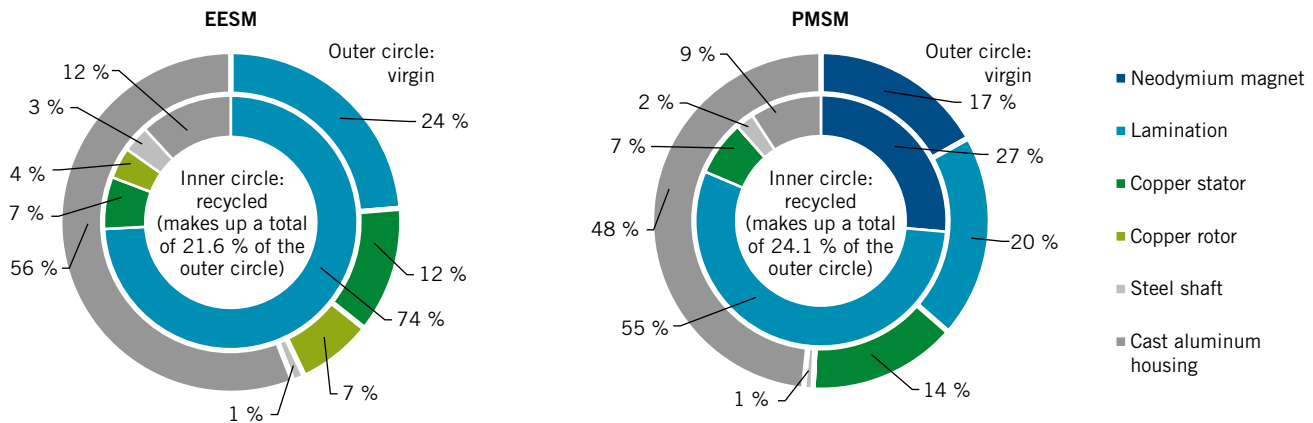


FIGURE 4 Exemplary effects of material selection on CO₂e emissions as a comparison between virgin and recycled materials (© AVL)

on AVL's sustainable Electric Drive Unit (EDU) solutions, optimized for efficiency within Worldwide-harmonized Light vehicles Test Cycle (WLTC) operating conditions, achieving an average efficiency of $\geq 92\%$ (calculated using AVL Cruise) for both EESM and PMSM variants [9]. Considering future scenarios in which 100 % of electricity is generated from renewable sources, manufacturing emissions will dominate the CO₂e footprint throughout the product lifecycle. Not only for this reason were high-speed techniques applied, maximizing energy density while minimizing magnet material usage [10]. These methodologies yield similar environmental and performance profiles for the EESM and PMSM.

REGULATORY RELEVANCE AND MEASUREMENT READINESS

The quantified cradle-to-gate CO₂e reduction potential of about 75 to 79 % from secondary material routes underscores why EU policy is increasingly focused on upstream impacts: Once use-phase emissions decline, the performance and stability of the supply chain, along with the embedded material performance, become the decisive battleground. This directly aligns with the EU's Circular Economy Action Plan logic of keeping materials in circulation plus improving product information transparency. Further on, this approach ties in with the emerging Digital Product Passport infrastructure under the Ecodesign for Sustainable Products Regulation (ESPR). In parallel, the Corporate Sustainability Due Diligence Directive (CSDDD) requires companies to identify and ad-

dress environmental (and human-rights) risks throughout the entire value chain – making the use of materials with a high environmental impact increasingly less acceptable. Practically, OEMs and suppliers should prepare for data readiness by tightening material traceability, collecting supplier-specific footprint factors or EPDs, and putting robust verification in place for recycled-content claims (mass-balance rules, auditability, chain-of-custody). The aim must be to actually achieve the reported reductions and to document them in a manner acceptable to regulatory authorities.

SUMMARY AND OUTLOOK

The controlled comparison of representative 150-kW traction-machine designs shows that high-speed PMSM and EESM exhibit similar cradle-to-gate CO₂e levels, while the induction machine trends higher, primarily due to increased material demand under the aligned design constraints. More importantly, the scenario switch from primary to best-feasible secondary material routes reduces cradle-to-gate CO₂e emissions by more than 75 % across all three topologies – an effect that is larger than the technology spread itself. It therefore cannot be treated only as a detail in drivetrain optimization.

The next steps are as follows: first, improve the availability and comparability of public data for NdFeB supply chains and recycling routes, and strengthen alloy-specific circular loops (especially where material quality determines down-cycling versus closed-loop feasibility). In addition, extend the assessment from cradle-to-gate toward a full life-cycle view –

including use-phase and end-of-life. This allows design decisions to be directly linked with circularity performance and system-level climate impact.

