cti magazine

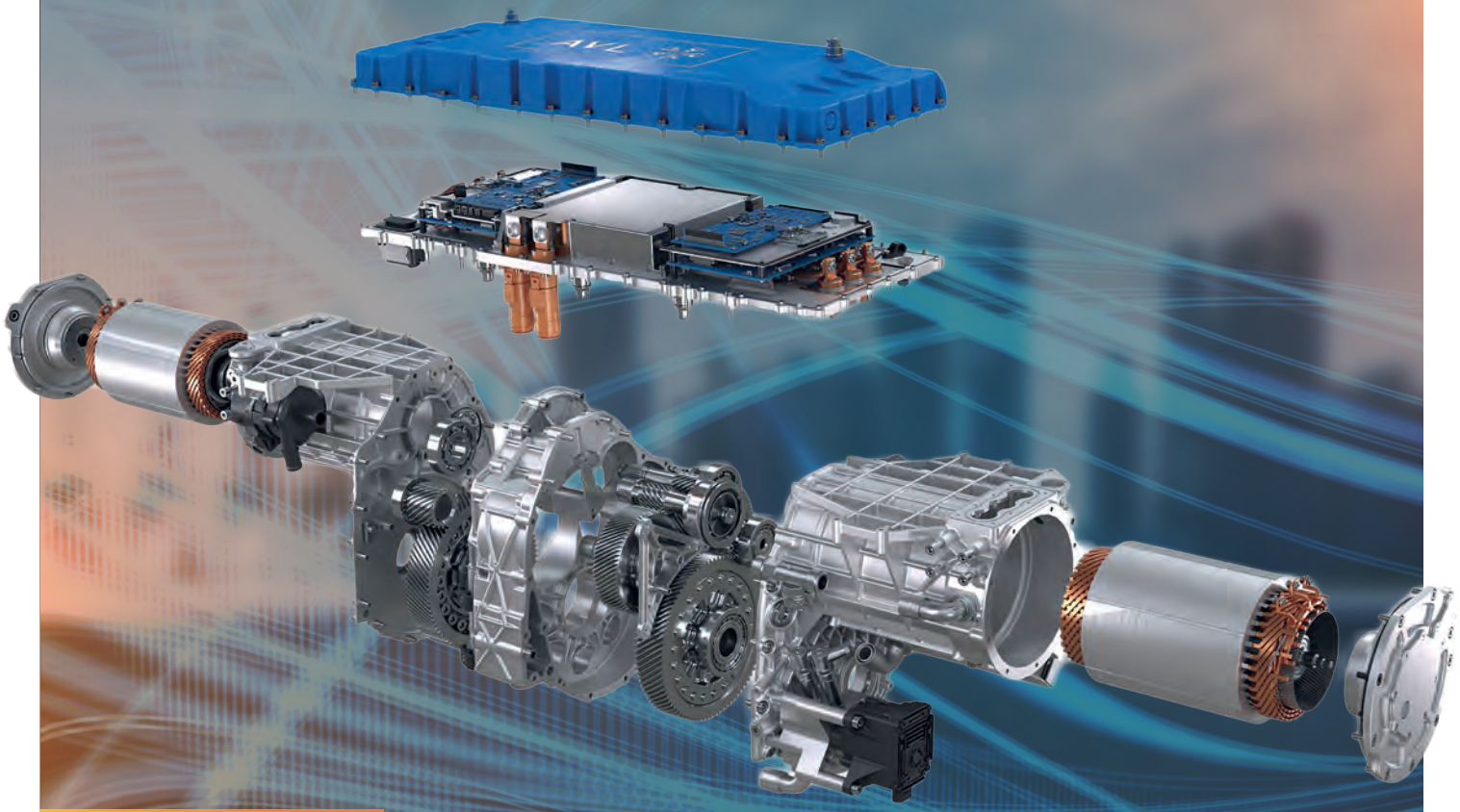
December 2024

Dr Norbert Alt

We should make a clear commitment to electromobility

TotalEnergies

The first standard specification for EV fluids



Brudeli

Powerhybrid™ beyond P2 hybrids

Image source: AVL

cti magazine

Dear Readers

2024 saw some reluctance to buy electric cars in some European regions and the USA. How should we respond to this?

In our interview with Dr. Norbert Alt, FEV, he recommends „making a clear commitment to electromobility“, and including next-generation REEVs, as are common in China. In fact, innovation is continuing unabated:

In this issue of the CTI Mag, AVL reports on the design of high-speed e-motors up to 30,000 rpm, for example. The Munich-based company Hyperdrives presents its Hollow Conductor Technology for stator cooling. Brudeli from Norway has developed a new plug-in hybrid drive for heavy commercial vehicles in a P2.5/P3 arrangement, which is said to offer a significantly better TCO than diesel powertrains.

With Lixiang, Infinium, and Total Energies, three companies are reporting on fluid solutions for electric drives and their particular challenges. New requirements also apply to electric drives' mechanical and acoustic design: Furtwangen University presents damped roller bearings for e-drives, JJE an electromechanical differential lock, and the University of Prague introduces a dog clutch without angular backlash. Regarding sustainability, the International Copper Association discusses: How can we achieve net zero in copper production?

Our thanks go to everyone who contributed to this CTI Mag. We wish you an inspiring read – and invite you to take the electrification discussion further at the next CTI Symposium USA on 13 & 14 May in Novi, Michigan!

Your CTI Magazine Team

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cti symposium

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Interview

“We should make a clear commitment to electromobility”

Dr Norbert Alt, COO of FEV

There is uncertainty about which drive solutions will be best in the near and longer term. In our interview, Dr Norbert Alt, COO of FEV, an innovation driver in the mobility sector, advocates a technology-open approach but with a clear commitment to electric vehicles. Hybrid BEVs are included, he says – but e-fuels will not be realistic for passenger cars in a market-relevant quantity by 2035.

Dr Alt, what do you think about the current reluctance to buy battery-electric cars?

Looking at BEV sales figures in China, the USA, and the EU, you see continuous growth and an all-time high in absolute terms. If you count BEVs, PHEVs, and REEVs together, the overall market share has grown from 22 in the first half of 2023 to 25 percent in the first half of 2024. In China, for example, New Energy Vehicles – the NEVs – have a market share of 45 percent. In Germany, we did see a decline of 16 percent for BEVs and an increase of 13 percent for PHEVs in the first half of the year. In contrast, 94 percent of new cars registered in August were electric in Norway. These are just examples. So, we should look more at international developments, not so much at ourselves in Europe. When I talk to industry stakeholders, everyone agrees that in the long term, we‘ll mainly drive electric, meaning BEVs with some PHEVs or REEVs and continuously decreasing shares of ICE in passenger cars.

How do you define REEV as being distinct from PHEV?

A while ago, we had REX, which was a Range Extender with a low-power combustion engine. Today's REEVs – range-extended electric vehicles – have a powerful combustion engine that keeps the electric drive motor operating at full power even when the battery is low. At FEV, we actually call them Hybrid BEVs. So a Hybrid BEV / REEV should be, battery-electric born', meaning it's an electric car that we then hybridize. You can only have one vehicle platform, a BEV platform because that will be the mainstream. Hybrid BEV / REEV gives you the driving dynamics of a BEV plus additional range from the combustion engine. In China, Hybrid BEV / REEVs have a significant market share. In the spirit of technological openness, we in Europe could learn something from this. Hybrid BEVs would also help people make the transition to pure electric cars.

Interest in REEVs seems to be growing in North America, too ...

Under the ACC-II Regulation of the California Air Resources Board, 35 percent of all vehicles must be ZEVs, or zero-emission vehicles, from 2026 – and 100 percent by 2035. Almost one-third of the US states are adopting this legislation. Here's the surprising part: Of those ZEVs, 20 percent can be hybrids, provided they have a minimum electric range of 70 miles. So basically, this opens a little window where Europe can say to the authorities: ‚Hey, look at the rest of the world; these concepts are successful in China, and they're enshrined in law in the USA'. As engineering service providers, we always have our ears to the ground so we know what's coming down the line. And right now, the Hybrid BEV or REEV topic is in a strongly increasing development focus. We believe that taking a similar approach as China or the USA would make more sense than unproductive debates about banning ICEs.

And what if e-fuels were to become established?

The future will be significantly electric. In Europe, we discuss using e-fuels after 2035, which, in theory, are great. But with an existing fleet of a good 1.3 billion cars worldwide, we'd need them very quickly. In the years leading up to 2035, they cannot help. It takes eight to ten years to approve and build the production facilities. Even if we built 100 percent of the plants being discussed worldwide, the total amount of e-fuel would cover just 10 percent of German requirements – in areas outside individual mobility! Even the aviation industry is concerned about how to hit its targets. By 2032, the goal is to replace 1,2 percent of aviation fuel with sustainable e-fuels known as RFNBOs, or renewable fuels of non-biological origin'. So, we don't see a realistic way of getting meaningful quantities of e-fuels on the road in 2035. One option not yet on the table would be similar as in US and China allowing Hybrid BEVs that burn fossil fuels and can drive 150 km electrically for example, to stay on the road longer than planned. If we were to regulate for 70 percent BEV and 30 percent Hybrid BEV, for instance, we would still be driving around 90 percent electric overall.

Moving to vehicle technology – how would you design a Hybrid BEV drive architecture?

The question is, do you want just serial, or do you want series-parallel? Obviously, engineers want the latter because you have high efficiency on the highway, too. But if one has a battery range of 150 or 200 km, maybe one can live with a purely serial drive that consumes a little more fuel at 140 or 150 km/h, which you can only do in Germany anyway. And in the city, the serial hybrid drive is 5 to 7 percent better than a conventional parallel hybrid. Also, we're continuing our efforts to make combustion engines more efficient. We already have engines with 43 percent efficiency in production, and we'll soon be heading for 45 percent and more.

How will electric drives and charging technology develop in the future?

There's a clear trend towards 800V. But market penetration will be top-down for cost reasons, with 400V systems widespread in the lower sectors. In the truck sector, we're talking about megawatt charging with even higher voltages. Another exciting development path involves optimizing the charging curve for 400V systems. The aim is to minimize losses even when fast charging to 80 percent. We are currently developing 400V systems, which you can charge from 20 to 80 percent in 19 minutes, and which are on a similar level as an 800V system. Several factors make this possible: a special cell chemistry that is well understood, an accurate battery management system, and improved heat dissipation. So, it's not just about high charging power – you also need the smoothest possible charging curve. That's something that offers excellent customer benefits.

What about trends in electric motors?

There is a somewhat unexpected trend here. In the past few years, motor speeds have increased – up to 30,000 rpm in the Far East. Higher speeds mean smaller motors, which is good, but also more friction, which is not good for efficiency. Some German manufacturers have now reduced EDU rpm to 13,000 and are seeing excellent consumption at 120 or 130 km/h. You only need higher rpm for sporty applications or when the package is a high priority. Another trend – one we are working on with a German company – is dual-rotor motors, which enable high efficiency at part load, high power and torque density and lower costs. And a topic the whole industry is working on is externally excited electric motors. These require no heavy rare earths and can reduce our dependencies on raw materials.

Which way is battery chemistry heading?

Nickel-manganese-cobalt (NMC) and lithium-iron-phosphate – LFP – batteries are used mainly in passenger cars, especially LFP in the cost-sensitive segment. We're also developing sodium-ion batteries. Sodium Chloride is available in large quantities in nature, so that's more favorable concerning raw materials. Also, sodium-ion is already not far behind LFP regarding energy density. And since Hybrid BEVs batteries require less space in a standard BEV platform, they can also cut production costs for Hybrid BEVs. Then, in the high-performance sector, we're talking about solid state, but that will take a while. Semi-solid-state batteries will come sooner. We're currently working with manufacturers on joint developments here.

What drive technologies do you foresee in trucks in the next few years?

Surprising as it may seem, there is also a trend towards full electrification in Europe. At the last IAA, almost all major OEMs shared that view. The trend also applies to long-haul trucks because this is an industry where TCO rules. We are talking about 30, possibly 40 percent BEV share in 2035. Hydrogen will also play a role. FEV is working with manufacturers to develop both fuel cells and hydrogen-powered combustion engines. But the majority will be battery-electric trucks. Some OEMs have allied to install 1,700 charging stations along main routes in Europe by 2027. The electric trucks and infrastructure operators are there, but we need support and commitment at the political level.

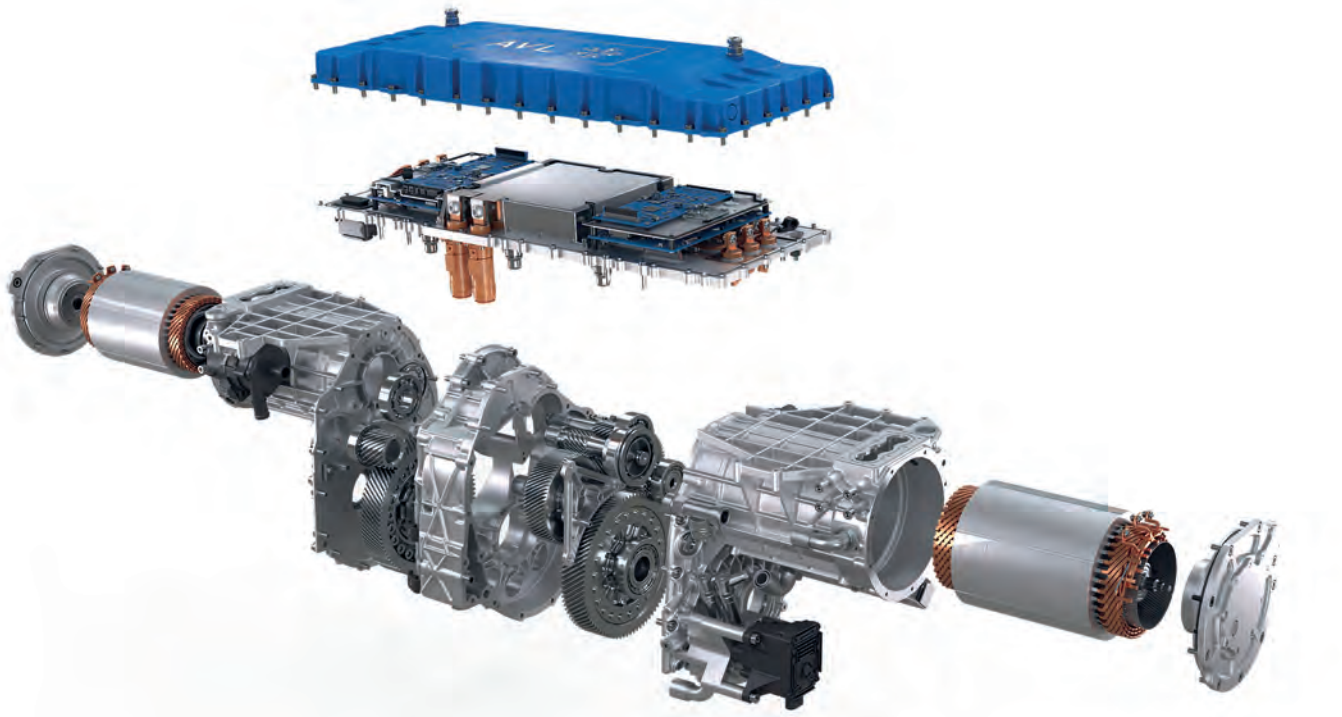
Some people say China is well ahead of Europe in BEV technology. What's your view?

The BEV vehicles that German and European manufacturers offer today are on a high level of technology. They have good efficiency, high charging power, system design, drag coefficient, and more. On the other hand, the Chinese are ahead in battery cell technology and production know-how; they have invested strongly in the development and have better access to raw materials. But in the future, more and more processes will be sustainable, through to a circular economy. This will reduce the need to add further raw materials. That will put the issue of „who has the raw materials?" back into perspective. What's more, German manufacturers are spending billions on setting up battery cell production. At FEV, we have our own cell chemistry department, too – and as a development service provider, we work with the Chinese. Another topic is automation, which means ADAS systems, autonomous driving, etc. Here, some other countries are nowhere near as advanced as German manufacturers. So, from a technology perspective, the outlook is a lot brighter than some people say, and we will see continuous innovations in all areas. Additionally, one has to mention that low-cost BEVs are very important for the expected market penetration of BEVs, and the capability of the Chinese to produce on low cost is very high which is the major challenge for the European.

How could decision-makers in politics and the industry advance electric mobility?

We would like the EU to look at the regulatory approaches of the USA and China, and to use them as a model to some extent. At the moment, we are letting car owners hope they can have e-fuels in 2035. That's not going to happen, only for a very small share of the market. We should also make a clear commitment as a tech community, saying we will drive more and more BEVs, some of them Hybrid BEVs. We should allow a defined percentage of Hybrid BEVs and stop the unhelpful discussion about the ICE ban. By 2045, we may reach the point where filling stations no longer stock fossil fuels, just bio and e-fuels. Another critical point we really need to tackle is electricity prices. You can generate electricity with a photovoltaic system for 10 cents per kWh, or even less. If people could charge their vehicle for 10 cents, electric cars would sell like hot cakes. Hybrid BEVs would benefit, too, because people would prefer electric driving whenever possible.

Interview: Gernot Goppelt



High speed – The enabler for cost reduced and power dense sustainable electric drive units

Mathias Deiml, AVL Software and Functions GmbH
Katharina Berberich, AVL Software and Functions GmbH
Wilhelm Vallant, AVL List GmbH

The e-mobility market is facing the challenge of an increasing pressure to reduce unit costs and increase power density and performance at the same time. AVL's second-generation high-speed e-axle increases power density to reduce material usage, focusing on the e-motor and gearbox, with CO_2-equivalent footprint as a key comparison criterion.

With the updated design in Generation 2 it achieves a power density of over 4.3 kW/kg, features a 30,000rpm motor, silicon carbide double inverter, and loss optimized gearbox. It minimizes magnet and copper use, reducing unit costs, CO_2 emissions and improving efficiency.

Speed and cost – Why 30.000 RPM

Electric motors, such as PMSM based machines widely used for automotive applications, consist of high masses of expensive materials: dynamo sheet metal, magnets, copper. Reducing the size of the motor reduces these costs. Downside of this characteristic is that scaling down motor size means to reduce its torque.

$$P_{mech} = \omega * M;\ M \sim d^2 * l;$$

d: diameter; l: lamination length

To maintain the power rating the rotational speed needs to be increased when reducing motor dimensions. An increase of factor 2 in motor speed results in a reduction of active motor material by a factor of 2. Provided that special or expensive technologies in motor and transmission can be avoided there is a substantial cost saving in the motor. Weight and size of the motor can be reduced accordingly and are additionally beneficial for vehicle features and again costs.

