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Can you see the light?

Forvia Hella's ADB and
the J3069 challenge



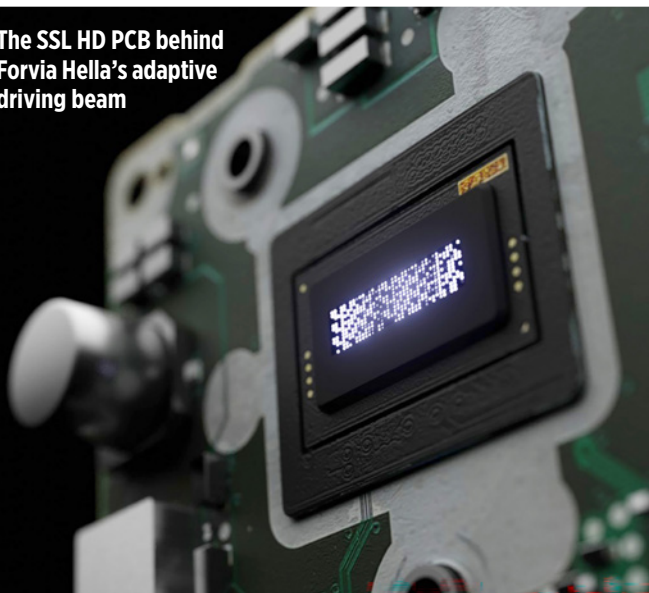
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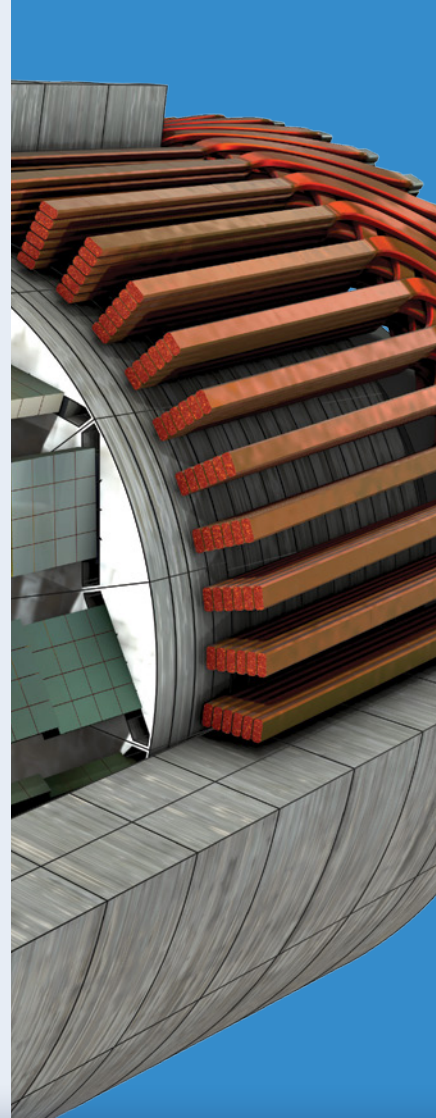
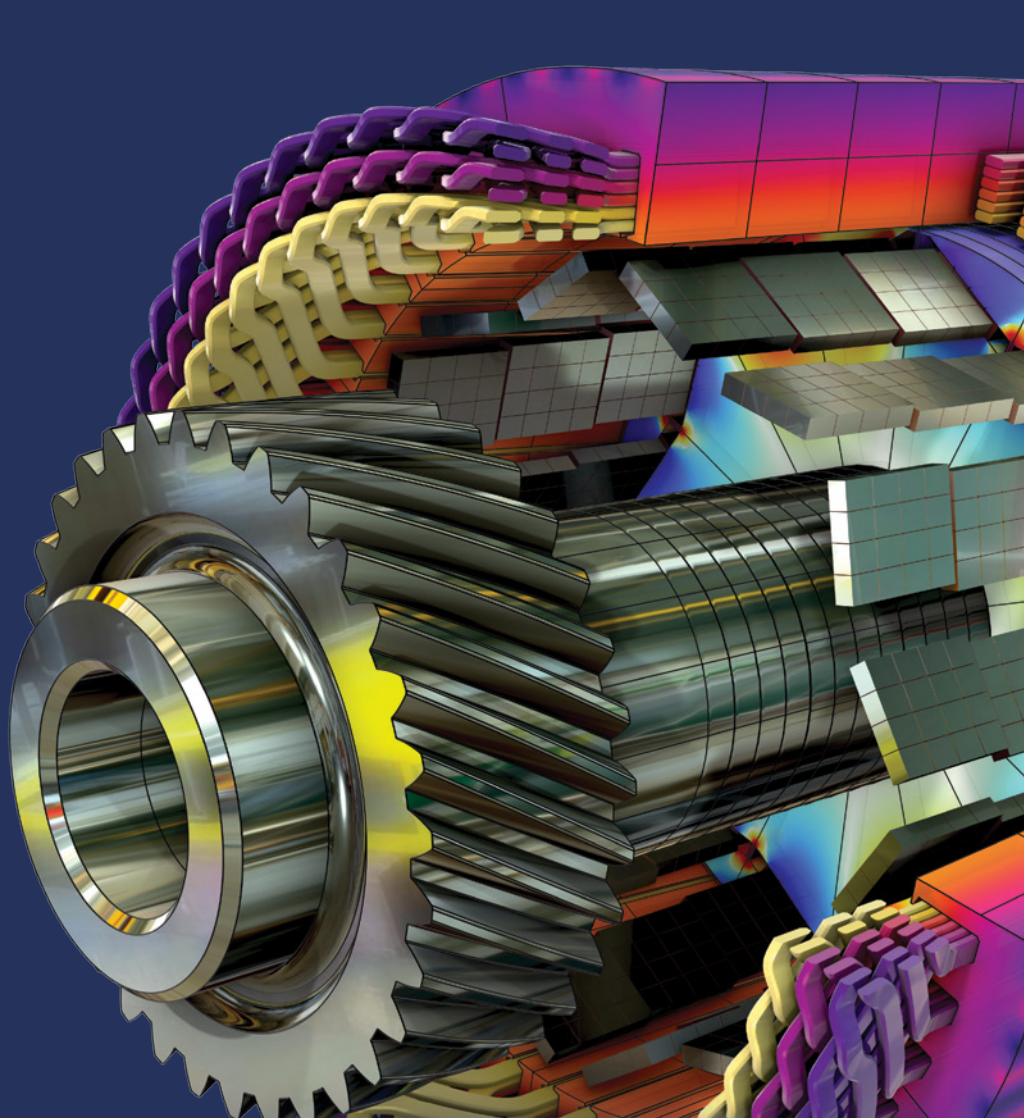
**Better simulations
for motor, battery
development**