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Three-dimensional Renewal

The German automotive industry has experienced success over decades, which led to booming development activities and a continuous increase in production figures. Although the last ten years have been marked by individual crises such as the diesel crisis, which brought challenging changes in legislation, or such as the Covid pandemic, which turned directly into supply chain bottlenecks and the chip crisis, record figures have been achieved, and financial success has remained stable.

Today, however, the industry seems to be deeper in crisis than ever. While the automotive industry has overcome the individual crises, a completely new challenge has developed coming from the technology industry over the last few years. The technological disruption caused by rapidly advancing software development and artificial intelligence is hitting now radically, abruptly, and ruthlessly honest from the outside an industry that has always been able to develop out of the crises on its own with traditional virtues such as drive technology, premium quality in body and interior, and driving experience. Now the industry is facing a challenge that requires new skills, more flexible ways of working and, above all, much faster development cycles, thus shaking the foundations of its previous success.

How does the German automotive industry manage to maintain or even use its traditional strengths and to reinvent itself at the same time? Renewal must take place in three dimensions – technological, structural and cultural. In the technological con-

text, there are two major transformations to be mastered – the development toward an electrified portfolio and toward a Software-defined Vehicle (SDV). The latter in particular requires new approaches and skills. Defining the vehicle from the software and the electronic architecture and working in decoupled development cycles between vehicle development and software development is the basis. In addition to new skills in the field of software development and new ways of working in short-cycle development steps, this path offers endless possibilities in the context of data-driven development and the use of artificial intelligence.

In order to cope with this and at the same time not overstimulate the accompanying dimensions of structural and cultural transformation, it is essential to maintain focus. Established manufacturers must face these changes, expand their existing competencies and, where necessary, enter into an intensive dialogue with cooperation partners to successfully implement the crucial interaction of highly networked functions as well as the integration into the customer's living environment and ecosystem. This development supports the transformation to an electrified powertrain portfolio, as data-driven development and interaction with the ecosystem create and expand solution spaces that are crucial for electromobility. This results in opportunities for optimizing the charging experience and increasing efficiency and thus range, for example.

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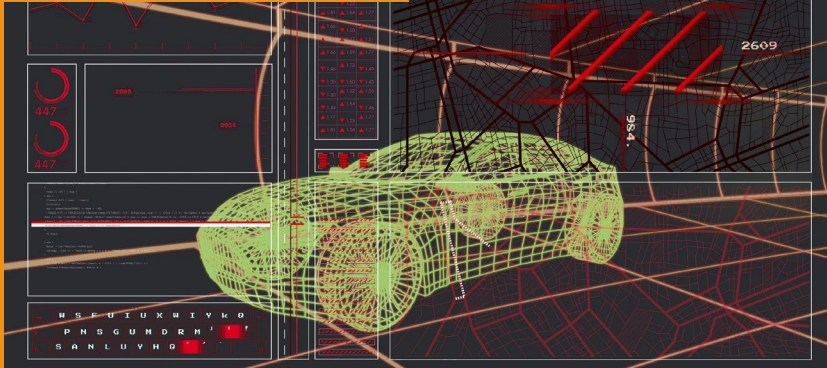
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COVER STORY

Simulation and Test



The current challenges in automotive electronics lie in managing increasing system complexity, ensuring signal integrity and interactions early on, and scaling test cases across all E/E domains. At the same time, simulations and HiL tests must accurately model real-world boundary conditions, timing uncertainties, and EMC influences to shorten development times and reduce validation risks. MathWorks describes how, in virtual sensor technology, AI models derive physical quantities that are difficult or costly to measure from available sensor data. This enables more efficient monitoring

and reduces the need for additional hardware. Kristl, Seibt & Co, Keysight Technologies, PTS-Prüftechnik, and IPG Automotive present an indoor vehicle-in-the-loop approach that couples the real vehicle with a virtual, reproducible environment, thereby enabling function-centric validation at the system-of-systems level. Synopsys has developed a capability-based analysis approach that allows for the systematic evaluation of test efficiency. The focus is on feedback latencies, evaluation effort, reusability, and integration across the entire lifecycle.