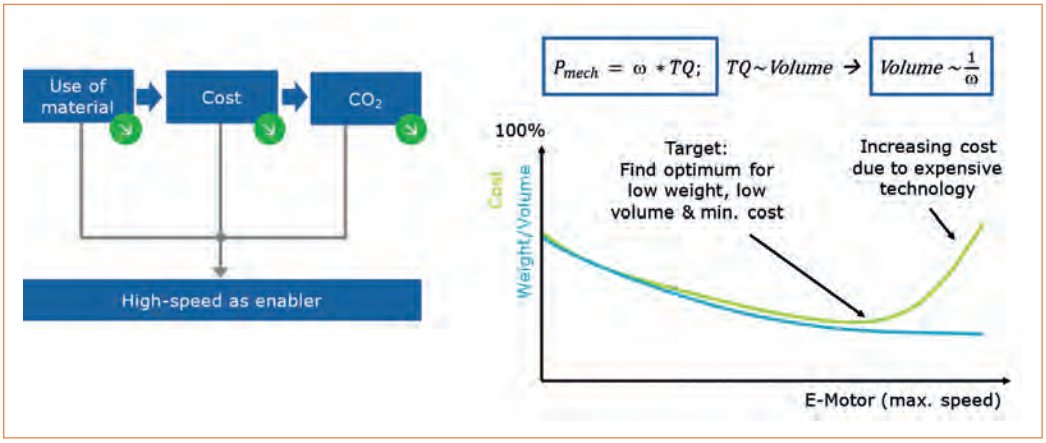


Fig. 1: Speed vs Cost

These relations between speed and weight/volume/cost are shown in Fig. 1. AVL's engineers were looking for the optimal speed, at which weight and cost are both low [1] and found it at 30.000 RPM.

High speed e-machine development

To develop this e-motor for the required 30.000 rpm without using expensive technology like cobalt steel lamination, the following challenges had to be overcome:

- Mechanical rotor strength due to high centrifugal forces
- Bearing technology at high rotational speed in partnership with SKF
- High frequency losses in copper windings
- Increased iron losses due to higher fundamental frequency of 1500Hz

The developed Solutions included new innovative designs for

- Hairpin Windings
- Cooling concept

Selecting hairpin winding technology helps to deal with the high frequency losses:

A six-layer hair pin winding with bended copper on one side and copper forming and welding on the other side was chosen. A copper fill factor of 60% was achieved. This factor includes the oil channels for cooling, described in the cooling chapter. A slot-liner with only 0.1 mm thickness was used. The slot was optimized for coolant flow in combination with copper fill factor.

There is no need for resin in the slot. Thus, additional micro-oil channels along the copper improve coolant flow. Recycling of copper is facilitated; the winding can be removed in one piece without shredding. [2]

The prototypes were manufactured using SLM selective laser melting, a 3D copper printing process. This has further advantages:

- Smaller winding heads possible
- Low cost for tooling
- Smaller resistance compared to welding

Copper printing, may be only the beginning, further optimizations like free shaping of super short winding heads can be realized in later steps. It is suitable for small series production. For large scale volumes welding shall be used. AVL's current design enables both manufacturing processes. [2]

The sophisticated direct cooling concept shown in more detail:
Direct oil cooling means that the coolant is directly in contact with the copper winding in the slots and winding heads. The stator is fully filled with oil, which is pumped along the stator slots. Thus, the copper losses are very efficiently cooled. An air gap tube keeps the oil away from the rotor space, so no friction or splashing losses are present. [3]

The transmission uses a dedicated lubrication fluid with an own oil pump and filter. In addition – compared to Gen 1 – there is now a transmission fluid cooler integrated. This device can be installed optionally, for high performance application, where it is needed. [2]

The magnets are cost-effective quality with low heavy rare earth content.

Achieved eMotor performance

The efficiency map shows a maximum of over 97%, in a wide range. Due to NO20, segmented magnets and high copper fill factor the losses at high speeds are well balanced. This is shown in Fig. 2.

The map is generated for 180°C copper temperature. Thanks to direct oil cooling, the copper temperature is typically 90°C, resulting in ever better efficiency.

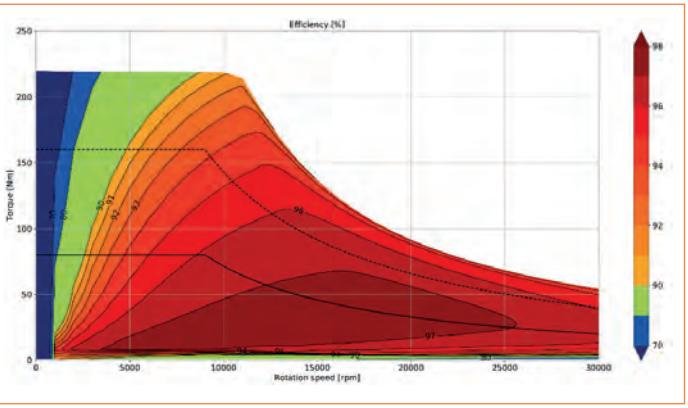


Fig. 2: High Speed E- Machine Performance and Efficiency at 180° C Machine Temperature

Overall EDU system implementation

The EDU design with the new e-Motor continued to focus on overall cost reduction, reduction of material usage and increased power density without losing efficiency. Scalability and high-volume rollout were also key considerations. With these requirements the resulting concept is described:

1. EDU:
a. dual motor, dual torque path to enable torque vectoring for premium segment
b. central gearbox for optimal length of drive shafts in various vehicles
c. low profile design to support flat chassis

2. High speed motor:
a. standard materials for sheet metal and magnets
b. PSM technology for best power density and system efficiency
c. high frequency winding for low factor $^{AC\_loss}/_{DC\_loss}$
d. cooling with best-in-class effectiveness, combined with the inverter
e. mechanical rotor stability up to 1,2 * n_{max}

3. SIC inverter:
a. high power density in complete package
b. best efficiency, fast switching slopes, variable switching frequency
c. combined DC link, interleaved switching, low EMC emissions

4. Gearbox:
a. 2 stage transmission, single speed
b. lay shaft concept
c. high efficient tooth geometry, optimal NVH tradeoff
d. injection lubrication, separate fluid than motor

CO_2e footprint and comparison to other systems for AVLs e-axle technology

Besides the already discussed technological and cost targets, a future proven EDU concept must also comply to a sustainable design to reduce CO_2e footprint and increase efficiency in the life cycle.

„Design-to-CO_2e" as a holistic approach in the course of the systems engineering meant a transition from an original focus on „design to function" and „design to cost", to the additional dimension of CO_2 equivalent over the life cycle. [4] The total life cycle includes Production, Use and End of Life with. recycling or 2nd life.

Cost, weight & CO_2e comparison
To compare our EDU system with different solutions, three systems with a peak power rating of 160 kW were evaluated: a baseline PMSM system, AVLs new high-speed PMSM system, and an externally excited synchronous motor (EESM) system.

For the complete EDU system, the evaluation included weight, cost, and CO_2e of active motor parts, power inverter, and transmission, considering additional components like rotor shaft, bearings, and motor housing. Rotor excitation for the EESM system is considering cabling, sensors, and rotor interface as part of the power inverter.

Collector ring and copper bars/wires to the rotor windings are already considered with the E-Motor active parts. A potential for saving in terms of weight and cost was identified in the magnitude of 17 kg and 8% respectively with the use of high-speed motor, where EESM shows the potential of 5% cost saving but a disadvantage of up to 13kg in terms of system weight (see Fig. 3).

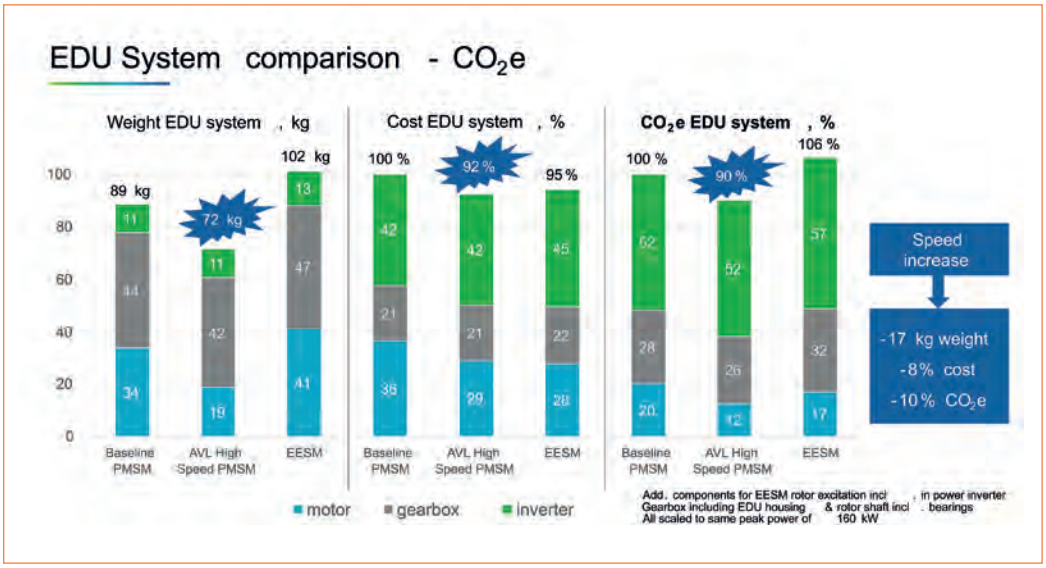


Fig. 3: Weight, cost & CO_2e evaluation – EDU System

Evaluating the sustainability of EDU systems by comparing calculated CO_2e emissions shows an advantage of 10% with the High Speed PMSM System and a potential increase in terms of CO_2e emissions of up to 6% with the EESM system. [3]

Conclusion and outlook

AVL's high speed EDU is in the second generation with an efficiency and performance above state of the art and improved sustainability due to high power density of 4.3kW/kg.

The described technology is tested continuously, e.g. in 2 AVL demo cars, which are running since 2020. Furthermore, the AVL torque vectoring function has been developed for and demonstrated in the vehicle.

Planning of our Gen 3 includes further improvement of inverter power density by 50%, a single motor derivate EDU for compact cars with only 25kg at 120kW/3400Nm, and intensive use of AI based machine control, such as rotor temperature determination.

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The new benchmark in stator cooling: Hyperdrives' hollow conductor technology

Michael Numberger, CTO, Hyperdrives GmbH

Hyperdrives' hollow conductor technology improves stator cooling for electric motors by an order of magnitude, achieving exceptional power density and efficiency. Seamless integration of proprietary manufacturing processes into existing hairpin stator lines makes it ideal for high-volume automotive, heavy-duty and aerospace applications.

Introduction and objectives

The ongoing electrification in the automotive sector and other industries demands a new generation of electric drives that are more powerful, efficient, and cost-effective. A central challenge is thermal management, as high power densities must be combined with more efficient heat dissipation. Hyperdrives' hollow conductor technology presents a novel solution for stator cooling, boosting both power density and efficiency while reducing motor production as well as operational costs. This article aims to present the technical innovations, performance capabilities, and application areas of this technology.

Technical basis

Hyperdrives' technology utilizes hollow copper conductors, focused on optimizing the heat flow between cooling fluid and copper winding. At maximum torque, over 90% of total motor losses are attributed to the copper winding. Hyperdrives achieves an unprecedented low copper-to-coolant temperature gradient by leveraging several key design features:

- **Direct coolant-to-copper contact**:
  The hollow conductors allow the cooling fluid to be in direct contact with the copper conductors' inner channels' surface, enabling direct heat dissipation precisely where it is generated.
- **Hollow pin topology:**
  Defined and even hollow channels, typically between 1 and 2mm in size, are engineered to maximize cooling surface area and facilitate consistent fluid flow and heat transfer at all sections of the winding.
- **Decoupling of electric and hydraulic connection:**
  Optimization of the hydraulic cooling fluid flow path independent from the electrical winding layout.
- **Low-viscosity cooling fluid:**
  Hyperdrives employs a low-viscosity dielectric oil as the cooling fluid, combining water-like viscosity with electrically insulating properties. By solving the pressure drop challenge – maintaining a minimal pressure drop of less than 1 bar – Hyperdrives enables the use of standard, cost-effective pumps with minimal energy consumption instead of specialized, high-cost and high energy-consuming alternatives.
- **High-velocity, turbulent fluid flow:**
  The cooling fluid moves at high velocities, promoting turbulent heat transfer with a heat transfer coefficient (HTC) exceeding 2,000 W/m²K. This turbulence intensifies cooling by enhancing heat dispersion from the copper surface.

Together, these features enable superior stator cooling by precisely and uniformly dispersing heat across the copper windings. With cooling integrated directly through the hollow conductors, there is no need for a conventional water-cooled jacket, freeing up valuable installation space around the stator. This allows for a more compact motor design or can be leveraged to increase torque output by enabling a larger airgap diameter and optimized stator geometry.

Hyperdrives motors can handle ultra-high current densities of **up to 75 Arms/mm²** copper cross section in steady-state operation, pushing the boundaries of motor performance. The entire cooling circuit, including both the inverter and motor in one circuit, remains compact and low-cost, offering a highly efficient, space-saving, and economically competitive solution for high-demand, high-volume applications.

Comparison with conventional stator cooling

Compared to state-of-the-art water-jacket plus spray-oil cooled hairpin stators, Hyperdrives' hollow conductor technology enhances heat dissipation by a factor of 10 and boosts continuous current density by a factor of 3 (75 vs. 25 Arms/mm² continuous). This breakthrough enables the **system** (motor incl. inverter) to achieve **peak power densities up to 15 kW/kg** and **over 12 kW/kg** continuous.

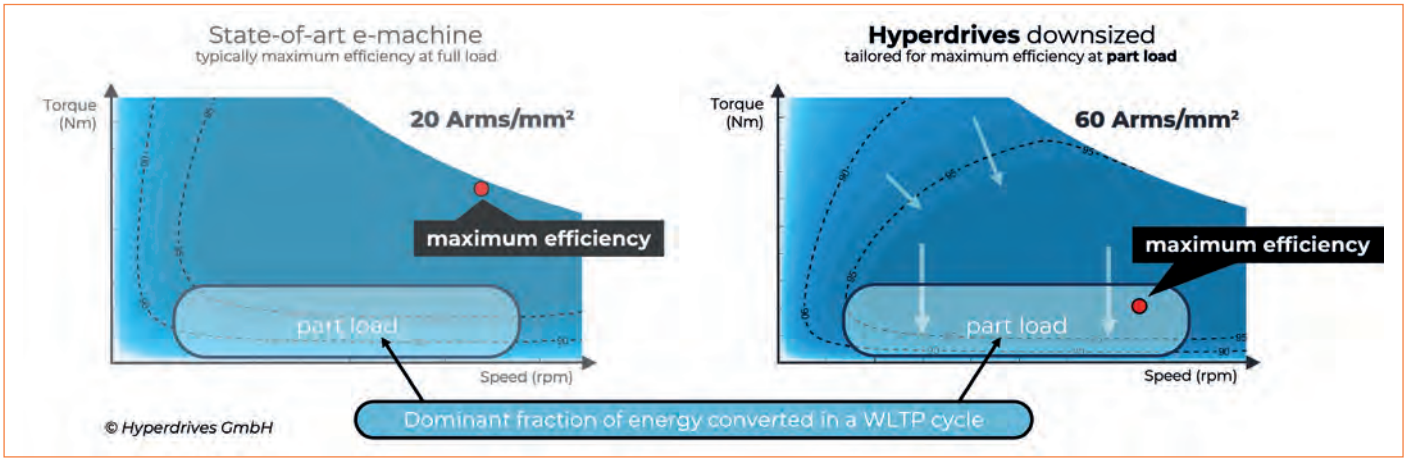
All while using standard materials without relying on costly Cobalt-Iron laminates, or 3D-printed windings. By achieving these results with conventional materials, the established inner runner motor topology and proven manufacturing techniques, Hyperdrives sets **a new benchmark for performance-to-cost** in electric motors.

Efficiency gains and customer benefits

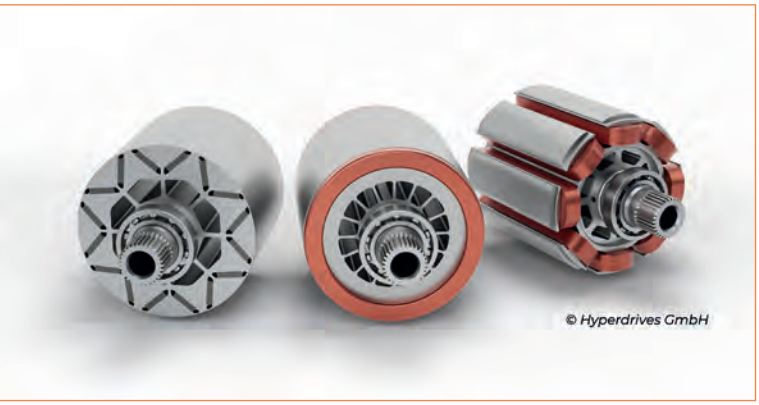
Optimal motor sizing for maximum efficiency is unique to each application and should be evaluated on system level rather than focusing solely on the motor. In aviation, for example, weight savings can take precedence over pure peak efficiency. Hyperdrives' technology enables groundbreaking designs by shifting conventional thermal boundaries, making it possible to achieve maximum efficiency exactly where it matters most. For the majority of automotive, heavy-duty, and aerospace applications, this is part-load. The enhanced motor efficiency characteristics can yield up to a **10% improvement in energy consumption and range.** These efficiency gains translate into significant lifetime cost savings and deliver clear customer benefits.

Mass production and cost reduction

One of Hyperdrives' key advantages in using hollow I-pins and hairpins is its **compatibility with existing automotive hairpin stator manufacturing processes,** which enables full automation, fast scaling and



cost-effective integration in existing production lines. Hyperdrives' proprietary methods for joining hollow pins and sealing the cooling manifold fit seamlessly into current production workflows, reducing conversion costs and simplifying adoption in mass production.



Distributed stator windings enhance **compatibility with all available rotor topologies,** offering increased design flexibility, especially for cost-sensitive applications. Rare-earth magnets can be optional, mitigating potential geopolitical dependencies and tackling the environmental aspect.

Durability and reliability

Hyperdrives has successfully completed extensive testing to validate the durability and reliability of its technology. Test specimens have demonstrated extreme robustness by withstanding rigorous heavy-duty shaker tests, followed by 25,000 full thermal cycles and pressure pulses, effectively simulating ten years of daily use. This testing confirms that Hyperdrives' cooling system is engineered for long-term performance, ensuring reliability and robustness under real-world conditions in demanding applications.

Market model and commercial application

Hyperdrives' system not only maximizes performance but also minimizes production complexity and cost. This makes it ideal for large-scale deployment across automotive, heavy-duty, and aerospace sectors, providing a scalable solution that meets the rigorous demands of these industries without compromising on quality or efficiency.

Hyperdrives follows two business models: direct sales of complete systems for customers with low-to-medium production volumes and technology licensing for large-scale manufacturers. Leveraging on close partnerships with industry innovators, along with established production processes, both models remain cost-effective and scalable.

Product specifications and outlook

Hyperdrives now offers an integrated **silicon carbide (SiC) inverter** and **ready-to-go motor control** with its motors. The development of the **Hyperdrives ONE** model, aimed at automotive applications, has been successfully completed. Building on this achievement, Hyperdrives has initiated the development of **Hyperdrives ULTRA**, a model tailored to meet the rigorous demands of aircraft applications.

	ONE	ULTRA
max. speed	16.000 rpm	24.000 rpm
max. torque	380 Nm	180 Nm
max. power	400 kW	300 kW
cont. power	260 kW	250 kW
nom. voltage	800 V	800 V
weight	19,6 kg	19,6 kg
availability	Q1/25	Q4/25

The Hyperdrives team is excited to connect with potential partners and clients to discuss **custom development** of drive systems tailored to your specific application using our versatile and scalable technology. Whether the need is for high-speed or high-torque direct drives, our team is ready to collaborate and create a solution that meets your unique requirements. Reach out to us at **info@hyperdrives.de** to explore how we can support your project with cutting-edge, adaptable drive technology.