**Bosch's new electrolyzer
supports H2 efforts**

**Return of
The Navigator**

The SSL HD PCB behind
Forvia Hella's adaptive
driving beam





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Adaptive driving beam headlights have been approved in the U.S. since 2022. Suppliers like Forvia Hella have systems at the ready. But OEMs are having trouble passing NHTSA's test. (Image: Forvia Hella)



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INSIDE STORY

Digital twins originated as virtual models of physical products, systems, or processes, explains Marc Serughetti, Vice President of Product Management at Synopsys. As vehicles and other products have evolved to include more embedded electronics and software, the digital twin paradigm is evolving. Electronics digital twins (eDTs) now enable the modeling of entire electronic systems, including both hardware and software. This holistic approach is transforming design, validation, lifecycle management, and even business models — especially in the automotive industry.

Automotive Engineering: What distinguishes eDTs from traditional digital twins?



Marc Serughetti: Traditional digital twins primarily replicate physical hardware. In contrast, eDTs provide comprehensive virtual models of electronic systems — integrating software, sensors, and embedded silicon. In automotive applications, this means simulating not only the physical car but also the software that governs features like adaptive cruise control, automatic braking, and real-time diagnostics.

AE: Why is the automotive industry embracing eDTs?

Serughetti: The priorities are clear: reducing development time and cost, accelerating time-to-market, and enhancing product quality. With eDTs, issues can be identified and addressed virtually, saving time and resources. eDTs also support the entire product lifecycle, from development and validation to in-field monitoring and ongoing software updates delivered over the air.