IN THE SPOTLIGHT

Photonics as a Strategic Complement to Electronics

DEVELOPMENT

Enable the Ramp-up of Heavy-duty Electric Vehicle Fleets

Enhanced Fault Management in Electric Vehicle Powertrains

ATZextra VEHICLE ELECTRICAL SYSTEM

Centralized E/E Architectures in Software-defined Vehicles

PCB-based Diagnostics for Reliable Vehicle Systems

Compact CAN Gateways for Secure E/E Architectures

Tolerance Compensation in Board-to-Board Connections

Passive Laser Welding of Aluminum and Copper



Mostafa Elemam
Embedded Software Engineer
at Avelabs, Arrow Electronics
in Cairo (Egypt)

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What CRA Means for OTA Updates

Cybersecurity requirements in the automotive industry are increasing at an ever-faster pace, and thanks to the transition to software-defined vehicles (SDVs), OEMs can both implement new features more quickly and address security vulnerabilities. In light of new standards and the advent of post-quantum cryptography, cryptographic foundations must be designed to protect secure boot chains, over-the-air (OTA) updates, and ECU authentication for secure, risk-controlled OTA. The UN-ECE guidelines R155/R156 underscore this necessity by regulating cybersecurity and software updates, while the EU Cyber Resilience Act (CRA) raises the baseline cybersecurity requirements for products with digital components. The same SDV platform must remain secure via OTA for ten years from the start of production, even as cryptographic requirements and threat levels evolve. Updating an ECU's security anchor is challenging and requires a comprehensive risk analysis in the field to avoid breaking chains of trust or introducing new attack vectors. For example, if the underlying cryptography is changed because an algorithm is no longer considered secure or new standards are mandated, the SDV requires a secure migration path. This requires a secure update function for the firmware of the hardware security module (HSM).

OTA security requires end-to-end authenticity and integrity, protected signatures, robust verification, and protection against rollbacks to a less secure software version to prevent compromise of the entire fleet. The transmission channel

should be secured during transmission, for example via the Transport Layer Security protocol, and authorized by cryptographically signed metadata or commands. Encrypting the payload can further reduce the risk of sniffing and reverse engineering. These controls are particularly important for security anchor updates, as errors can compromise both secure booting and the OTA chain of trust. Updating the HSM firmware is extremely challenging, as the HSM is involved in verifying system integrity and updates. The platform must therefore be based on an immutable verification foundation, such as code in non-rewritable memory or one-time programmable security bits (so-called fused keys). This authenticates a firmware update package and ensures secure recovery after failures. Ultimately, remote updates for HSM firmware are both a technical feature and a critical security measure throughout the entire lifecycle. Since the compromise of the signature infrastructure could enable large-scale attacks, the signature keys for HSM updates must be isolated as a critical resource through strict controls. The processes of development, testing, release, and production of HSM firmware should be rigorously reviewed in accordance with ISO/SAE 21434. A structured threat analysis and risk assessment should be employed to identify threat scenarios, evaluate the feasibility and impact of attacks, and derive cybersecurity objectives and requirements that remain valid as algorithms, standards, and attacker capabilities evolve.



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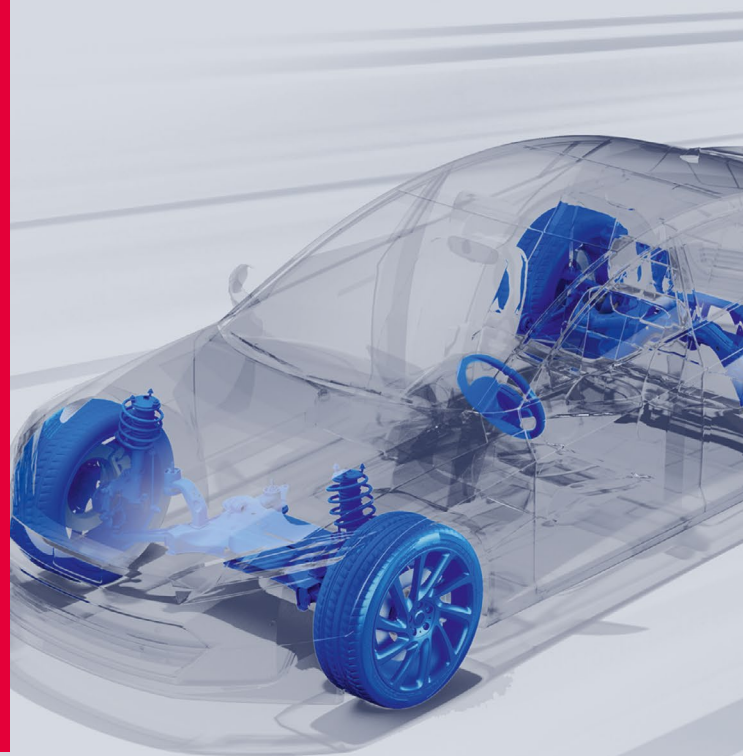
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