Brudeli A0 truck is on the road, driving 35-80% with 270 kW of electric power and battery size of 200 kWh, with a plan for pilot operation with selected fleet customers in 2026. Serial production of the patented Brudeli Powerhybrid™ is scheduled to commence in 2028.

Beyond P2 hybrids:
Brudeli Powerhybrid™ for improved efficiency and competitive TCO of heavy-duty trucks

Team Brudeli Green Mobility

The heavy-duty trucking industry faces significant challenges in reducing emissions and meeting increasingly stringent regulations. With medium and heavy-duty trucks contributing approximately 5% of global carbon emissions, there is an urgent need for innovative solutions beyond the fully electric vehicles. Brudeli Green Mobility (Brudeli) has developed and tested the Brudeli Powerhybrid™, a plug-in hybrid powertrain technology that promises to accelerate electrification in these hard-to-abate sectors.

Technical approach and configuration advantages

The Brudeli Powerhybrid™ utilizes a P2.5/3 configuration (figure 1), a sophisticated plug-in hybrid system designed specifically for heavy-duty trucks. This configuration integrates two electric motors into the transmission.

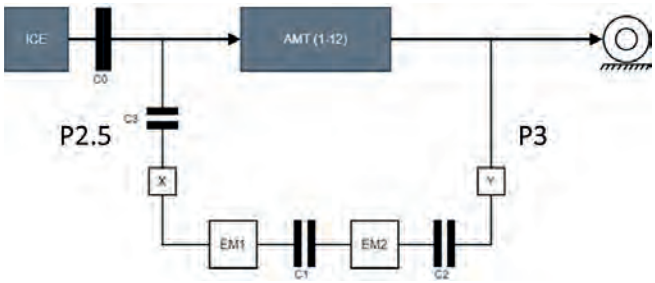


Fig. 1: Schematic overview of the Brudeli Powerhybrid™ patented concept.
ICE – Internal Combustion Engine,
AMT – Automated Manual Transmission,
C – Clutches,
X – Input fixed gear,
Y – Output fixed gear,
EM1/EM2 – electric motors.

The new principle makes it possible to drive the vehicle entirely electrically. Two electric motors are controlled and will act as a mechanical gearbox. In our concept, this is arranged by electric motor 1 (EM1) being permanently connected to the input gearbox shaft (AMT – Automated Manual Transmission), while electric motor 2 (EM2) is alternately connected to E1 or, during gear changes, connected to the output gearbox shaft.

The P2.5/3 design offers several key advantages over the more common P2 configuration. Its flexible power management through a dual-motor setup allows for both parallel and serial hybrid modes, optimizing efficiency across various driving conditions. In serial mode, efficiency is improved as one motor can generate electricity while the other drives the wheels, particularly enhancing performance in low-speed or stop-and-go traffic. The enhanced powershift capability, achieved through integration within the transmission, enables smoother gear changes without power interruption, improving driving comfort and energy management during acceleration and deceleration.

Higher electric power potential is achieved through the dual-motor design, which can deliver more electric power and higher power density than a single P2 motor, enhancing performance in electric-only mode. The system features seamless AMT (Automated Manual Transmission) integration, as being integrated into the transmission allows it to work optimally with the AMT for precise gear shifts and power delivery. Advanced regenerative braking is achieved through eMotors positioned at two drivetrain points, allowing for more efficient energy recuperation during braking.

Key technical features of the Brudeli Powerhybrid™ include:

- Dual electric motor design (2 x electric motors, totally 429 kW, 800V)
- Advanced Powershift capability for seamless gear changes
- Integrated electric power takeoff for auxiliary systems
- Power takeout could also run mechanical from ICE engine
- Compatibility with existing diesel, gas, and hydrogen drivetrains
- Real-time route optimization and energy management

Methodology and development

Brudeli's development approach is focused on maximizing energy efficiency and flexibility while minimizing costs. The company conducted simulations and is performing real-world tests to optimize the system for various driving scenarios.

Although novel at system level, each functional element can be seen as established and mature technology, allowing for optimized time to market. Furthermore, the modular and scalable architecture – the external electric motors make a key element – enables scaling of system cost and performance per use case.

A target area of innovation at Brudeli is the real-time route optimization, accounting for factors such as geography, topography, traffic conditions, and available charging infrastructure. In a driving plan, continuously the driving modes and gear shifts are optimized to maximize efficiency. Clearly, energy efficiency and emission can be traded vs cost and time.

The development process also prioritized compliance with upcoming regulations. The Brudeli Powerhybrid™ system is designed to meet the EU's VECTO standards for 2024 and beyond, as well as the US EPA Phase 3 and California's Advanced Clean Fleets (ACF) regulations. Furthermore, the flexible configuration is optimal for meeting future, more stringent regulations.

Results and innovation

The Brudeli Powerhybrid™ demonstrates several significant advantages over conventional powertrains and competing electrification technologies:

1. Up to 80% electric driving capability, reducing diesel consumption and emissions proportionally
2. Lower total cost of ownership compared to both conventional diesel and fully electric trucks for long-haul routes
3. Flexible operation, allowing trucks to complete all routes without range limitations
4. Smaller battery (200-400 kWh) requirements compared to fully electric trucks, reducing upfront costs
5. Electric driving and leading cost without the need for Higher Power charging infrastructure
6. Superior CO_2 abatement cost-effectiveness, performing on par with battery electric technology in standard drive cycles

Brudeli's analysis shows that for a typical long-haul route of 480 km per day, the Powerhybrid™ system achieves a carbon abatement cost of 644 EUR/ton CO_2, comparable to 602 EUR/ton for battery electric and significantly better than other alternatives like hydrogen fuel cells (1514 EUR/ton) or standard hybrids (3007 EUR/ton). If including compensation for cost factors such as charging infrastructure, vehicle availability, and payload, this would skew such analysis further toward the Powerhybrid™.

Market impact and future outlook

The Brudeli Powerhybrid™ addresses a critical gap in the electrification of heavy-duty trucking. While battery electric vehicles are making inroads in short-haul and urban applications, long-haul and heavy-duty segments remain challenging to electrify due to range and infrastructure limitations. Total addressable market of heavy- and medium duty trucks worldwide is 4.3 million vehicles.

Brudeli projects that by 2050, nearly all diesel and alternative fuel trucks, including hydrogen-powered vehicles, will incorporate plug-in hybrid technology. This transition is driven by both economic factors and regulatory pressures, with new EU targets calling for a 45% reduction in heavy-duty vehicle emissions by 2030 and 90% by 2040.

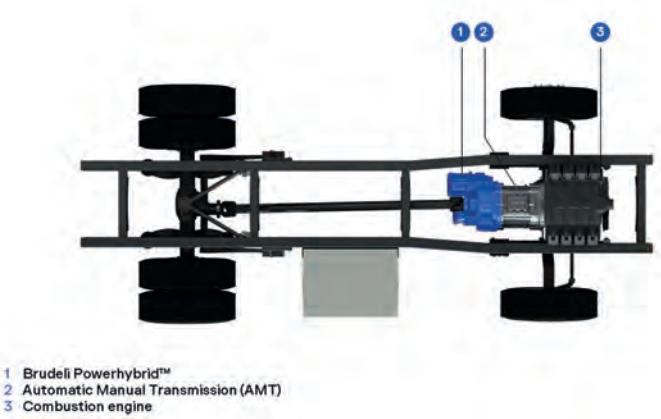


Fig. 2: Brudeli Powerhybrid™ in the powertrain/chassis

The Brudeli Powerhybrid™ system's flexibility and compatibility with various fuel types position it as a „future-proof" solution. As charging infrastructure expands and green electricity becomes more prevalent, hybrid trucks can progressively increase their electric driving percentage, further improving their environmental performance.

Conclusion

The Brudeli Powerhybrid™, with its advanced P2.5/3 configuration, represents a significant innovation in heavy-duty truck electrification. By offering a flexible, efficient, and cost-effective solution that can be implemented across existing fleets and routes, it has the potential to accelerate emission reduction in a sector that has proven difficult to decarbonize. The system's sophisticated power management, enhanced efficiency, and the compatibility with various drivetrains make it a compelling option for manufacturers and fleet operators looking to meet increasingly stringent emissions regulations while maintaining operational flexibility.

As the transportation industry continues its transition towards sustainability, technologies like the Brudeli Powerhybrid™ will play a crucial role in the gap between conventional powertrains and fully electric solutions, paving the way for a more sustainable future in heavy-duty trucking.

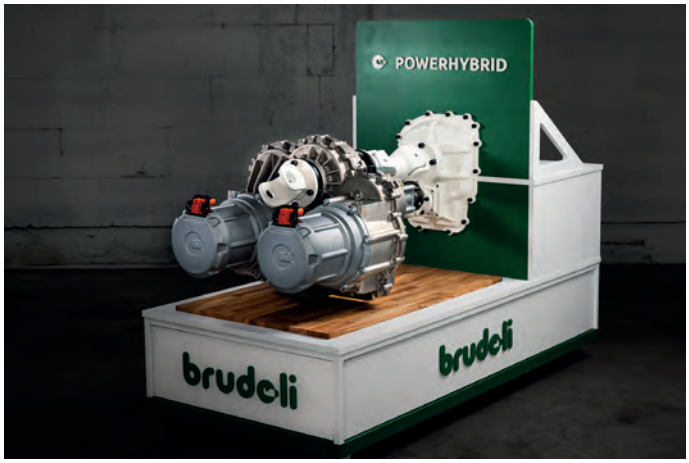


Fig. 3: Brudeli Powerhybrid™ MK1 exhibition model shown at ACT Expo 2024 and IAA Transportation 2024

References

[1] Statista, 1.8 GtCO2 of 37.15 GtCO2.

[2] Statista (https://www.statista.com/outlook/mmo/commercial-vehicles/trucks/worldwide#unit-sales)

[3] 2050 projection: BEV 59%, IEA „Net zero by 2050" https://www.iea.org/reports/net-zero-by-2050

PHEV: Projection based on dialog/inside from OE. Volume production from 2028

JJE advances differential locker technology

JJE differential locker driven by DirectFlux™ electromagnetic clutches

Ping Yu, CEO, Chief Engineer, Founder, Jing-Jin Electric

Dr Yang Cao, Transmission Clutch Team Manager, Jing-Jin Electric

Differential locker locks up differential to ensure torque output on vehicle's wheel under low traction conditions. the axles together to provide 100% of available torque to the wheel with traction. At 2022 CTI US, JJE debuted its mono-stable and bi-stable DirectFlux differential locker (eLocker). Now this eLocker has been equipped by mid- and full-size SUVs, pickup trucks, and off-road vehicles. JJE eLocker features compact size, high torque, and high engagement speed. JJE has achieved maximum 18,000Nm locking torque in JJE's 2-speed electric beam axle. Depending on vehicle requirement, JJE's eLocker can be bi-stable, which is fail-safe (prevent sudden locker release and loss of traction); or can be mono-stable to achieve "default to open" function.

DirectFlux™ electromagnetic clutch makes locking faster and safer

DirectFlux™ electromagnetic technology clutch is used to drive the locker. The clutch uses direct magnetic force, or magneticflux in the same direction as the magnetic force. JJE created unique magnetic circuit that greatly reduces flux leakage, hence utilizes the magnetic flux to generate force more effectively, generating higher electromagnetic force than conventional reluctance clutches.

With the DirectFlux™ electromagnetic technology clutch, eLocker can be designed as mono-stable or bi-stable based on vehicle requirement. A mono-stable eLocker is locked by magnetic force generated by current, and is unlocked by spring force when the current is turned off. A bi-stable eLocker will only change its state when there's an affirmative current command, which is only a pulse; otherwise, it will hold its state.

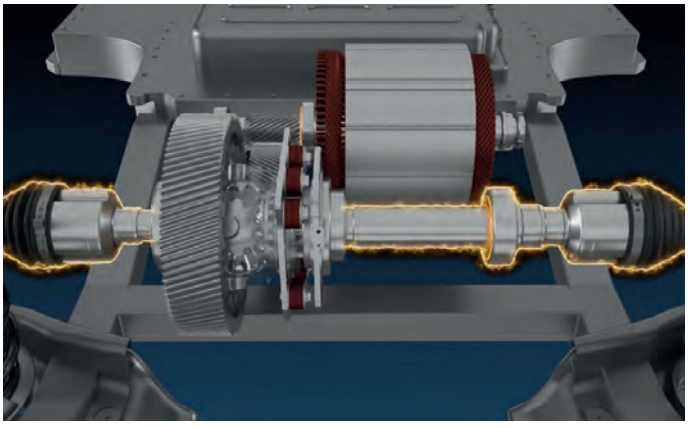


Fig. 1 JJE Differential Locker Integrated in Gearbox of an Electric Drive System

Normally, bi-stable differential locker provides higher safety level, as it won't change state in the event of loss of control. This fail-safe feature can prevent sudden locker release due to control failure. This security enhancement is valuable for rear axle, or the "main drive axle", for conditions such as claiming steep rock trail or pulling heavy boat out of water on slippery ramp. While for front steerable axle, mono-stable differential locker is sometimes preferred as it will default to open position in the event of control failure, which unlocks the front differential to allow easier steering at higher speed.

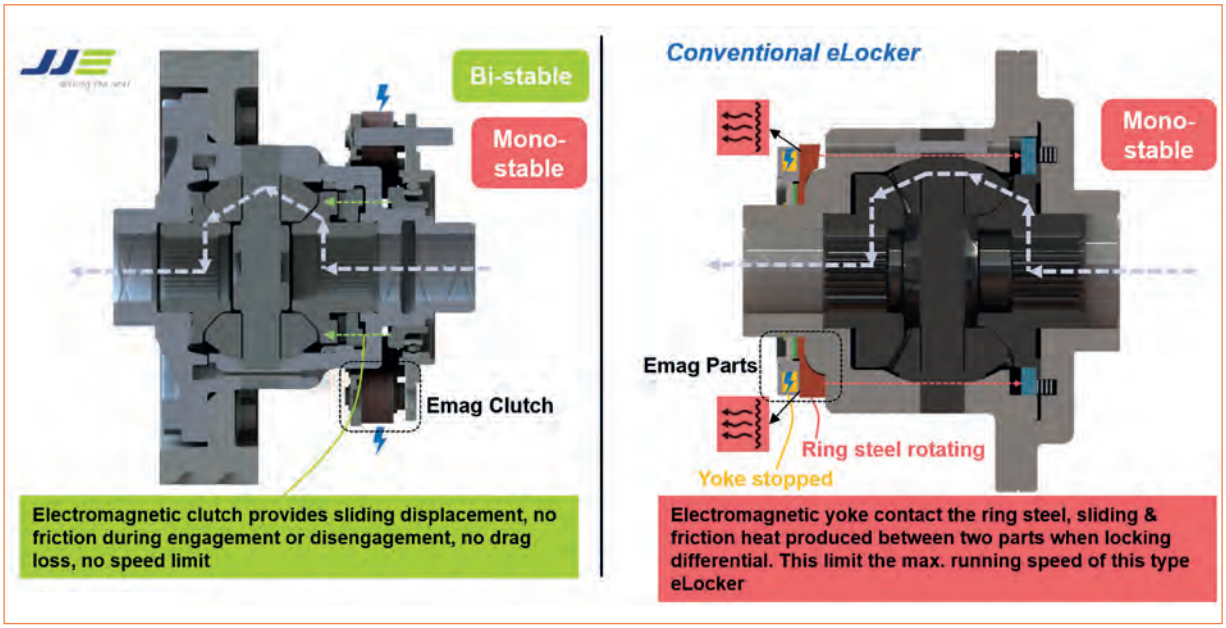


Fig. 2 Comparison, JJE eLocker vs. Conventional eLocker

No speed limit, no drag loss

Conventional locking differential must limit vehicle speed very low for engagement, and also limit vehicle's running speed after engagement. "The locker engagement should not be maintained greater than 30kph", or "the locker only can be engaged when vehicle speed is below 5kph". The operating speed is limited by the rotational friction between differential case and electromagnetic coil case during locker's engagment. And the conventional locker can only be mono-stable.

JJE's eLocker is driven by DirectFlux™ electromagnetic clutch, which has no contact or friction between moving plate and coil assembly during engagement and disengagement. Therefore, there is no mechanical wear, no drag loss, no heat generation. Therefore, JJE eLoker does not limit speed for engagement or operation.

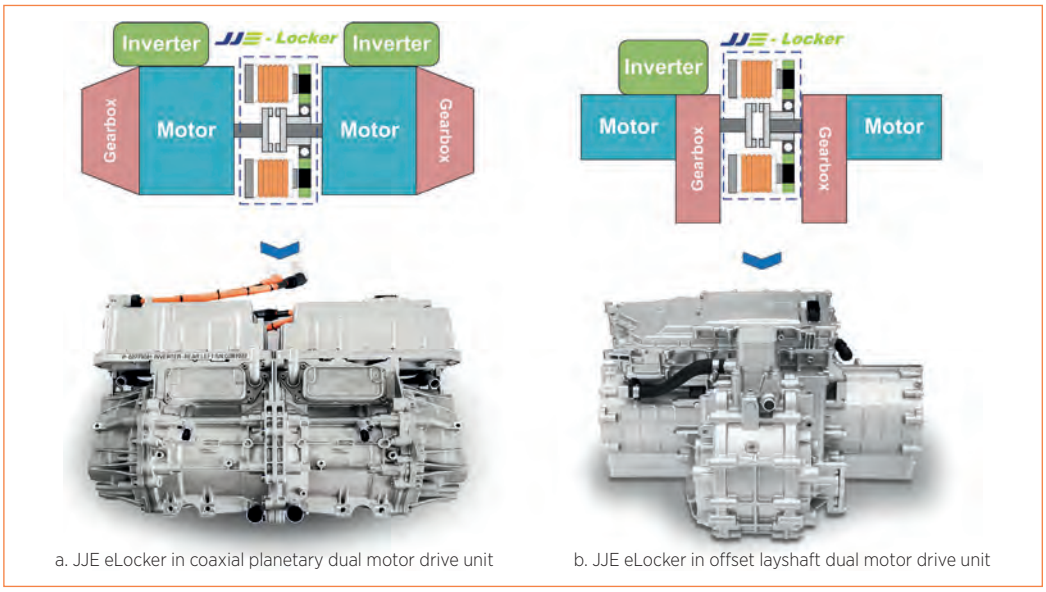
Wide application

Differential locker is indispensable in off-road vehicles, and other high capability vehicles such as heavy duty pick-up trucks JJE's eLocker has been used in several independent axle 3-in-1 drive units, with output torque ranging from 3000Nm to 6,000Nm. The differential locker is also adopted in JJE's 18,000Nm electric beam axle. JJE eLocker does not limit operating speed, which enhances these vehicles' capabilities when both locking and speed are needed, e.g., driving through sand or mud.