AE: How are eDTs acquired and implemented?

Serughetti: eDTs are delivered as platforms rather than standalone tools. Implementation depends on a robust ecosystem of partners, third-party technologies, cloud providers, and system integrators. The technology stack includes engines and models for building digital twins, integration tools, verification and validation features, and collaboration capabilities, often leveraging cloud technologies. Artificial intelligence is increasingly part of the stack, supporting everything from model creation to predictive analytics. Flexibility and scalability are critical, enabling organizations to tailor eDTs to their evolving needs.

AE: What are some key automotive use cases?

Serughetti: In automotive engineering, eDTs are used to validate semiconductor designs and automotive software

before physical prototypes are built. They enable virtual prototyping, facilitate testing of software-hardware interactions, and support collaborative development across teams. Data management is another important use case — collecting field data, replaying it in digital environments, and using it to improve products. eDTs are very flexible and can be tailored for specific engineering or business priorities, but this needs to be defined upfront.

AE: What guidance can you offer to companies exploring eDTs?

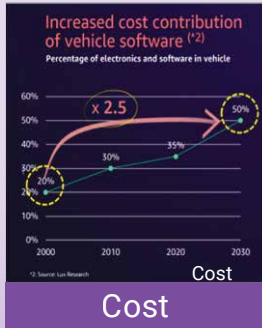
Serughetti: Alignment with business goals is essential. eDTs should be viewed as part of a broader digital transformation, supporting objectives such as faster development, improved quality, and new revenue streams. Deployment and scaling require careful planning, including integration into existing processes, expansion across product lines, and selection of partners with proven expertise. Success depends on both technological innovation and re-engineering organizational methodologies.

AE: What role does Synopsys play in the eDT landscape?

Serughetti: Synopsys is at the forefront of electronics digital twin development. We recently launched the Synopsys eDT Platform, an open, cloud-ready infrastructure that empowers companies to build, deploy, and manage eDTs in a highly flexible and scalable way. Two initial use cases are focused on the automotive industry. One enables suppliers to expose their electronic designs to select customers for evaluation and early software development in a hosted cloud environment. The other enables end-to-end software development, system validation, and collaborative engineering within an OEM or Tier1 private cloud environment. Across all use cases, eDTs help customers innovate faster, improve quality, and unlock new opportunities in the software-defined era.

To learn more about the Synopsys eDT Platform, visit <https://www.synopsys.com/edt>.

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EDITORIAL

All the ways: Learning via print in a digital era

Welcome, once again, to our annual digital-only issue. We remain committed, of course, to our eight print issues each year, but letting the benefits of digital media come to the fore is always its own fun challenge. No matter what your role is, you should find something engaging and educational among these virtual pages.

We've got videos, animations and other multimedia components for you to click on and learn from in this issue. My personal favorite example in here of a video replacing a thousand words can be found in our cover story. It's not like the text is indecipherable, but simply seeing how adaptive headlight beams adjust where they throw their high beams so as to not blind other drivers in almost all situations is just cool. Headlight technology has come a long, long way in the last decade, from the low lights of old helping clear a path home to today's often-annoying high beams that may provide extra safety to the driver, but make the blood of oncoming drivers run dry.

So I don't discourage investigation, I won't spoil the rest of the links and videos. We've made it as easy as possible to identify when an article includes extra content with big "play" buttons. You'll find video and webinar links, animations, and more.

When you're done reading this issue and want more digital content, you'll find countless hours of webinars and videos on sae.org and our other sites, including MobilityEngineeringTech.com, that will help you in your engineering work. We

also have a monthly podcast (listen on Spotify or Apple Podcasts) and editor Chris Clonts can regularly be heard on the "Eye on Engineering" segment over at WJR radio in Detroit (listen online here, where you'll find recent items on China's autonomous vehicles and Volvo's new H2 commercial trucks). Finally, editor Roberto Baldwin brings you video car reviews where he not only tells you how a model drives but also explains how this or that tech improves the car on the road.