Fig. 3 An off-road SUV equipped JJE eLocker in both front and rear drive unit

JJE eLocker for back-to-back dual motor drive

Back-to-back dual motor e-drive does not require a differential, but some vehicles do require a locker that mechanically locks up left and right wheels. JJE's electromagnetic clutch is suited for such locker function. JJE has two back-to-back dual motor drive units – coaxial planetary and offset layshaft – and both drive units use bi-stable electromagnetic clutch as locker.



a. JJE eLocker in coaxial planetary dual motor drive unit

b. JJE eLocker in offset layshaft dual motor drive unit

Fig. 4 JJE's eLocker for back-to-back dual motor drive unit

JJE eLocker & eDisconnect combo system

JJE eLocker can also be integrated with JJE eDisconnect, which becomes a compact disconnect & locker combo. This combo is most valued for secondary drive axle, where disconnect is used for changing configuration between 4x4 and 4x2, and locker is used for traction assurance. As example, a 4x4 off-road SUV needs such flexibility.

The eLocker-eDisconnect Combo packages nearly the same as JJE's single eLocker, thanks to the deeply integrated mechanical design and very its compact electromagnetic elements. This new Combo product will be launched in a high-end off-road SUV in 2025.

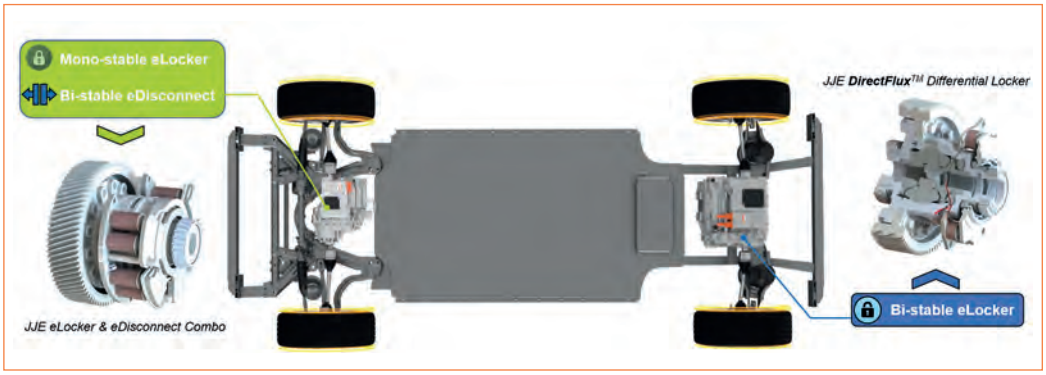


Fig. 5 eLocker & eDisconnect solution for high-end off-road SUV

eDrive application rapidly expands and now reaches almost all market segments. Users accept no compromise in vehicle's capability, and even expect more from eDrive than ICE. JJE eLocker, eDisconnect and the Combo are designed to meet such high market expectations, and will continue to push out the envelope of technology.

A unique collaboration for the development of the next generation electric transmission fluid

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Influence of lubricant on electrical drive unit

In the rapidly growing Chinese EV market, for a new EV product to stand out, it needs to provide premier performance in range, NVH and reliability under all operating conditions, regardless of drive cycle (city, rural or highway) in climate extremes.

To make an EV successful, the electrical drive needs to have the highest efficiency while enduring high power density to provide outstanding reliability. To achieve this, the lubricant plays a crucial role as it is the means to remove heat from the motor while providing lubrication and protection for gears and bearings. The list below displays examples of how a lubricant can influence an EV's drivetrain performance.

Scuffing, Pitting and Wear Protection – Poor lubrication is the primary failure mechanism for all of these phenomena. When a lubricant fails to provide proper extreme pressure or scuffing and anti-wear protection during high contact pressures and high sliding speeds, the gears and bearings can rapidly fail.

Coefficient of Friction – The gear meshing and bearing frictional losses account for 30-40% of total power loss in EDU, especially when experiencing higher power demands. All gears and bearings are lubricated with the electric transmission fluid (ETF), so lowering the coefficient of friction is one of the most effective ways to improve a drivetrain's efficiency.

Electrical Properties – Breakdown voltage, resistivity, and permittivity can influence the electrical induced bearing damage (EIBD) behavior, which is a unique and challenging problem for all inverter driven motors due to common mode dV/dT events and circulating currents.

Understanding that the appropriately formulated ETF technology is the key to promote efficiency, durability and reliability of an EDU, Li-Auto has engaged with Afton Chemical Company to develop a customized ETF to best suit the Li-Auto in-house-designed drive unit.

Li-Auto's Methodology on the customized ETF's development

The next generation ETF, Advanced Performance Fluid 1.0 (APF1.0), was designed and developed specifically for Li-Auto's next generation, in-house designed drive unit, Scalable Power Drive (SPD) (see Figure 1). This is the main drive platform for both REV and BEV models.

SPD is an 800V electrical drive unit platform. The inverter, motor and gearbox are integrated as one whole assembly, but its peak power and torque could be tuned from 200-300kW, 3500-5000Nm by adjusting power modules, stator & rotor, or geartrain as it is a modular designed drive unit. It enables SPD to suit various car models. Apart from that, SPD has boost charging function, which significantly reduces charging time but meanwhile much more heat is generated from the rotor. The system poses great challenge on cooling and lubrication,

and APF1.0 needs to have great heat dissipation and hardware protection performance. On top of that, Li-Auto has focused on how this directly contributes to the vehicle range and battery cell cost, which ultimately influences the overall vehicle performance.

The ETF design is an optimum combination of chemical additives and base oil technology to deliver balanced performance. If the balance is not adhered to, the desired level of performance in the drive unit can be compromised.

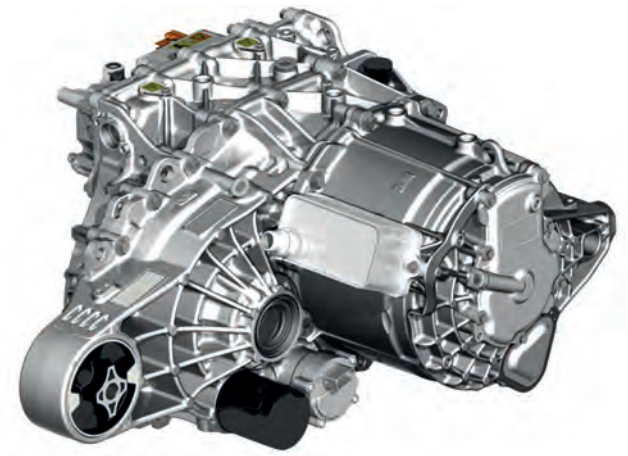

Fig. 1 Isotropic view of SPD

The primary design target for the APF1.0 development was efficiency, while providing adequate hardware protection, especially under low lambda ratios. To improve efficiency, a geartrain power loss model was developed to calculate the contribution from sliding and rolling losses and churning losses (gears and bearings) to better guide the lubricant formula design. During the modeling work, it was found that different hardware configurations yield different power loss contributions. For example, churning loss is greatly reduced in a geartrain with intermediate shaft placed on top (no contact with sump oil, as illustrated in Figure 2) compared to that placed at the bottom (partially submerged in oil sump) and rolling frictional loss could be greatly reduced with ball bearings versus tapered-roller bearings.

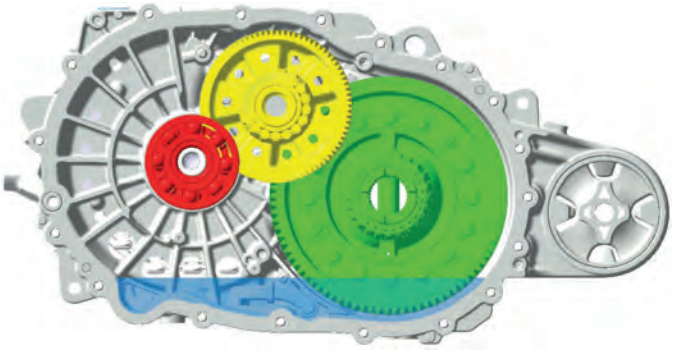

Fig. 2 Cross section view of SPD showing the intermediate-gear-on-top structure

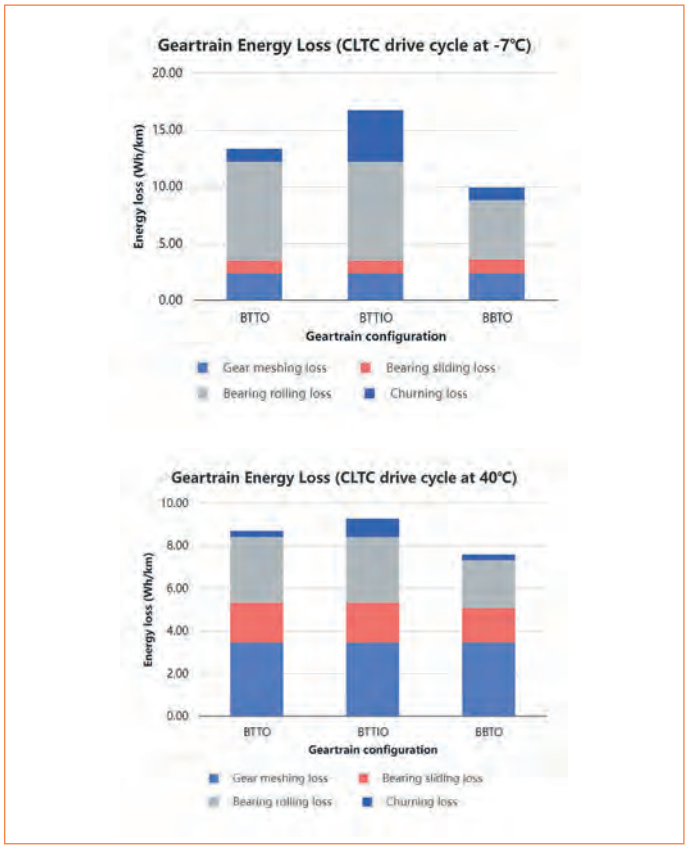

Fig. 3 Power loss composition example

**Geartrain configuration of above figure:*
BTTO – Ball bearings on input shaft, Tapered roller bearings on intermediate and output shaft, intermediate shaft on top with churning from output gear only
BTTIO – Ball bearings on input shaft, Tapered roller bearings on intermediate and output shaft, intermediate shaft on bottom with churning from both intermediate gear and output gear
BBTO – Ball bearings on input and intermediate shaft, Tapered roller bearings on output shaft, intermediate shaft on top with churning from output gear only
**Power loss calculation models:*
Gear mesh & churning loss is calculated per ISO14179-1;
Bearing loss is calculated per SKF's public bearing loss empirical model

The same to hardware protection. For example, pitting life reduces exponentially as contact stress in-creases for gears and bearings. If the hardware design puts the contact stress near the limit, it will be required to have an ETF that has ultra-high-performance regarding pitting and scuffing. In this scenario a higher viscosity would be preferred to ensure oil film is sufficient. On the contrary, if the drivetrain is under lower stress level, a lower viscosity fluid could be applied to provide the greatest vehicle range.

Based on the aforementioned performance factors, Li-Auto decided that the APF1.0 design had to be customized to obtain the best performance with the SPD hardware. An off-the-shelf product will not provide the ultimate performance. Li-Auto selected Afton Chemical as cooperation partner as Afton fully understands Li-Auto's

technological capability and provides a new formulation that meets the specified requirements, providing both range extension and hardware durability.

In this cooperation project, both parties agreed that as OEM, Li-Auto's role is to provide clear and specific evaluation methods for the lubricant based on Li-Auto's hardware design; and as the lubricant expert, Afton's role is to design and develop formulas that could meet Li-Auto's requirement. During this process, it was found that the conventional lubricant evaluation methods such as FZG (spur gears) and FE8 (cylindrical roller) do not appropriately evaluate APF1.0 as related to the end application utilizing helical gears, ball and tapered roller bearings. Thus, we designed our own evaluation methods in terms of pitting prevention, friction optimization and churning loss based on our hardware design and actual operating conditions from fleet statistic data.

Performance evaluation of APF1.0

The efficiency performance of APF1.0 was evaluated by comparing it with the previous generation fluid on the same dyno and the same drive unit (a selected SPD drive unit, with baseline efficiency of 91% – CLTC drive cycle at 40°C). APF1.0 provides a 0.3% efficiency increase per CLTC drive cycle at 40°C oil sump temperature; 1.1% increase per CLTC drive cycle at -7°C oil sump temperature; 0.5% increase under 120kph highway cruising condition at 40°C. It showed significant efficiency increase at both normal and cold temperatures, both city-road and highway conditions.

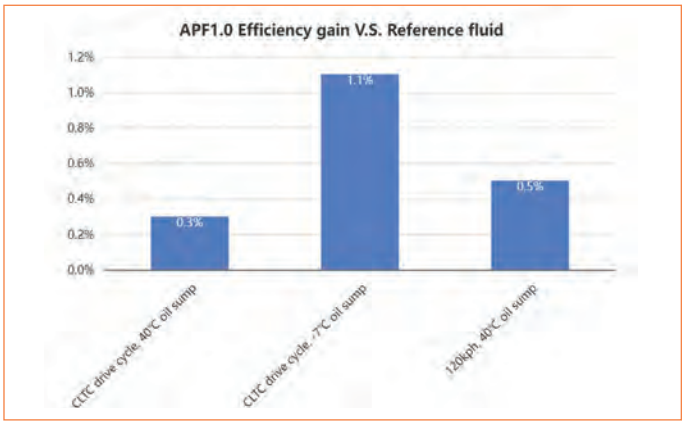

Fig. 4 Efficiency gain chart of APF1.0

On the reliability side, we performed the geartrain endurance test, high temperature high speed test, power temperature cycling endurance (PTCE) equivalent to the EV life of 300,000 kilometers, covering driving intensity of 99.7% of fleet drivers. No failure was detected after any of the tests.

Before performing efficiency and endurance tests on full drive unit level, we conducted a series of lubricants screens to ensure valuable dyno stand resources were maximized for candidates. We set coefficient of friction reduction targets for the lubricant at multiple operating conditions based on the power loss simulation model and set clear requirements on the lubricant's hardware protections. Only those formulas that met all the requirements would be selected to the drive unit level test phase.

For friction evaluations at lubricant level, MTM was used to determine the friction performance of the fluids. The friction performance was compared to the reference at different loads, entrainment speeds, slide-to-roll ratios and bulk oil temperatures. The operating conditions are derived from the drivetrain's actual operating conditions and allows an appropriate insight as to how the fluid can influence overall efficiency as related to friction reduction.

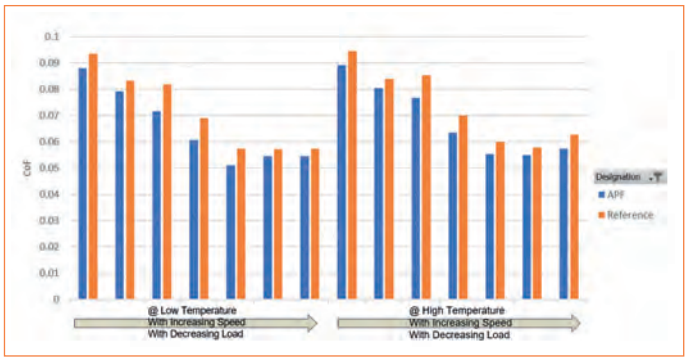

Fig. 5 Friction Performance Comparison between Reference Fluid and APF1.0

On the hardware protection lubricant level test side, since APF1.0 is a low viscosity lubricant used in a high power density, high torque drivetrain, we are most concerned about a fluid's pitting and wear protection capability. For pitting, we used MPR test equipment for evaluation. We specified contact stress, sliding speed, entrainment speed and run time based on one of the most aggressive drivers' driving profiles collected from fleet data. The reference fluid pitted after 38.77 million cycles (43.7hrs) but APF1.0 was able to complete 87.83 million cycles (99hrs) without pitting.

	Time to Failure (hrs)	Total Cycles (millions)
Reference fluid	43.7	38.77
APF1.0	99 (no fail)	87.83

Table 1. MPR Macro Pitting Test Results (767N, 23% SSR, 70°C)

Projection of ETF trend

We believe the items listed below will be the future of ETF development from an OEM standpoint.

Efficiency is always the first priority, as it is the key to reduce the overall cost of the vehicle and resolve EV range anxiety. New combinations of additives and base oils are currently underway to reduce coefficient at thin film conditions, and improve durability while improving EDU efficiency at lighter load duty cycles. In the future, base oil and additives with new molecular structures could potentially further bring friction down.

Viscosity should be carefully selected based on hardware protection needs. Low viscosity does not always provide higher efficiency gains in an EDU. An ETF with properly selected viscosity could allow more operating conditions to fall into the elastohydrodynamic regime (which gives lowest coefficient of friction). To achieve such, the OEM needs to build capability to perform drivetrain power loss analysis and component loss simulations with input from gear, bearing and lubricant suppliers.

EIBD is a unique phenomenon and challenging topic for BEV and REV drivetrain. Lubricant properties such as breakdown voltage, resistivity, and permittivity could result in different EIBD performance theoretically, and it has been observed from tests that different lubricants do yield different discharge event frequency and severity. It is valuable for the lubricant and powertrain industry to make further study on ETF's influence to EIBD and provide formula that mitigates EIBD risk in the end.

Li-Auto highly encourages all of its partners in the drivetrain supply chain to join in this effort to make the next significant steps to improve EVs further in cost and performance.

Leading the way in e-fluid developments

Andrew Wood, Driveline Fluids Technologist, Infineum UK Ltd

Scott Campbell, Hitesh Thaker, Masahiro Ishikawa, Driveline Fluids Technologists, Infineum USA

As automakers work to decarbonise, most are opting for powertrain electrification, an option that is driving growth in dedicated hybrid and electric vehicle transmissions. However, these systems present new performance challenges that require dedicated fluids to ensure their complete protection. As leaders in driveline additive technology and e-fluid formulation, Infineum has invested in the development of step-out technology and innovative new test methods to ensure our e-fluids deliver the required performance in critical areas.

The pressure to decarbonise, coming from both regulators and consumers, means the number of hybrid and battery electric cars on our roads is growing. Which in turn means the use of reduction gearboxes and dedicated hybrid transmission systems are also increasing.

This expanding electrified vehicle parc needs bespoke e-fluids, that provide not only traditional transmission fluid properties but also meet new e-specific requirements.

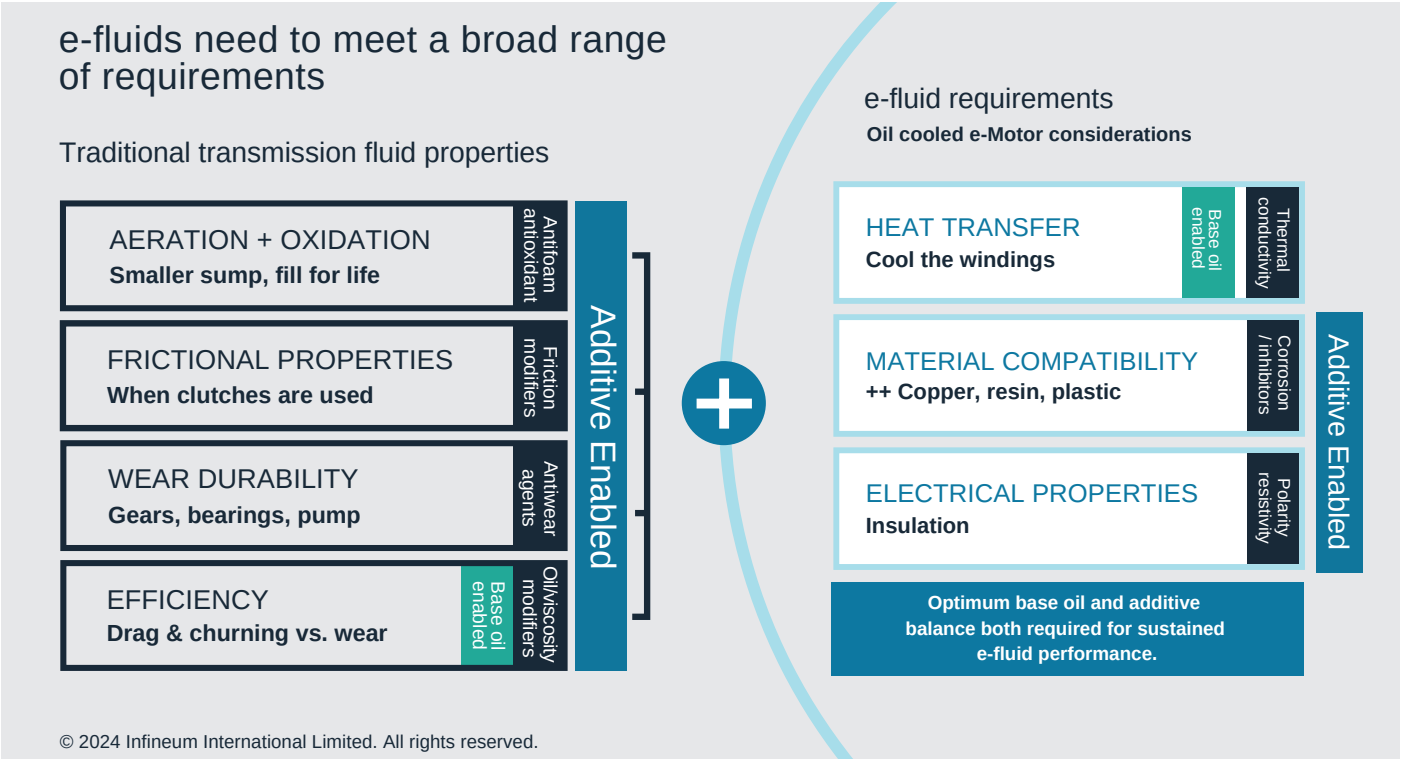

Fig. 1 e-fluid requirements

It's a careful balance. As well as meeting all of the requirements in Figure 1, fluids must be formulated to optimise transmission performance and protection. And, in today's lower viscosity environment, this is even more vital, which means careful component selection is important when formulating fluids for these applications.

These new electrified vehicle performance challenges require dedicated e-fluid technology. As leaders in driveline additive technology and e-fluid formulation, Infineum has developed dedicated e-fluids, optimised for excellent field performance. To assess these new fluids, we've developed innovative new tests in some of the critical areas, designed to be closer to the real-world application than currently available industry test methods. Two recent examples are a high-speed aeration test (HSAT) and an energised copper test (ECT), which have given our technologists new and exciting insights into fluid performance.

Material compatibility testing

With motors now being placed into the transmission, a number of materials are being introduced that are significantly different from those used in conventional powertrain architectures. For example, the copper wire and connections are susceptible to corrosion, which can lead to electric current leakages or to a short circuit in the transmission. These potential issues mean many OEMs see copper compatibility as an important e-fluid design parameter.

While energised copper corrosion tests exist, multiple testing parameters can lead to test result variability and results can be hard to interpret. In addition, the methods do not deliver the granular understanding on deposit formation to enable the impact on formulation parameters to be assessed. We wanted to develop a new test that could help us visualise the corrosion mechanisms live, including the formation of tarnish, deposits and dendrites.

Infineum's energised corrosion test (ECT) uses a single printed circuit board with copper grids, that can be used with a covering board to provide a capillary gap (Figure 2). Board spacing can be tuned with a spacer washer and various board designs have been used to investigate trace spacing impact.

Fig. 2 The oil immersed energised corrosion test (ECT) allows us to screen technology to ensure good copper compatibility.

Tuning trace and board spacing had a significant impact on fluid performance (Figure 3). These data highlight the critical importance of tuning test conditions and set-up to screen for real world performance.

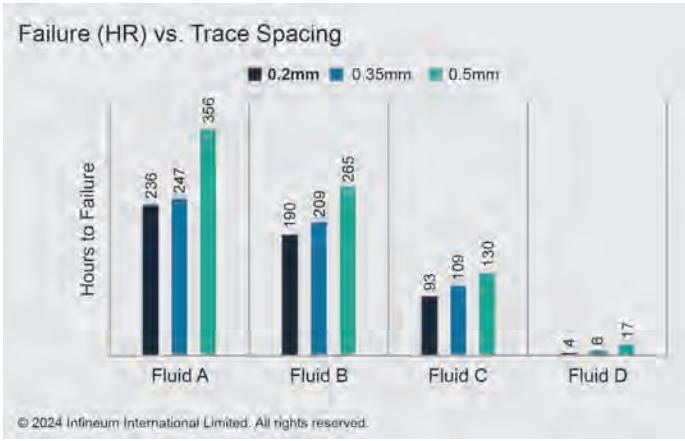

Fig. 3 Impact of trace and board spacing

The novel video imaging system has delivered new insights into copper corrosion mechanisms (Figure 4).

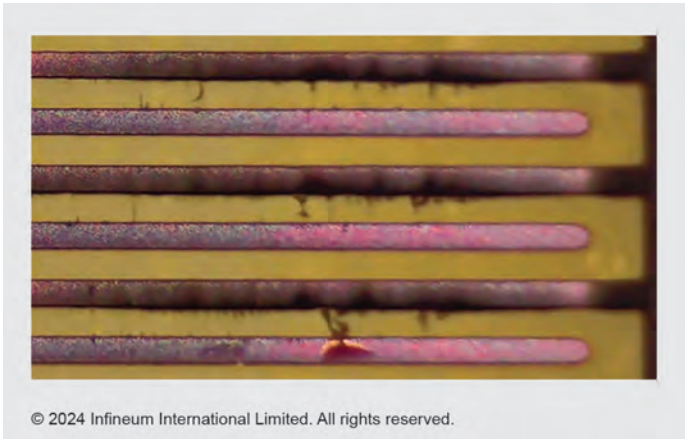

Fig. 4 Deposit / dendrite growth between anode and cathode

This new rig is helping us to better understand some of the parameters impacting corrosion and the ways corrosion progresses. These insights will be helpful in developing advanced e-fluids capable of delivering better material compatibility performance.

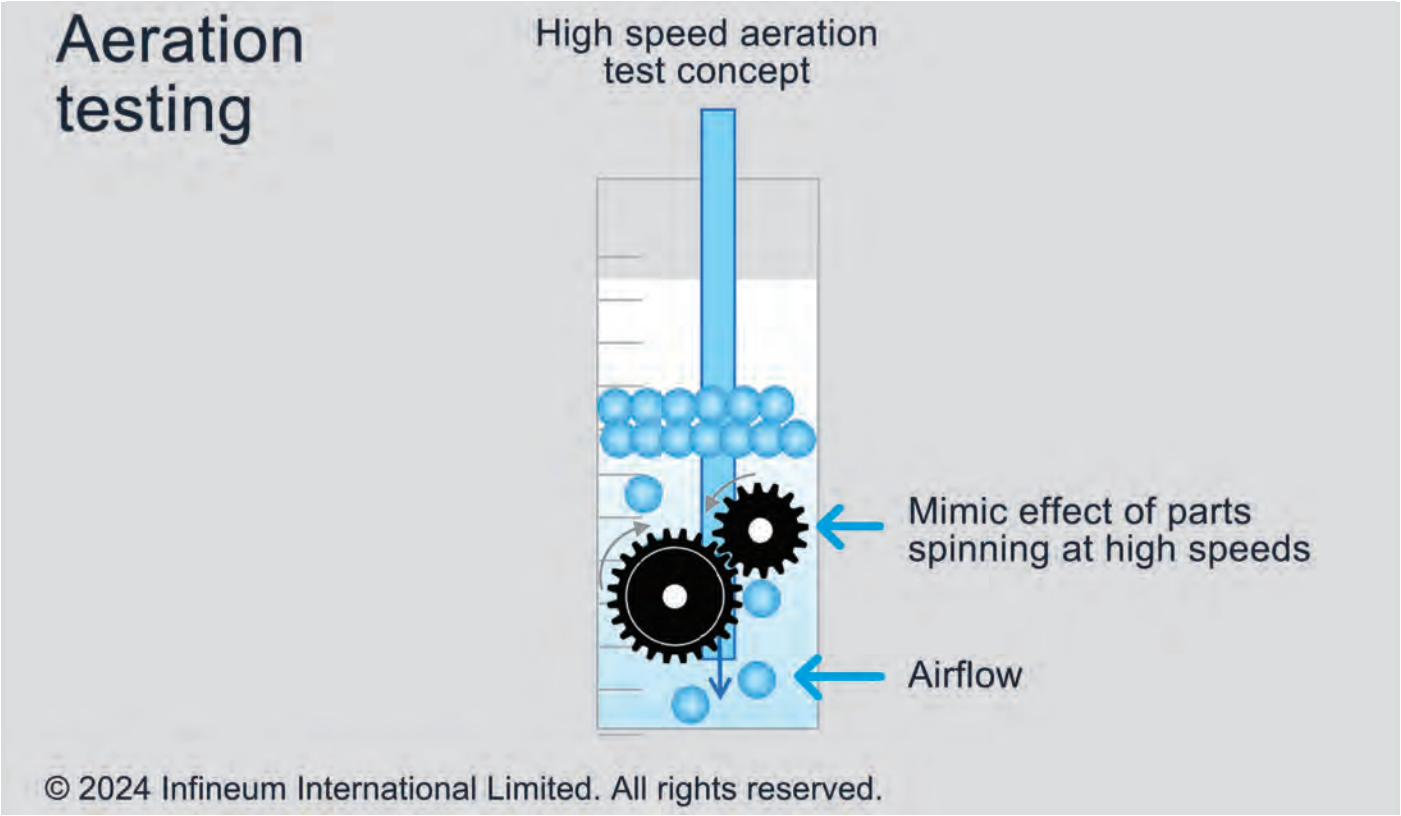

Fig. 5 The Infineum HSAT test set up mimics the effect of parts spinning at extremely high speeds under shearing/churning

New high speed aeration test

Infineum has also developed a high-speed aeration test (Figure 5), which more closely matches the conditions found in high-speed e-motors and gearboxes vs the standard ASTM test – addressing a gap in e-fluid performance.

While ASTM D892/D6082 use airflow to generate foam in the test fluid the foam may not be representative of aeration experienced in real world electric vehicle hardware, where e-motors and gears spin at >20,000 rpm – much faster than in conventional ICEs.

In electrified applications, high speed shear from gears and bearings can lead to increased aeration of the driveline lubricant. This is a challenge since it can cause cavitation. This leads to irregular fluid film and loss of hydraulic performance, resulting in wear.

Using the existing ASTM D892 and D6082 foaming test as a starting point, our objective was to mimic the impact of parts spinning at speeds of up to 27,000 rpm and to add in a high-speed shearing and churning effect to simulate the aeration caused by parts spinning at these very high speeds. Automation and video capture help to ensure heating and timing accuracy.

The newly developed High Speed Aeration Test (HSAT) has been used to assess the impact of fluid viscosity, viscosity modifier and anti-foam selection on aeration.

Following the successful development of this new test, Infineum is pursuing options for industry standardization of the HSAT.

Conclusion

As leaders in driveline additive technology and e-fluid development, Infineum has invested in developing new test methods to provide insights into critical performance areas. The deeper understanding of materials compatibility and aeration is helping us to develop step-out dedicated e-fluids with the optimal performance balance designed to protect electrified transmission systems.

Our new test methods give us a fast and effective means to screen a wide number of formulations.

Following on from these laboratory tests, our advanced e-fluids are tested in real-world conditions. We have already completed almost three million kilometres of field trials across the globe – testing our extensive e-mobility product portfolio in a wide range of hybrid and electric vehicles.

Infineum technology is setting the e-fluids benchmark with next generation products to provide performance you can rely on.

About Infineum

Infineum is a specialty chemicals company with strong research and development capabilities focused on innovative chemistry that plays a crucial role in sustainability. They provide products essential for the electrification of mobility and work towards making internal combustion engines as clean as possible. Their expertise extends to generating sustainability advantages for numerous new markets globally. The company has a rich heritage supported by leading-edge research and development activities, having been innovators of additive products for nearly 80 years. These products are used in automotive, heavy-duty diesel, and marine engine oils, diesel fuels, and specialty applications such as transmission fluids and gas engine oils. Their smart solutions have become key components of today's most demanding applications and advanced hardware systems. The organization operates worldwide production facilities with sales representation in more than 70 countries

The first standard specification for EV fluids by TotalEnergies

Liang XUE, Emmanuel PINOT, Emmanuel MATRAY, TotalEnergies Lubricants Technology and Product Engineering

Flavio SARTI, Richard VERNAY, TotalEnergies R&D

TotalEnergies Lubrifiants developed the first standardized specifications for Electric Drive System (EDS) fluids. This new performance standard is a first in the industry for hybrid and electric vehicles.

Pioneering electrical lubrication

In 2019, TotalEnergies Lubrifiants introduced Quartz, Rubia and Hi-Perf EV Fluids, the world's first ranges of fluids specifically engineered for hybrid and electric vehicles, covering both light and heavy vehicles as well as two-wheelers. These fluids were designed to meet the specific requirements of hybrid and electric vehicles, as well as associated electrical, thermal, and frictional constraints.

TotalEnergies Lubrifiants EV Fluids were also designed to meet the needs of automobile manufacturers and support them in developing eicient driveline systems, while maintaining the vehicles in optimum operating conditions throughout their service life.

Today, TotalEnergies Lubrifiants is once again demonstrating its commitment to innovation in hybrid and electric vehicle lubrication by developing the first standardized specifications for Electric Drive System (EDS) fluids.

This development comes at a time when no standard exists for EV fluids, unlike conventional transmission oils. This standard has been drawn up to ensure that EV fluids meet strict criteria such as viscosity, oxidation, corrosion, durability and material compatibility, while optimizing the fuel eiciency and performance of electric motors and transmissions.

A comprehensive specification

TotalEnergies Lubrifiants has taken the lead in developing this specification tailored specifically for these fluids. Leveraging its expertise and cutting-edge testing resources, TotalEnergies has introduced this new performance standard, a first in the industry for hybrid and electric vehicles. This standard is designed to provide crucial support for automobile and parts manufacturers.

This very first specification has been achieved through a selection of test procedures. Based on TotalEnergies Lubrifiants' extensive expertise in the field of fluids, this methodological development process firstly guarantees the good physicochemical properties of Quartz, Rubia and Hi-Perf EV Fluids, as well as their compatibility with diferent materials, in particular the new materials used in electrical applications, compared with conventional transmissions. Next, the tribological properties and durability of TotalEnergies Lubrifiants EV Fluids has been verified and confirmed at component level for gears and bearings. In addition, this process has included the creation of several test benches. First, a standardized bench was created to test the eiciency of the transmission at high speed in order to classify fluids according to their ability to improve battery life. A standardized bench was then developed for drive units to classify fluids according to their thermal capacity in electric motors. Finally, a durability methodology has been designed, based on road data and implemented on powertrain test beds, to speed up the vehicle validation process by reducing the time required.

The new specification is an industry first for electric vehicles. It is designed to ensure that TotalEnergies EV Fluids deliver outstanding performance when faced with the specific challenges of electric applications. It demonstrates once again TotalEnergies' pioneering role in the transition era of vehicle electrification and its commitment to developing cutting-edge vehicle technologies, as well as its commitment to supporting vehicle manufacturers with innovative and tailored solutions and tools. With this new EV Fluids standard, TotalEnergies Lubrifiants continues to strengthen its position as a leading innovator in electric and hybrid vehicle lubrication.

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Intelligent bearing monitoring with LubeSecure from HCP Sense

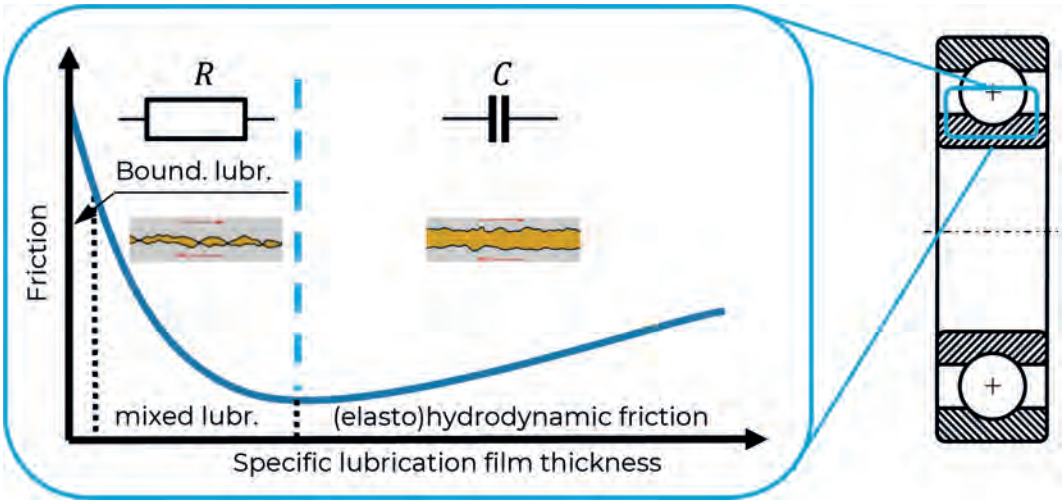
Nico Kratz, Test Field Manager, HCP Sense GmbH

Ansgar Thilmann, Managing Director, HCP Sense GmbH

HCP Sense is an innovative start-up from Darmstadt that develops intelligent bearing monitoring systems for industrial applications. With a focus on predictive maintenance and condition monitoring, HCP Sense offers solutions to maximize operational efficiency, minimize downtime and extend the lifespan of machines.

The LubeSecure technology utilizes the fact that a bearing under full lubrication can be viewed as a capacitor in the electrotechnical sense in which the lubricating film acts as a dielectric. By measuring the electrical impedance, it is possible to differentiate between different lubrication states. This innovative approach makes it possible to react to inadequate lubrication at an early stage, before permanent metallic contact and the associated increased wear and tear occur. With that, LubeSecure technology doesn't detect damages when they occur, as comparable condition monitoring technologies, but detects the underlying reasons for damages before they can actually form.

The following graphic shows the Stribeck curve from an electrotechnical perspective, illustrating the relationship between the specific lubricant film thickness and the electrical behavior.



Specific applications of LubeSecure technology

LubeSecure technology offers the following applications for rolling and plain bearings, among others:

1. Lubricant film monitoring:
Over 80% of bearing damage is due to lubrication problems in the bearing. HCP Sense's impedance-based lubricant film monitoring enables early detection of a lack of lubricant or the use of a lubricant that is unsuitable for the application in question. In addition, natural and temperature-related lubricant ageing can be reliably identified.

Furthermore, in the development of the drivetrain of electrically powered vehicles for passenger cars and commercial vehicles, energy consumption can be reduced without jeopardizing durability. This is achieved because the use of LubeScure allows the lubrication to be ideally matched to the mechanical components and the framework conditions prevailing in reality.