Learning styles are as varied as the people reading this magazine. You won't be surprised that, as a writer, I learn best from well-written words. Others grasp

things better with pictures or video. Others shine under one-on-one instruction. While we can't recreate that here, exactly, we can approach that vibe through interviews and webinars. We've got all that for you. With the auto industry going through its many, many rapid changes, we remain committed, of course, to providing our readers with as many ways of staying on top of the latest advances as we can.

Sure, in the end, any of our extra content in this digital issue could easily live online in a social media post. But the World Wide Web, as us old-timers used to call it, is just that – wild (and, with social media algorithms dominating what we see, less and less worthwhile). With this issue's digital experiments, we're trying to respect your scrolling time with curated content. Do with it what you will. We'll be back next month with more news you can put your hands on.

Sebastian Blanco, Editor-in-Chief

You'll find countless hours of webinars and videos on sae.org and our other sites, including [Mobility-Engineering-Tech.com](http://MobilityEngineeringTech.com).

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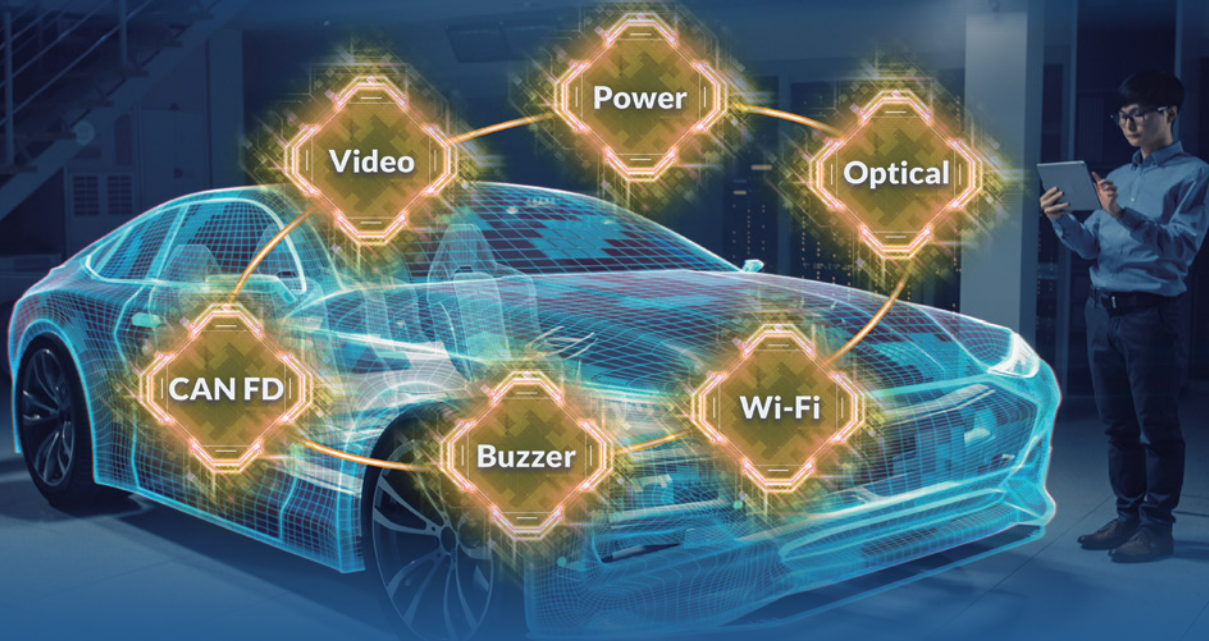
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Uber wants a piece of every robotaxi

It's good to be back on the pages of **Automotive Engineering** magazine after several years away. It's been more than a decade since former **Uber** CEO Travis Kalanick established what was then known as **Advanced Technology Group** (ATG) to develop its own automated driving system (ADS) and commented that robotaxis were an existential threat to his company. ATG's efforts didn't end well, with a fatal testing crash that killed a civilian. Eventually, Kalanick was pushed out of the company and ATG was sold to **Aurora Innovation**. Uber is no longer in the business of building an ADS, but it still has dreams of being the biggest operator of robotaxis in the world.

Back in 2017, while ATG was in the midst of trying to develop an ADS, it struck a deal with **Mercedes-Benz** to deploy its future robotaxis on the Uber platform, much as human drivers do today. The goal was to fill the platform with as many driverless vehicles as possible from as many sources. Uber made it clear it was open to other partnerships. While Mercedes-Benz eventually cancelled the robotaxi that it was developing with **Bosch**, the idea stuck with Uber.