2. Determination of the viscosity ratio κ:
The viscosity ratio κ is the measure of the quality of lubricant film formation in bearings. This makes it possible to determine in real time when the operating condition changes from mixed to liquid friction, for example, and whether the lubricating film is sufficiently formed. The additives contained in many lubricants are also taken into account. By using machine learning, HCP Sense can determine the viscosity ratio of a wide range of lubricants in real time, thus laying the foundation for optimized and low-wear machine operation. Our machine learning algorithms are trained with customer data and test data from our in-house testbenches, making sure that we use high quality data to further improve the predictions made by LubeSecure.

3. Identification of contamination:

The technology's high measuring frequency ensures that even the smallest particles in the bearing can be identified at an early stage. Be it metallic debris from wear in the system or non-metallic particles from your process, LubeSecure detects changes in the lubricant condition almost immediately. This allows machines to be stopped in good time and maintenance measures to be initiated before major damage occurs.

By implementing LubeSecure technology, companies can not only plan their maintenance intervals more efficiently, but also optimize the energy consumption of their machines and increase overall operational safety.

The HCP Sense technology is currently being used successfully in numerous Gearbox test benches, field tests and from 2025 as a sensor installed as standard in new machines. Customers are already benefiting from the fact that they can prevent lubrication-related bearing damage, recognize machine failures at an early stage and plan maintenance more effectively. The areas of application are diverse and range from tunnelling machines to drivetrains and household appliances.

For more information:
www.hcp-sense.com
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„In addition to reducing the risk of failure, the optimum operating condition identified by LubeSecure also contributes to significant energy and CO_2 savings."

Ansgar Thilmann,
Founder & Managing Director,
Commercial Director,
HCP Sense GmbH

Driving sustainability – Reducing the embedded emissions of copper in electric vehicles

Bruno De Wachter, Independent Advisor, International Copper Association

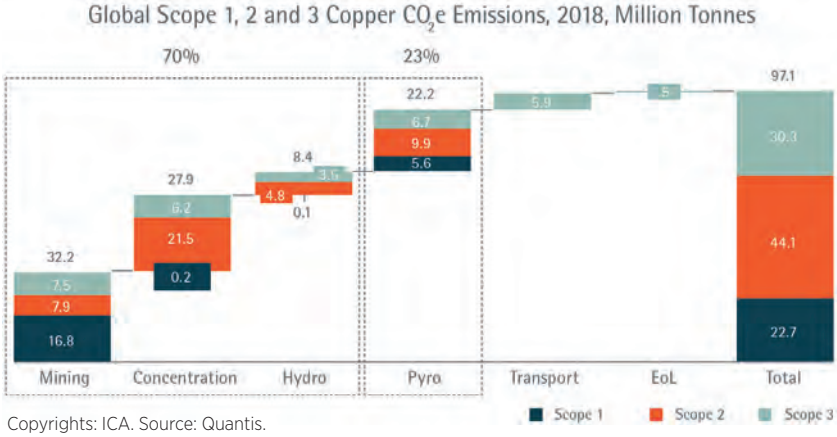
Since the publication of the EU Green Deal, e-mobility OEMs and Tier 1 suppliers in Europe have been actively seeking ways to evolve towards carbon neutrality. For such a journey to be successful, open communication across the entire value chain is essential. This article develops the case for copper, a key raw material of the EV powertrain.

Copper in EVs

There is great potential to significantly reduce embedded GHG emissions associated with copper in the years to come.

Copper has the highest electrical conductivity of all non-precious metals, a quality put to good use in the stator windings of electric motors and induction motor rotors, as well as batteries, cabling and electrical connections. As OEMs and Tier 1 automotive industry suppliers develop their decarbonization plans, reducing copper's embedded greenhouse gas (GHG) emissions is one of the challenges. A common approach to achieving this is by setting out a series of KPIs and milestones for their copper suppliers.

The good news is that there is certainly potential for reducing the carbon emissions from copper production to net-zero over the coming 30 years, and without the need for major technological break-throughs. But for these conditions imposed by manufacturers in the automotive industry to be effective and actually help the copper industry speed up their decarbonization process, they have to be formulated in the right way, which requires some insight into the copper production process and material flows.



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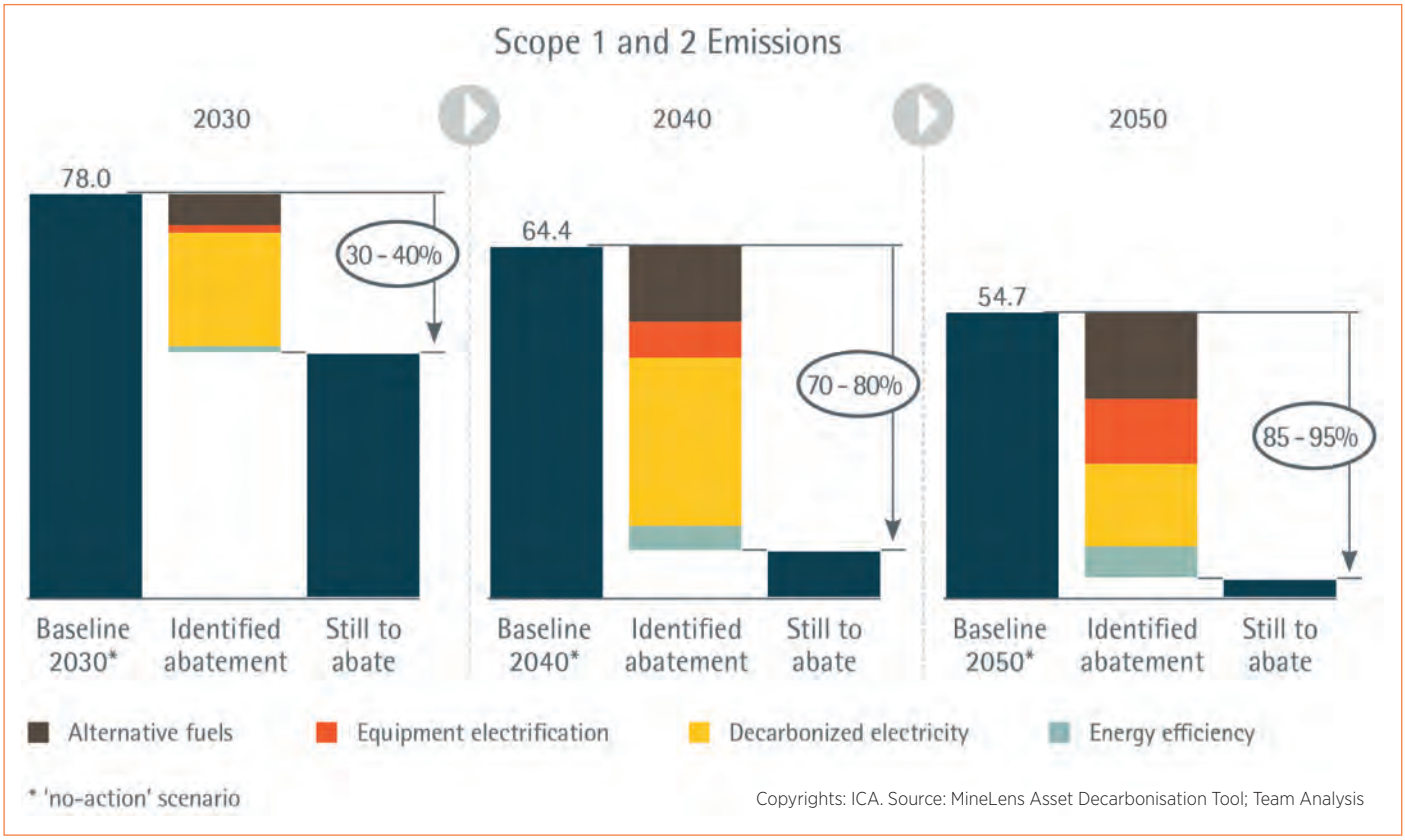

The copper production process and its emissions

A whole sequence of processing steps is required to produce high-purity copper. The process of extracting primary copper from ores begins, of course, with mining, followed by concentration through a flotation process, and a first stage of refining in smelters using pyro-metallurgical methods. The material is then subjected to a second stage of refining through electrolysis. An alternative route for low-grade ore is the hydrometallurgical process, which separates the copper from the ore through leaching and then extracts it from the remaining solution through electrowinning.

Secondary copper is produced from scrap originating from manu-facturing processes or end-of-life products. High purity scrap can be remelted directly with no need for refining, while less pure scrap requires additional processing. This can take place in dedicated secondary smelters, or the material can be added to the primary production process at various stages, depending on the scrap's purity. This means that high-quality copper metal is often produced from a combination of primary and secondary sources.

According to an analysis by the International Copper Association (ICA), copper production currently leads to a total of 97 million tonnes of GHG emissions annually, or 0.2% of total global emissions. Of these emissions, approximately 70% are generated by mining, 23% originate from smelting and refining, and the remaining 7% come from upstream and downstream transport and end-of-life treatment of products.

A major component of the GHG emissions associated with primary copper comes from electricity, from fossil fuels used in mining transport and equipment, and from fuels used in smelting furnaces at various stages of the production process. The GHG emissions of secondary copper depend on the purity of the scrap, since this determines at what stage in the refining process it is added, but they are generally lower than those from primary copper. That said, using secondary copper can never be the sole and complete solution to decarbonization, as explained later. For this reason, reducing the impact of the primary production routes should receive major focus in the decarbonization process.

The pathway to net-zero

The decarbonization of the copper production process has already started, with numerous initiatives by individual companies involved in copper mining and refining. To step up the momentum, the ICA with its members developed a path forward to bring the carbon foot-print of copper production as close as possible to net zero by 2050 ('Copper – The Pathway to Net Zero'). Made public in March 2023, the Pathway sets out a pragmatic approach to decarbonizing copper production, using existing technologies. It delineates which decar-bonization options can be activated, by when, and with what impact. It also outlines some enabling conditions that should be in place to achieve this.

For scope 1 and scope 2 emissions, the Pathway identifies four major types of levers. The first is equipment electrification, to include the haulage trucks used in mining. An example of good practice is demon-strated by Boliden, a Swedish mining company which introduced electric trolley assistance in its haulage trucks in 2018, saving significant amounts of diesel fuel (Boliden, 2018). At the same time, underground mining machinery is being electrified at a rapid pace, coming with the additional benefit of saving the energy and cost of ventilation. The second lever is decarbonizing the electricity supply. This includes switching from standard to green electricity, along-side the option of installing wind and solar energy farms at copper production sites. A third lever is replacing fossil fuels with biofuel, biogas, or green hydrogen, particularly in smelting furnaces. A fine example of this is at German copper producer Aurubis, which has started using hydrogen instead of natural gas for the reduction

process in its anode furnaces – an innovation set to reduce GHG emissions by around 5,000 tonnes each year (Aurubis, 2023). The fourth major lever encompasses various kinds of energy efficiency improvements at various stages of the production process. In a collective commitment, ICA members declared that they will be applying these and other measures to reduce their scope 1 and 2 emissions by 30 to 40% by 2030, 70 to 80% by 2040, and 85 to 95% by 2050.

A similar approach has been followed for scope 3 emissions, subject to the proviso that the results for this category depend on all the actors in the value chain collaborating. ICA members aim to reduce these emissions as far as possible by 2050, and will do what they can to unite every stakeholder behind this goal.

Recycling and decarbonization

Copper's infinite recyclability is a major advantage. About 80 percent of copper is used in an unalloyed form, making the recycling process more straightforward. Even for copper that is alloyed or contains other materials, recycling can still be achieved without downgrading. Unwanted elements can be efficiently removed to recover the copper in its pure state, ready to be re-used in any kind of application. Because of its high degree of recyclability, copper already in use in its various applications is not regarded as lost, but can instead be legitimately considered part of the world's copper reserve, often referred to as society's „urban mine".

Its high level of recyclability, combined with the fact that copper from secondary sources produces fewer GHG emissions than primary sourced copper, could lead to the simplistic conclusion that increasing the share of secondary material would be a good strategy for reducing embedded emissions. While this solution will work at individual plant level, it does not make sense on a European or worldwide scale. Due to the long average lifetime of products using copper (typically 25 to 30 years) and strong growth in copper demand (practically doubling every 30 years), the availability of end-of-life material is far too limited to meet the demand for new material. Additionally, no process is 100% efficient, and there will always be losses associated with collecting, separating, and re-processing copper scrap.

Note that a distinction should be made between fabrication scrap, which originates from the production of end-use material out of semi-finished goods, and end-of-life scrap, which originates from end-of-life products.

Globally, scrap recycling rates from end-of-life products averaged around just 15% over the period from 2000 to 2020. Estimating future recycling rates is complicated by various uncertainties, but MineSpans by McKinsey expects the end-of-life recycling input rate to increase to 23 percent over the next 30 years.

Fabrication scrap contributed to about 16% of semi-finished goods production globally, a figure expected to remain stable. Bearing this in mind, any requirement set by raw material purchasers to increase the total recycled content of new copper above 35%-40% can only result in less recycled material being used elsewhere, leading to zero net reduction in GHG emissions at global level.

Moreover, the main levers for increasing recycling rates are in the collection and separation of end-of-life material, and consequently not in the hands of copper producing companies. Design engineers at every level of the automotive industry can play their role by favouring product designs that facilitate dismantling and separation at end-of-life ("design for recycling"). In some cases, collaborations between various stakeholders and the copper industry to capture and process the cleanest scrap and create a closed loop can set a good example. Recycling rates could also benefit from incentives for end-of-life collection, from staff upskilling for end-of-life management, and from improved separation techniques for treating multi-metal scrap streams. Improved systems for car registration and waste stream reporting could avoid end-of-life vehicles being exported from the EU or going under the radar in other ways.

Collaboration across the value chain

All this considered, e-mobility OEMs and Tier 1 suppliers should not be over-concerned about the feasibility of reducing the embedded GHG emissions of copper conductors. The ICA and its members have developed a decarbonization pathway for the next 30 years based on existing technologies and that will bring the carbon footprint of copper production as close as possible to net zero by 2050. But to unlock its full potential, the pathway depends on stakeholder across the value chain communicating and collaborating with each other, upstream from copper production as well as downstream.

Purchase managers from the automotive industry can work with their copper suppliers to develop a roadmap to reduce embedded emissions and offer collaboration avenues to accelerate the process.

Raw material sourcing managers responsible for purchasing copper products should be aware of the limits of using recycled content as a means of reducing embedded GHG emissions. At the same time, they could consider developing closed loop business models for copper used in the automotive industry. Design engineers can play their role in this process by facilitating dismantling and separation at end-of-life.

With this level of collaboration across the entire value chain – stakeholders communicating and interacting and achieving what is within their reach – there is great potential to significantly reduce embedded GHG emissions associated with copper in the years to come, while improving the collection and recovery rates of copper in end-of-life vehicles.

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Dog clutch without angular backlash

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Center of Vehicles for Sustainable Mobility, Czech Technical University in Prague

Dog clutches are cost-effective but often suffer from angular backlash, causing discomfort. A novel, patented design has been developed to eliminate this issue using a purely mechanical blocking mechanism. This design, fully interchangeable with conventional mechanisms, requires no extra modifications but needs an external synchronization system. Featuring innovative gearshift dogs and blocking mechanisms, it was tested with two prototypes on test benches. The results showed the design's effectiveness, and robustness especially for hybrid and electric vehicles, addressing key shortcomings of traditional clutches.

Keywords: Dog clutch, Angular backlash, Gear shifting, Blocking mechanism, Automotive gearboxes, Hybrid and electric vehicles.

Introduction

Greenhouse gases, CO_2 regulations, alternative fuels, and vehicle electrification are critical issues driving the rapid growth of hybrid (HEV) and electric vehicles (EV) [1]. This shift demands innovative solutions in automotive engineering. This research focuses on developing a new gearshift mechanism to meet these demands. In HEVs and EVs, the electric motor can act as an external synchronization mechanism, potentially reducing costs. Parallel hybrids, requiring a wide range of gear ratios, benefit from cost-effective gearboxes like manual parallel shaft gearboxes (MT) or automated versions (AMT) [2][3]. These gearboxes commonly use synchronizers, a prevalent gearshift mechanism in passenger cars [4].

This research aims to replace the synchronizer with a new, cost-effective gearshift mechanism that eliminates the need for synchronization while maintaining or surpassing the synchronizer's functions [5]. Typically, a dog clutch is the simplest gearshift mechanism for constant mesh gears but has been limited by driving comfort and NVH (Noise, Vibration, and Harshness) concerns. In electric powertrains, NVH issues include gear whine and gearshift mechanisms [4],[6]. Reducing angular backlash is crucial for minimizing NVH, a feature of the new mechanism, while ensuring cost-effectiveness and compactness. More compact gearboxes tend to be stiffer, further reducing NVH [7].

This research introduces a patented dog clutch design addressing angular backlash, a common issue in traditional mechanisms [7]. Using a purely mechanical blocking system, it minimizes backlash and improves shifting quality. The form of dogs enables very fast disengagement of the speed even under load. Rigorous prototype testing confirmed its functionality, durability, and comfort, making it suitable for vehicle gearboxes.

Final design of dog clutch with blockchain mechanism

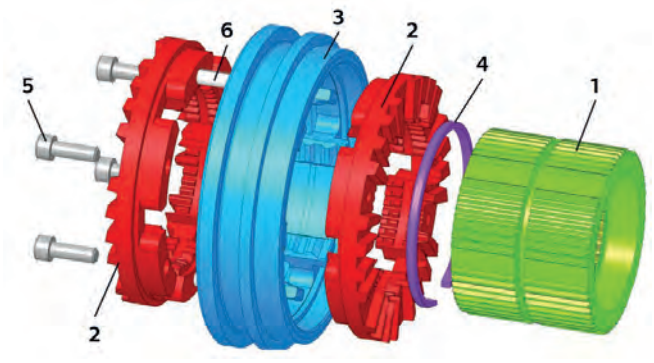

Fig. 1 Final dog clutch with blocking mechanism design (1–hub; 2–sliding gear; 3–gearshift sleeve; 4–blocking ring; 5–screws; 6–pins).

The clutch assembly (Figure 1) includes a hub (1) on the gearbox shaft, a sliding gear (2) that moves axially to engage gears, a gearshift sleeve (3) for controlling movement, and a blocking ring (4) to secure the sliding gear in positions. The sliding gear is split into two halves connected by screws (5) and pins (6). One blocking ring locks the sliding gear in all three positions (engaged/neutral/engaged) and secures the gearshift sleeve in neutral. No changes to the standard MT/AMT gear selector mechanism are needed. The design's uniqueness is confirmed by Patent No. 307443[8] and the utility model „Schaltungskupplung" [9]. Following design optimization, prototypes of dog clutches with a blocking mechanism were produced. Two clutches for the MQ200 gearbox were made to engage 1st, 2nd, 3rd, and 4th gears, see Figure 2. The prototype production was funded and supported by ŠKODA AUTO.

Figure 2: Fabricated protypes

Gearshift process

The blocking ring stays concentric with the hub due to its constant contact with the sliding gear or gearshift sleeve. With six contact points, the ring maintains its shape during compression. To prevent uneven deformation, which could interfere with gear movement and cause excessive wear, the ring's ends are bent inward. Figure 3 illustrates the gearshift process, where shifting the right gear involves:

Position 1 – neutral: Black arrows show axial backlash between the sliding gear and the gearshift sleeve. The blocking ring holds both components – sliding gear (upper) and sleeve (lower) – in neutral;

Position 2 – engagement preparation: The sleeve moves right, compressing the blocking ring, while the sliding gear remains in neutral until backlash is resolved;

Position 3 – engagement in process: With backlash removed, the sleeve pushes the sliding gear right, and the blocking ring stays compressed;

Position 4 – engagement termination: The sliding gear reaches its maximum position, engaging the gearshift dogs. Both components stop moving axially, and the blocking ring is no longer compressed;

Position 5 – engaged: The blocking ring expands back to its original position, fitting into the sliding gear's groove, preventing clutch disengagement due to torque;

Position 6 – disengagement preparation: The sleeve moves left to compress the blocking ring. Axial backlash is present, keeping the sliding gear engaged;

Position 7 – disengagement in progress: The blocking ring is fully compressed, backlash is gone. The sleeve moves the sliding gear to neutral;

Position 8 – Disengagement Termination: The sleeve reaches neutral, but the sliding gear remains slightly engaged due to kinetic energy. The decompressing blocking ring helps move the gear to neutral;

Position 9 – Neutral: The dog clutch returns to the neutral position, same as Position 1.

Prototypes of the clutch were designed for the MQ200 gearbox, where the blocking ring withstands axial forces up to 2 kN during dog engagement, transferring a maximum torque of 200 Nm. The force needed to engage and disengage the clutch via the gearshift sleeve is about 45 N, which is well within permissible limits and comparable to manual shifting forces. The sliding gear and gearshift sleeve have been optimized for powder metallurgy. For the sliding gear, only grooves for the blocking rings and threads on one half need machining, while the gearshift sleeve requires machining of the inner groove for the neutral position. The outer groove, for the gear selector fork, is for prototype compatibility and can be omitted in future designs. No additional parts are required between the sliding gear and gearshift sleeve, ensuring concentric alignment with the hub. The blocking ring is fixed securely and cannot rotate around the shaft axis due to the pin.

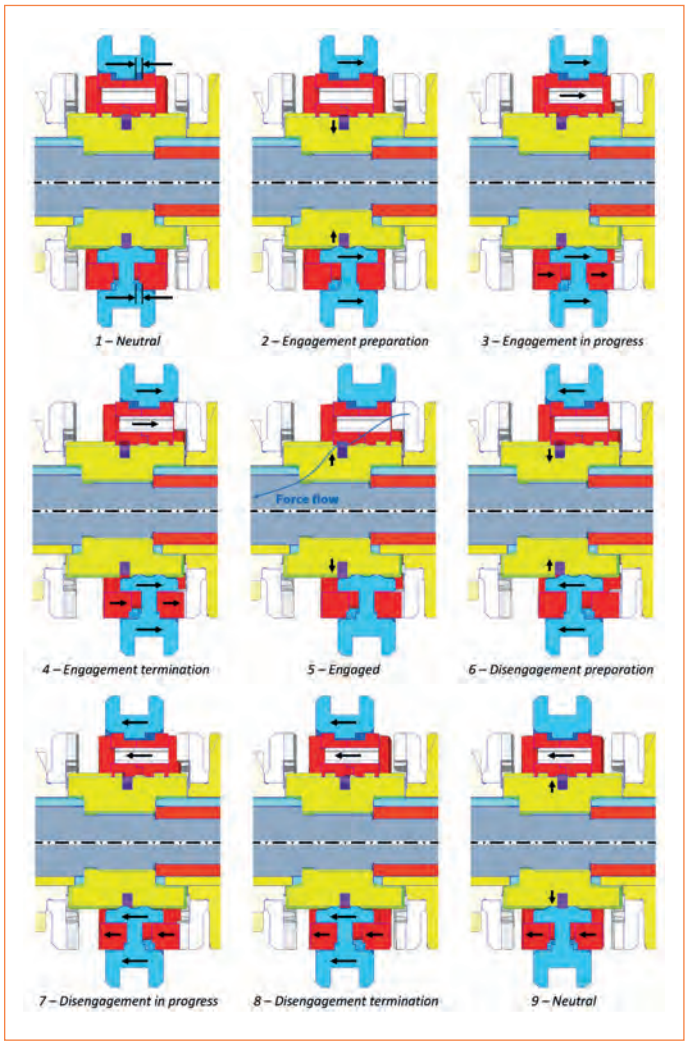

Fig. 3 Gearshift process of the dog clutch with blocking mechanism

Verification of the dog clutch

The fulfillment of the requirements for the dog clutch with a blocking mechanism needed to be validated against the design specifications. First experiments were static to verify the shift force and unwanted disengagement. The resulting gearshift force required to compress the blocking ring was measured to be 45 N.

Further was experimentally tested that the blocking ring functions as intended, preventing unwanted disengagement of the clutch.

The dynamic tests were dedicated for verification of function and for endurance tests. The first phase of clutch prototype testing used an inertia test bench with the output shaft connected to a large inertia disc. Tests focused on smooth shift sleeve movement and proper engagement / disengagement of the dogs. No unexpected behavior was observed.

The gearbox was connected to the gearshift robot on the inertia test stand, and gearshifts were performed with various input parameters. Mismatch speed was controlled by the difference between the stationary input shaft and the rotating wheel or by gear ratios between two gears. Figure 4 shows data from a gearshift with 3rd gear engaged at a mismatch speed of 30 RPM. The gearshift process began at 0.96 s, with rising displacement and force curves. A sharp drop in force at 1.02 s indicated compression of the blocking ring, allowing the sliding gear to move. The force increased as the dogs engaged, and by 1.08 s, engagement was complete. The gearshift took about 60 ms.

To proceed with dynamic check of the blocking mechanism, the gearbox was moved to dynamometric test bench. The function for the 3rd and 4th gears were performed with positive result. Due to test bench capacity 1st and 2nd speed were not tested.

Service life (endurance) tests were conducted for the 3rd and 4th gear clutches on the inertia test bench, with each gear being shifted 180,000 times and the gearbox output set to 89 RPM. This low speed simulated a mismatch speed of around 140 RPM, optimizing the gearshift process and eliminating the need for external synchronization. Each shift took just over 2 seconds, resulting in 220 hours of continuous testing per clutch and blocking ring.

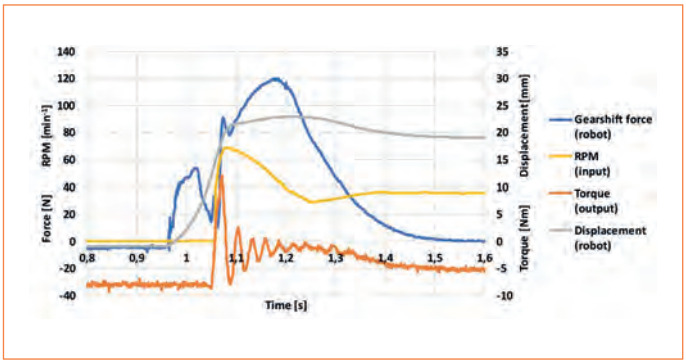

Fig. 4 Shifting 3rd gear; mismatch speed 30RPM.

Conclusion

The new patented dog clutch with a blocking mechanism enhances efficiency and reduces costs for electric and hybrid vehicles. It offers minimal angular backlash (less than 0.1°) and can disengage under load, improving shifting comfort and torque transmission. This purely mechanical design is compatible with standard gear selectors, including sequential shifting, and requires no additional modifications. The clutch's blocking ring withstands high axial forces, preventing unwanted disengagement. Prototypes, tested in a standard five-speed gearbox, demonstrated up to 30 mm axial space savings compared to conventional synchronizers. The design supports effective serial production using powder metallurgy and has proven durability with a service life of 700,000 cycles.

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External damping of roller bearings and its effect on the acoustics of an e-mobility gearbox

M.Sc. Kai von Schulz, M.Sc. Tilmann Linde, Prof. Dr.-Ing. Steffen Jäger

Furtwangen University, Institute for Product and Service Engineering

Reducing the sound emitted by the vehicle and the noise perceived by the passengers is an essential part of the development of modern (e-)vehicles. Bearings are crucial to the transmission of vibrations within the vehicle powertrain. This article presents a method for studying the impact of external bearing damping on acoustic properties. For this purpose, damping elements between the outer bearing ring and the gearbox housing of a gearbox used in electric vehicles are introduced, and parameters relevant to damping are varied by means of design of experiments.

Noise sources and sound transmission

At first, the noise sources that occur in a gearbox for electric vehicles will be identified. The gear mesh is determined as one of the primary sources of noise. The vibrations generated by the gear mesh are transferred through the shafts, the bearings, and the gearbox housing [1]. The design and material of the gearbox housing play a crucial role in how these vibrations are transmitted and whether they are dampened or amplified [2]. The vibrations can cause resonance in the housing, amplifying the noise emitted from the gear mesh. The air-borne sound emission occurs when the vibrations from gear mesh and structure-borne sound radiate into the surrounding environment. Due to deviations in the ideal meshing, a transmission error occurs between the driving and driven gear. The transmission error is primarily influenced by the manufacturing tolerances, variations in gear tooth geometry, and operational conditions such as load and speed [3]. The design and manufacturing quality of the gears have a considerable impact on their acoustic characteristics [4]. Moreover, the surface roughness of the gear teeth can influence friction and noise generation [5].

Bearings not only transmit the vibrations introduced by the gear mesh, but can also be a source of noise themselves. The primary sources of noise in bearings occur from various factors including design, manufacturing imperfections, operational conditions, and inadequate maintenance [6]. Factors such as load, speed and alignment are of significant importance. Imperfections in the surface finish of the raceways and the balls or rollers, as well as their roundness, can result in an uneven distribution of loads across the bearing surfaces [7]. The presence of high loads or speeds can exacerbate any existing imperfections in the bearing [8].

Finally, the electric motor can also be regarded as a source of perceptible noise. Electric motors, while quieter than internal combustion engines, introduce their own sources of noise, particularly through torque ripple and electromagnetic interference [9]. Torque ripple refers to the variation in torque output as the motor rotates, which can induce additional vibrations in the gearbox [10]. In addition, electromagnetic interference can cause vibrations in the motor's components, which may be transmitted to the gears through the coupling, thereby further worsening the acoustic behaviour [11].

Potential noise reduction measures

Following the overview of the noise generation mechanisms within the gearbox, it is evident that specific, targeted measures are required to mitigate the associated noise emissions effectively. The primary noise sources, as described in the previous section, are main areas of concern. Targeted measures in these areas can significantly improve the acoustic behaviour of electric vehicle gearboxes. The authors have examined a wide range of measures for reducing the noise of drive systems [4, 12]. The focus of this article is on damping of the excitation by both the tooth mesh and the ball bearings.

The modification of bearing damping characteristics has the potential to result in a reduction in noise levels [13]. Incorporating damping inserts within or around the bearings of a gearbox is an effective method to absorb vibrations at their source before they are transmitted to the gearbox housing. Materials commonly used for these inserts include elastomeric compounds, viscoelastic polymers, and soft metals which are tuned to absorb specific frequencies of vibrations that are prevalent in gearbox operations [14]. These damping elements are usually placed in the most effective locations in the bearing assembly, where they can absorb the vibration energy resulting directly from the interaction between the rolling elements and the raceways.

Design of experiments on external bearing damping configurations

Design of Experiments (DoE) is a statistical approach to study the impact of multiple factors on the systems performance. In the context of analysing external damping of roller bearings, DoE is applied to evaluate how different parameter sets affect the transfer of the vibrations. DoE is particularly useful in this context, as it enables the identification of the most influential factors affecting both noise levels and efficiency, as well as the optimal combination of these parameters.

The variables in this case are the number of O-rings, their rigidity and the cord thickness of the O-rings, and whether additional oil is pressed into the gaps or not. By allowing simultaneous variation of parameters, DoE not only saves time and resources but also uncovers interactions between these parameters that might otherwise remain hidden. In this way, DoE provides a more comprehensive understanding of how the variables work together to influence the system's behaviour, revealing possible synergies or trade-offs between different parameters. Here, the focus is on the system's response in terms of its structure-borne and airborne sound emissions. Additionally, the system efficiency is analysed. For example, reducing the stiffness of the O-rings may reduce the transferred vibration, but it may also reduce efficiency due to a higher transmission error in the tooth mesh. The application of DoE allows the reduction of the number of experimental runs while maintaining the comprehensive coverage of the interactions and effects of all factors within the specified range. This efficiency in test design is critical in experimental research involving complex mechanical systems, where a large number of tests could be impractical due to time, cost, or resource constraints.

Physical study

To evaluate the presented measure of outer bearing damping, an existing high-speed gear test rig (cf. Figure 1) is being converted so that different parameter sets of outer bearing damping can be tested for their effectiveness under different operating conditions, such as speed and torque.

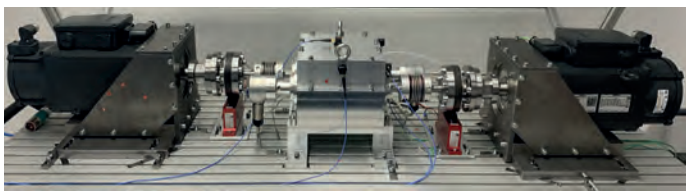

Fig. 1 Gear pair test rig.

For this purpose, the bearing seats have been modified to allow the use of up to three commercially available nitrile rubber O-rings. In addition, it is possible to fill the spaces between the O-rings with oil and apply an overpressure. Figure 2 shows a schematic illustration of the design.

In this study, the experimental parameters are varied within specific ranges, providing valuable insights into their effects on system behaviour. Various tests are carried out at different torques and speeds in the range between 0 and 6000 rpm and 0 and 45 Nm. The measurement results are analysed at static operating points. The experimental design includes varying the number of O-rings from 1 to 3 and varying the stiffness of the O-rings between 70 and 90 Shore. In addition, the cord thickness of the O-rings is varied between 1.8 mm and 2.8 mm and whether additional oil is injected into the gaps is also considered as a binary factor (yes/no). Through the application of DoE, this study aims to determine the optimal combination of these factors to achieve an appropriate damping characteristic: significantly reducing noise while maintaining high efficiency.

Once the test rig has been converted and the measurement campaign has been completed, the most promising damping elements will be further optimised.

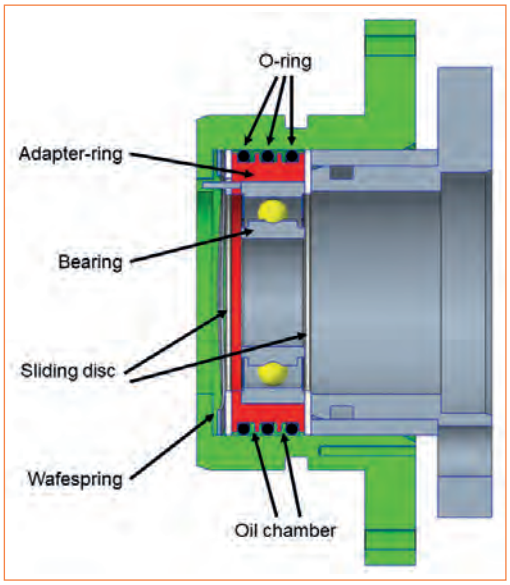

Figure 2 CAD geometry of outer bearing damping design.

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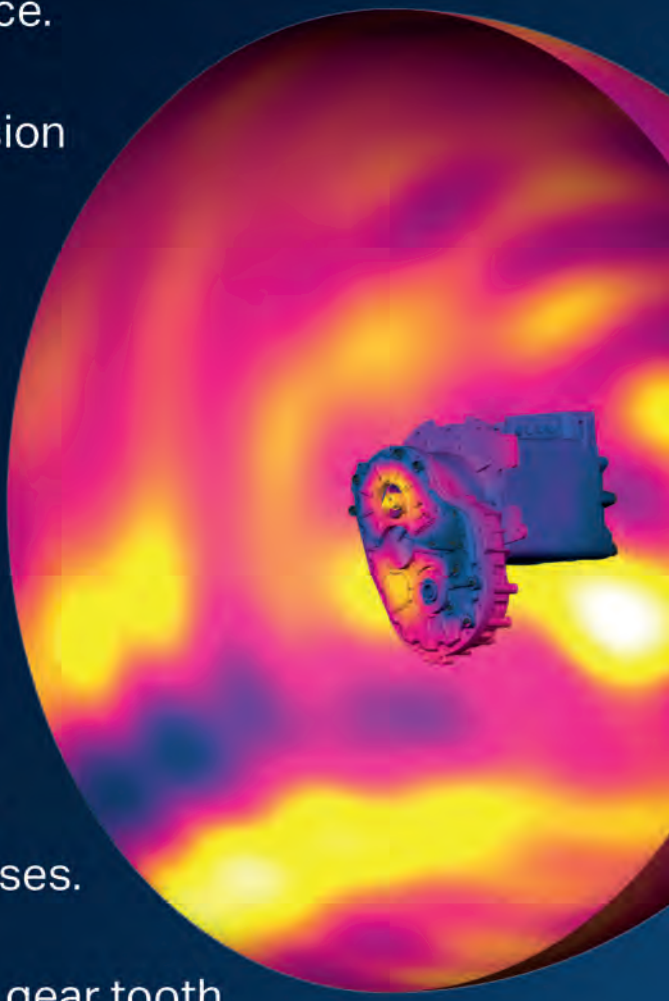

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Finding Focus

Many manufacturers focused on reduction of tailpipe emissions, increasing efficiency, aerodynamics and reducing weight. With the end of fossil fuels in sight, the grid becoming greener, embodied carbon will be key to net zero.

The Automotive Industry's Race to Zero Emissions

Mark Rushton, Sustainability Director, aPriori Technologies

Whether it is the end of the road for Internal Combustion Engines or not (due to synthetic fuels), the in-use phase of a vehicle's carbon footprint will soon no longer be the most significant impact. Tackling embodied carbon proactively and cost effectively is how leading manufacturers are staying ahead of the competition.

Beyond Tailpipe Emissions

In the automotive industry, we are facing unprecedented challenges with the transition to emission free mobility. Innovation holds the key to success, but some innovations are too expensive to put into production. How can we try new manufacturing processes to get a competitive edge, without detailed cost and carbon footprint analysis of these new processes? Time could be lost experimenting. In this article, we will explore the 4 levels of product sustainabilty maturity that we have identified in customers and prospective customers of aPriori Technologies, from the Automotive Industry and beyond. It also explores various strategies to reduce the embodied carbon in automobiles.

4 Steps to Optimizing Sustainable Design and Manufacturing

aPriori's four-phase sustainability maturity model integrates sustainable practices into manufacturing while balancing profitability and environmental impact

This framework guides manufacturers toward environmental stewardship using data-driven insights to make effective design, sourcing, and production choices

Designing products that balance profitability and sustainability is essential in today's market. This requirement is driven by a growing consumer demand for greener products, stricter environmental regulations, and a collective push to achieve carbon reduction targets.

Manufacturers must integrate sustainable practices into their existing operations without compromising on efficiency or competitiveness. This raises a pivotal question: How can manufacturers align their operations to promote environmental stewardship and spur growth?

To address this critical issue, aPriori has established a sustainability maturity model as a strategic roadmap for manufacturers to assess their current capabilities and the effectiveness of their green supply chain management initiatives. By monitoring their sustainability maturity performance, manufacturers can establish clear steps to reduce their carbon footprint.