Over the last several years, Uber has partnered with, and in many cases invested in, some of the world's leading ADS developers and has been deploying a wide variety of robotaxis in cities around the world. Depending on where you are, including the U.S., Europe, the Middle East and Asia, opening up the Uber app may provide you with access to robotaxis from **AvRide**, **Baidu**, **MayMobility**, **Momenta**, **Motional**, **Pony AI**, **WeRide** or **Waymo**. In the not-too-distant future, that list will also include **Nuro**-powered **Lucids**, **Wayve**-powered **Nissans** and as I write this column, even **Rivians**. Then there are the automated trucks from Aurora and **Waabi**.



Sam Abuelsamid
VP Market Research,
Telemetry
sam@telemetryagency.com

Why is Uber spending so much on getting robotaxis onto its platform?

Uber is estimated to have spent more than \$1 billion on the ATG effort before it was ultimately abandoned. But over the last few years, it has likely spent at least twice that amount investing in many of these companies' funding rounds. That includes \$300 million each in Nuro and Lucid, along with probably similar or larger investments in Waabi, Wayve and potentially others.

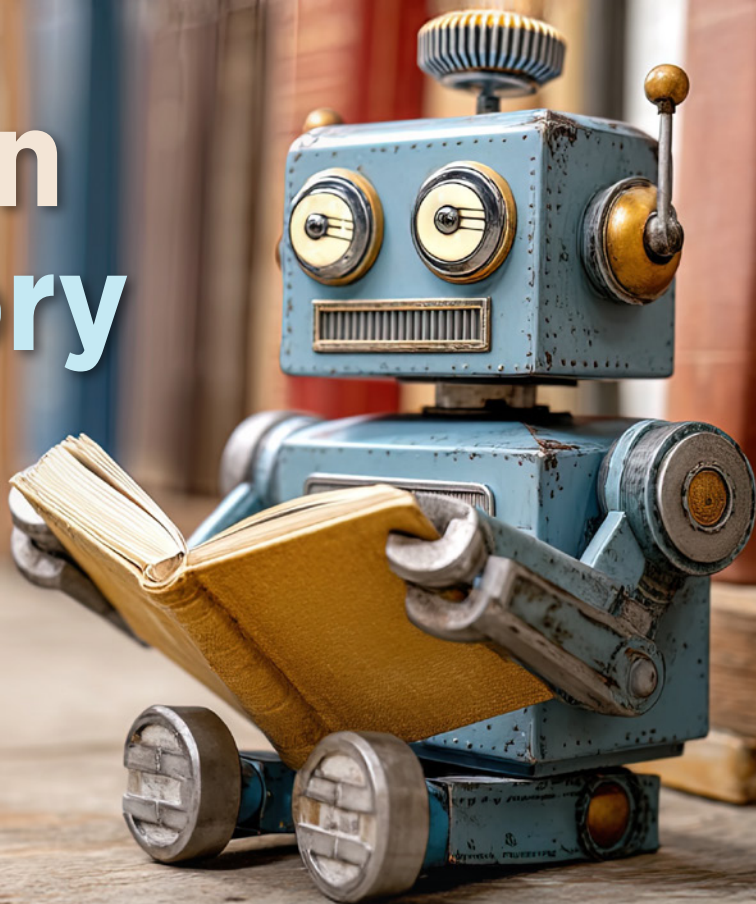
So why is Uber spending so much on getting robotaxis onto its platform? Flexibility is a big key. When Kalanick first started talking about robotaxis, he made it clear that he wanted to eventually eliminate human drivers. That's no longer the case, at least not anytime soon. The challenge is that robotaxis remain expensive and you need depots to charge, clean and service them. What you don't want is a large fleet of underutilized robotaxis.

Ride-hailing has very uneven demand throughout the day with peaks during rush hour and some other times. When I spoke with **Lyft** back in 2019, their goal was to have robotaxis as the base use case with human drivers coming in to fill the demand gaps. That's essentially what Uber is doing now. ADS is still relatively early and different companies are focused on different regions. Besides their home country, the Chinese are looking mostly at parts of Asia, the Middle East and Europe. Americans are largely focused here, Asia and Europe. Different companies also have different vehicle types.

With so many partners, Uber aims to fill as many gaps as it can in as many markets as it can so it is not left without options if any of its partners fall by the wayside. Focusing on the core of its business of connecting riders with vehicles while owning at least a slice of the technology seems like the best path forward at the moment. ■

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ALTERNATIVE ENERGY

Bosch shows off its first U.S. electrolyzer in support of hydrogen research



All the proprietary machinery behind Bosch's electrolyzer is contained in a relatively nondescript box. At top left you can see a UV/IR camera aimed at the hydrogen release stack. It can spot the nearly invisible flame of hydrogen to inform operators in the rare event a gas release ignites.

Two of the biggest hurdles to the adoption of hydrogen fuel cells are still the availability of hydrogen and its affordability.

Bosch recently took a small step toward addressing availability at its Farmington Hills, Michigan, engineering center, where the company unveiled a new electrolyzer that uses electrical current to split water into oxygen and hydrogen to power fuel cells.

The oxygen is released into the atmosphere while the hydrogen can be stored as a gas or compressed into liquid form. At the site, Bosch will use the hydrogen for R&D on its own fuel cell power modules, hydrogen internal combustion engines and more. There was even talk about possibly providing fuel for a small fleet of FCEV garbage trucks for a local community.

In addition to public remarks at a ribbon-cutting and hydrogen workshop attended by more than 100 engineers and executives, Peter Tadros, president of power solutions for Bosch North America, sat down with SAE Media to talk about the company's support of a hydrogen future.

"Here in Farmington Hills, we have the fuel cell power module (FCPM). We'll have engine dynos running hydrogen engines. In one of the use cases, again, to prove the economy of how to use the hydrogen, we can hook it up to the grid to supplement the energy."

That local-to-grid exchange would be through the FCPM, which is also the powerplant that is being readied for Class 8 trucks.

Tadros stressed that the development is not meant to be a primary source of energy for any one entity, but "more of a demonstrator to show how electrolyzers can support all these different use cases."

The Hybrion proton-exchange membrane (PEM) electrolysis stack is rated at 1.25 MW and can produce hydrogen at 22.9 kg/h with a max H₂ output pressure of 34 bar. It does this with a modest footprint of 85 x 100 x 154 cm (33 x 39 x 61 in), though the entire unit, which includes pumps, water purification and cooling systems is larger, about the size of a shipping container.

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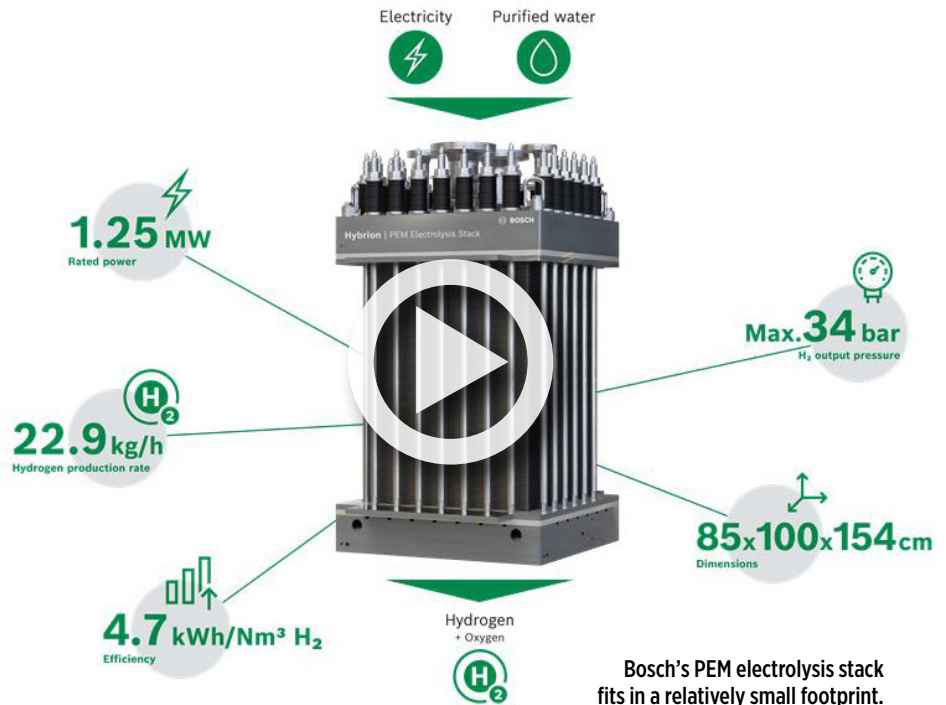
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One key to Bosch's support of an end-to-end hydrogen ecosystem strategy is the development of a next-generation cryopump by Bosch Rexroth that SAE Media learned about during a visit to a **First Element Fuel** hydrogen truck stop in Oakland, Calif. Bosch says the technology helps enable faster, safer and more energy-efficient handling of liquid hydrogen, an important step in supporting heavy-duty mobility, aviation and large-scale energy applications. Dave Hull, Bosch Rexroth regional vice president, said the cryopump makes delivery systems more efficient by quickly converting stored liquid hydrogen to gaseous H₂. "Our technology addresses critical challenges like boil off losses, reliability energy efficiency and scalability," he said, adding that it is helping companies move from pilot projects to commercial deployment.