The following figure illustrates how product development teams can assess and pinpoint their position across the four stages of sustainability maturity.

Manufacturers that don't advance their sustainability maturity to the fourth and final stage risk falling behind their competitors and being saddled with additional operational costs due to incurred carbon taxes and other regulatory policies enacted to spur the reduction of greenhouse gases (GHGs).

Learn more by downloading the aPriori Sustainability Guide at get.apriori.com/CTI-mag

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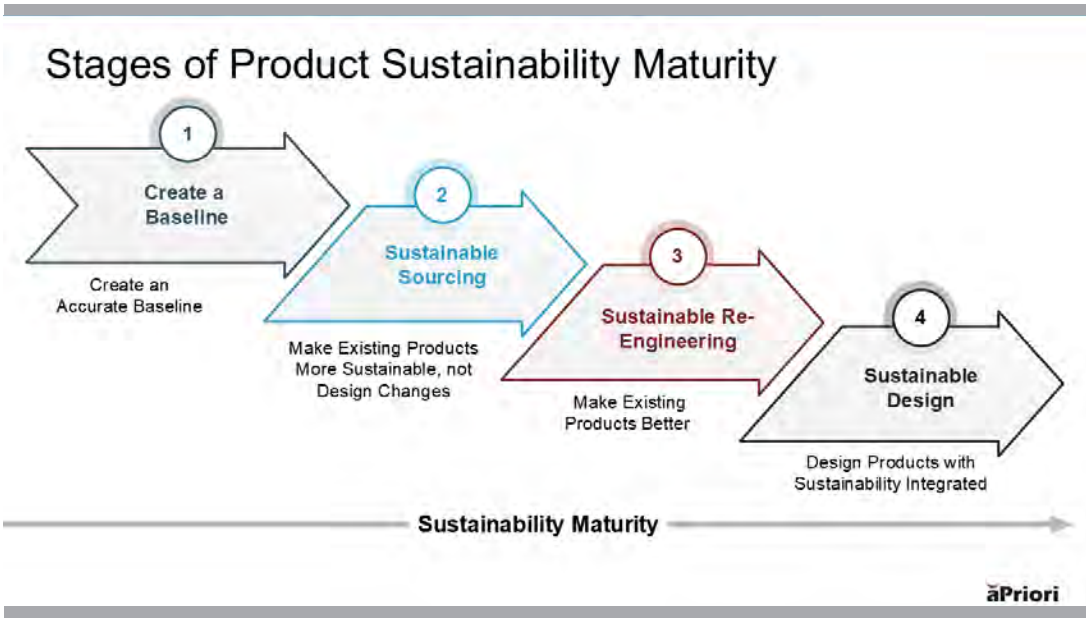

Figure 1: The 4 stages of Product Sustainability Maturity

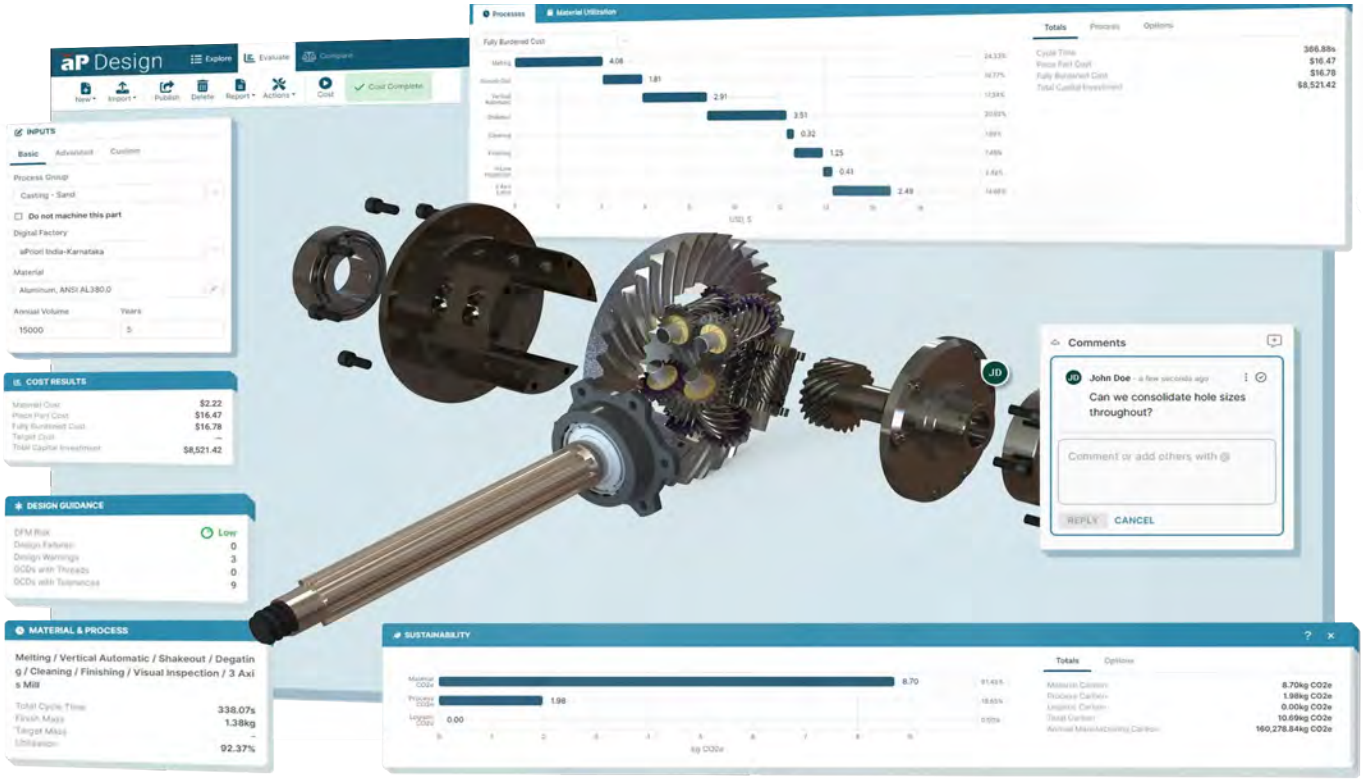

Figure 2: Composite screenshot of aP Design showing the insights that are gained from an analysis

Stage 1: Create Precise, Auditable CO2e baselines

Creating an accurate carbon emissions baseline is the first step in achieving a sustainable and green supply chain. This baseline empowers sustainable manufacturers to measure and quantify the carbon footprint of their existing supply chain operations, enabling them to:

- Use their current "state of sustainability" as the starting point to plan and track their progress
- Identify and focus on the areas with the highest cost and carbon reduction potential.
- Set realistic cost targets that guide and influence product teams' supply chain decisions.
- Adhere to environmental, social, and governance (ESG) standards and regulations.
- Benchmark and compare their sustainability performance against industry competitors.

Life cycle impact assessments (LCIAs) are a standard method to establish CO2e baselines and provide manufacturers with standardized emissions estimates for product lifecycle areas that are impossible to measure accurately.

Carbon assumptions for a product's in-use phase can be entirely different from reality. A car, for example, could burn fossil fuels for 300,000 miles within the range of established fuel consumption values, or it could be written off in an accident after 1,000 miles. Similarly, a product designed for 90% reuse could still end up in a landfill and not achieve its optimal contribution to the circular economy.

An LCA is a great tool for making assumptions and using averages. However, the manufacturing process doesn't require that level of guesswork, so a more precise baseline would be beneficial for that phase.

aPriori's automated sustainability insights solution closes the gap by integrating data from ecoinvent, a leading third-party LCA and inventory database tool. aPriori utilizes ecoinvent's database to quickly establish environmental baselines and Greenhouse Gas (GHG) emissions at the product level. With automated and more precise baselining, teams can quickly move to the second phase of sustainability maturity: evaluating and selecting sustainable suppliers.

Stage 2: Select Sustainable and Responsible Global Suppliers

Next, evaluate and select suppliers based on their local electricity mix, material supply, and processes (Scope 3). Procurement teams can create digital factories for each supplier to see each vendor's carbon impact, and then compare vendors using the same production criteria (e.g., the same production volume, manufacturing process and equipment, etc.). Digital factories will also show how the energy mix and energy consumption of a supplier in India, for example, compares with production facilities located in Mexico and China. Product teams aim to enhance the sustainability of existing innovations through informed supplier selections instead of resorting to costly design or material changes. Sustainable sourcing offers the most straightforward approach to reducing CO2e by minimizing the need for extensive design changes, and therefore can be implemented at any time. However, it is difficult for product teams to capitalize on this opportunity without a dedicated and standardized tool such as aPriori.

aPriori provides manufacturers with complete visibility into the sustainability of their supply chain, through a digital twin of the manufacturing facilities at their disposal, empowering them to make data-driven sourcing decisions.

By utilizing aPriori for sustainable sourcing, companies can:

- Explore various "what-if" scenarios (regions, routings, materials, volumes/batches, suppliers, make vs. buy).
- Reduce iterations and negotiation by digitally connecting buyers and suppliers.
- Fill skills gaps with exposure to granular, actionable, real-world sourcing data.
- Identify sustainable procurement strategies to support internal ESG goals and initiatives.

Stage 3: Optimize Existing Products for Cost and Carbon

The path toward greener products involves optimizing existing product innovations. In stage three, product teams can consider alternative materials with lower carbon or higher recycled content. And they can also make processes more efficient to improve cost and environmental sustainability, or look to utilize renewable energy sources.

The objective is to minimize cost overruns and release products at target costs to maintain profitability and competitive advantage. However, this is difficult to achieve when cost engineering teams are limited to conventional, labor-intensive costing tools like manual spreadsheets. And the complexity of this challenge heightens when the situation extends to CO2e emissions. This is because spreadsheet-based solutions cannot:

- Evaluate the complex interrelationships between direct and secondary cost & carbon drivers in real time
- Accurately manage cost & carbon variables in an ever-changing global supply chain
- Identify and capitalize on cost & CO2e reduction opportunities during early product design phases

aPriori provides a precise, real-world product cost optimization solution to make highly informed and effective manufacturing decisions. aPriori's cloud solution can simulate production based on product design (geometry), manufacturing overhead costs, direct labor hours, machine hours, and more. This capability can be fully automated through PLM integration.

Additionally, aPriori enables companies to navigate and manage rising material costs, inflationary pressures, and other external risks to build cost-effective products. aPriori also automatically notifies and provides actionable feedback to design, manufacturing, and sourcing teams when products exceed cost thresholds. This facilitates seamless collaboration among product development teams, enabling them to eliminate cost drivers early and maintain corporate profit margins proactively.

Stage 4: Remove Embodied CO2e Through Data-driven Product Design

The final stage of sustainability maturity represents the most challenging path and the greatest opportunity for reducing GHG emissions. Product engineers can typically compare multiple product designs and intuitively select the most cost-effective option for both cost and DFM. But when you add carbon to the mix, the answer is usually far from obvious.

But by using real-time CO2e feedback from the 3D CAD model, teams can proactively modify the product's design to reduce its embodied carbon. They can also ensure that a product meets its targets for cost, DFM, and sustainability by selecting the option that best balances all requirements for sustainable design.

Take the Next Step to Optimize Sustainable Design

Optimizing sustainable design and manufacturing is not just a choice: it's pivotal to addressing today's market requirements and customer demands. aPriori's four-step sustainability maturity model presents a comprehensive strategy for manufacturers to align their operations with environmental stewardship while enhancing profitability and market competitiveness.

aPriori's four-stage model provides a roadmap for best-in-class green manufacturing based on strategic design strategies. It also underscores the need for data-driven insights to make effective design choices amid increasingly complex supply chains. Mature companies in this area will contribute to global carbon reduction efforts and position themselves as leaders because sustainability is increasingly a determinant of success.

Once you have the capability for evaluating both cost and carbon during design, and leveraging the same data for sourcing or procurement, you can then start to include the "cost of carbon" as a strategic tool. Leaders in this space are utilizing an internal carbon price (ICP) to convert the units of measure from Kg of CO2e to currency. This is exactly how the Carbon Border Adjustment Mechanism, or CBAM is going to work from January 1st, 2026. This is why it makes a lot of sense to build carbon decision making into the same method as cost decision-making.

Furthermore, evaluations of a product's cost are rarely left to assumptions or industry averages, but that is usually how the majority of product carbon footprint assessments are done. We all need to care as much about carbon emissions as we do cost. In 2024 alone, it is estimated that climate-related disasters wiped $2 trillion from our economy. That is more than the recession in 2008. In manufacturing, we have both responsibility, but also an opportunity to increase competitive advantage, by reducing the environmental impact of not only the use of the products, but the manufacture of them.

If you are interested to learn more about how you can combine cost, carbon emissions and manufacturability evaluations, based on 3D CAD data, get in touch via get.apriori.com/CTI-mag

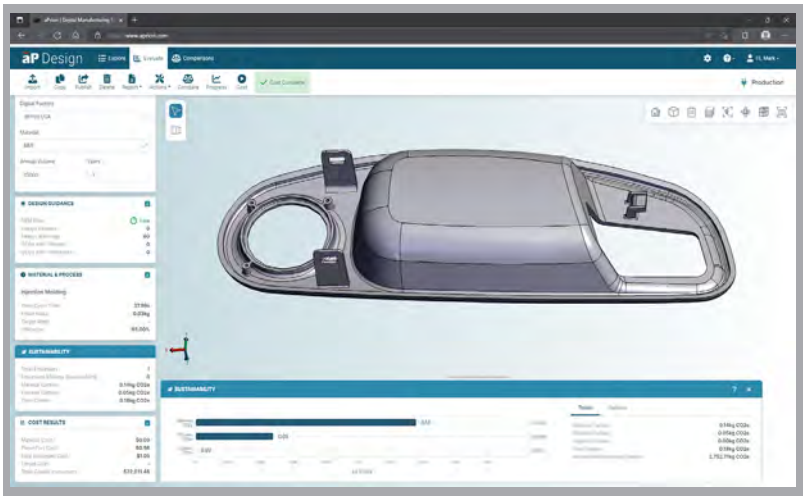

Figure 3: A screenshot of aP Design showing embodied carbon

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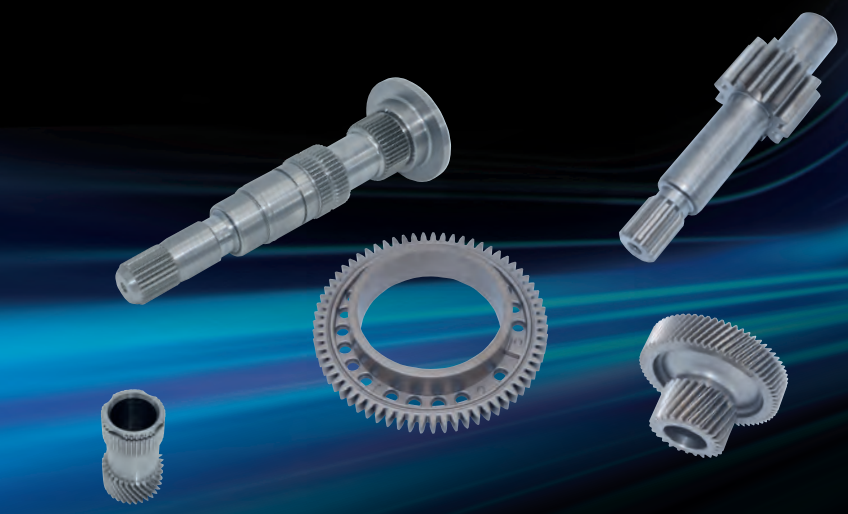

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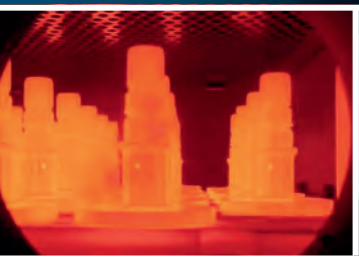


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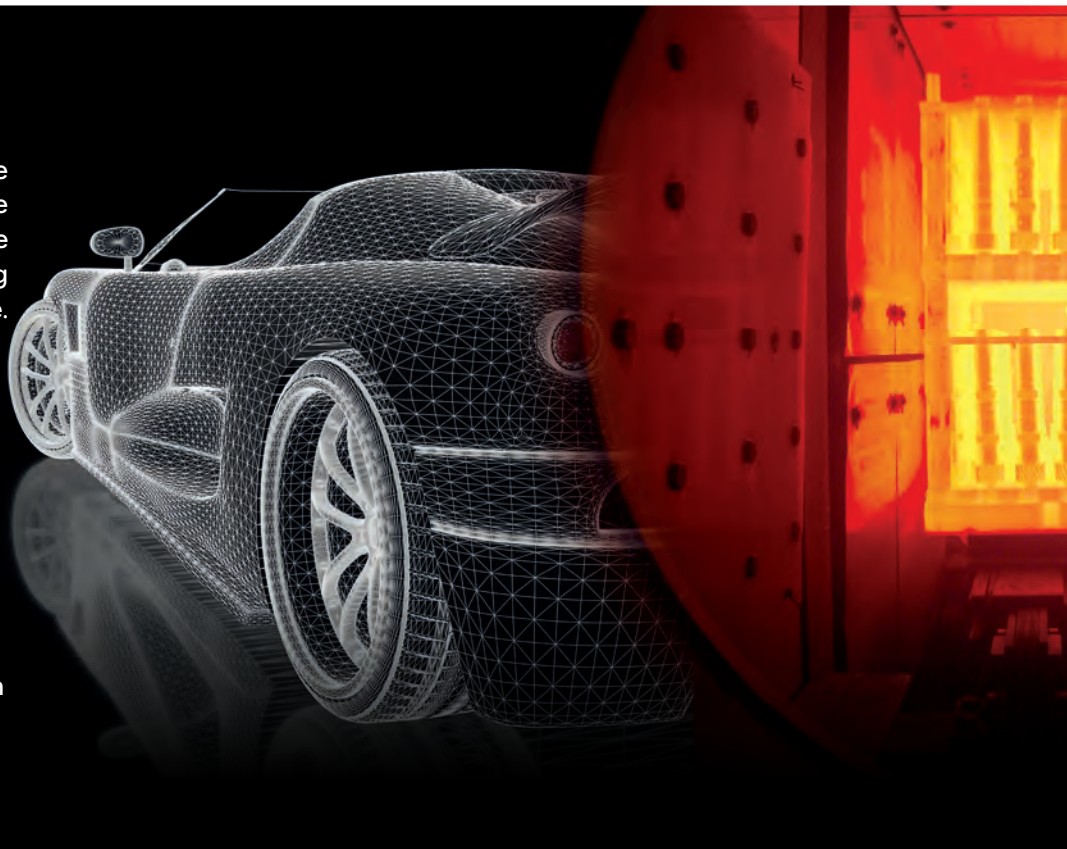

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Hyperdrives is a pioneering deep-tech engineering company revolutionizing how we design and build electric motors. Hollow-conductor-enabled super-efficient, extremely power-dense, and exceptionally cost-effective electric motors without rare-earth elements increase range and reduce cost by up to 50%. Hyperdrives' proprietary motor design is based on industry-standard materials and components only, and their patented manufacturing technology can seamlessly be integrated into the existing automotive hairpin production lines. With this, Hyperdrives aims to establish a new global gold standard for electric motors in cars, trucks, eVTOLs, and boats within the next 5-7 years.

https://www.hyperdrives.de

HCP Sense GmbH

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