For both the electrolyzer and the cryopump, Bosch's expertise with very



Bosch's PEM electrolysis stack fits in a relatively small footprint.

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Peter Tadros, president of power solutions for Bosch North America, said the hydrogen produced would be used largely for R&D on fuel cell power modules and hydrogen internal combustion engines.

small valves, actuators, and injectors, as well as hyper-accurate measurement and system controls, is at the forefront.

But about that future...

Tadros freely admits that the price of hydrogen is far too high now. For instance, First Element is charging about \$25 per kilogram (2.2 lbs), which, when used in a fuel cell, is roughly equivalent to one gallon of diesel. The industry often says the tipping point for hydrogen would be getting the price to about \$4 to \$5/kg. since that would roughly be at price parity with diesel, at least until the recent price hikes due to the war in Iran.

"It is possible with scaling. It is possible to get there. The near term is going to be definitely a challenge without subsidies, but this is what everybody right now is working on between us and the integrators, how to bring this cost down," Tadros said. "Hydrogen will have a place, but there are a lot of challenges because of the cost. The question becomes, what hydrogen can do that electrification can't do? Is it the long haul, fully loaded vehicle, the fueling time, things that the fleet operators depend on for total cost of ownership?" He also

mentioned aviation and defense uses, as well as stationary fuel cells powering the burgeoning data centers that are projected to outstrip the grid's current supply of electricity at some point.

Bloom Energy, one of the companies present at the Hydrogen Technology Day event, is aggressively pursuing the data center market with its focus on

solid oxide electrolyzers and fuel cells. The solid oxide process runs at a higher temperature and is more efficient than the PEM process.

Alissa Cleland, Bosch's VP for communications and government affairs in the Americas, said that despite the current federal administration headwinds against alternative energy, the company is actively pursuing a regulatory environment in which hydrogen could flourish. "I spend a lot of time pushing hard for hydrogen, and we haven't given up," she said. "We're in a position to help produce hydrogen, store it and convert it (to electricity), all of it is part of the same ecosystem."

Jason Smullen, a senior manager at consulting firm Roland Berger, agreed with Tadros about H2's chances of growth. "Despite the hype curve, there is a path to build scale and participation for fuel cells and hydrogen."

Bosch partner Toyota sticking with hydrogen

Toyota's group vice president, powertrain, Jordan Choby, gave a keynote presentation in which he shared why his company is optimistic about hydrogen's future as part of a mix of fully or partially green energy alternatives. "By 2030, there's been many announcements and



Bosch communications and governmental affairs executive Alissa Cleland said the company is still working for a supportive regulatory environment that would allow hydrogen energy to grow.

BOTH IMAGES: CHRIS CLONTS

maybe many announcements don't make it the full way to final production, but announcements already total 440 GW worth of (renewable) energy" for hydrogen production, he said.

"Next year, our Class 8 trucks will be running routes in Southern California in Toyota parts logistics fleets, moving vehicle parts from the port and also to dealerships in that region," he said. "Our goal is to build and show a sustainable logistics ecosystem, while lowering Toyota's overall carbon footprint. In California, working trucks represent about 25% of the state's overall pollution," he said, adding that long-haul trucking is about 3% of all U.S. greenhouse gas emissions. "That's quite a large number when you consider the number of refineries and large industries included."

Last fall, at Toyota's Arizona Proving Grounds, SAE Media rode in a lass 8 fuel-cell-truck that was, essentially, drag racing a traditional diesel-powered rig pulling a trailer of equal weight. It was no contest.

Bosch completed the installation of a 2.5 MW Hybrion electrolyzer in November at its Bamberg, Germany, factory.

An emphasis on safety

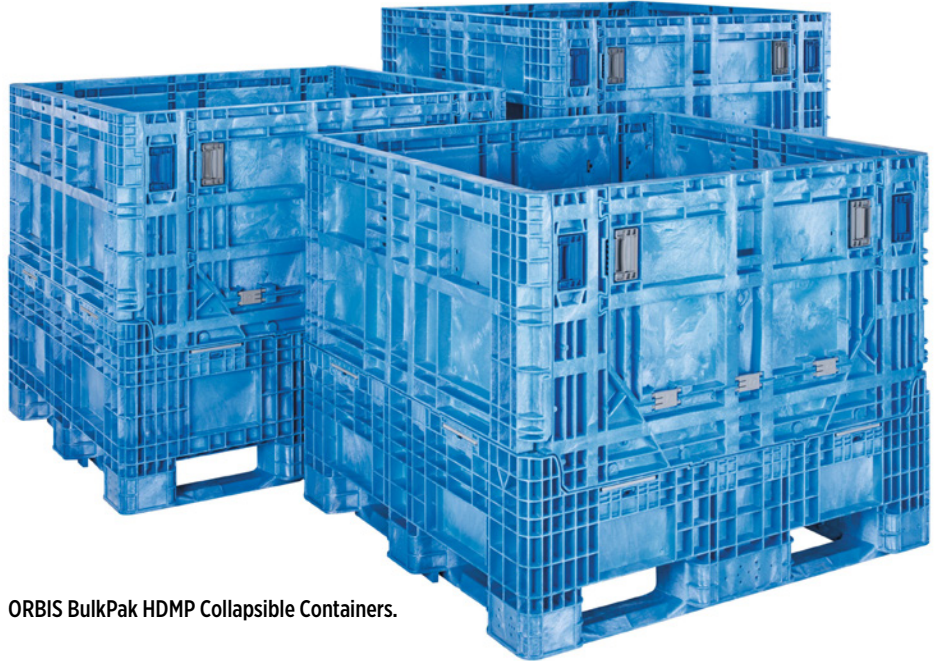
In response to questions from local officials, Bosch said the hydrogen electrolysis process is extremely safe and the Farmington Hills facility meets or exceeds NFPA 2, the national fire protection code that deals with equipment containing liquid and gaseous hydrogen.

While Detroit is used to seeing the flares from stacks at oil refineries, an ignited release of hydrogen is an extremely rare event. Even so, the company has an ultraviolet and infrared camera aimed at the hydrogen-out stack on the electrolyzer, since a hydrogen flame is invisible in daylight and even hard to see at night. A representative said extensive outreach was done to emergency management agencies to ensure everyone knows how to deal with possible situations, no matter how unlikely.

Chris Clonts

LOGISTICS

Engineering better reusable bulk containers for the industry



ORBIS BulkPak HDMP Collapsible Containers.

Reusable bulk containers protect parts and components as they move from suppliers to assembly operations. These containers are especially common in the automotive industry, where they help streamline material flow for OEMs and Tier 1s. Given this widespread use, it can be beneficial to learn about bulk container design. A key place to start is understanding the engineering considerations behind the container design, especially when considering their use in the automotive industry.

Starting with the part

The priority should be to plan for every part, specifically when engaging with OEM customers during a new vehicle launch. The priorities are part protection, shipping optimization and line-side efficiency. Designers should look at part size, type and shape to maximize the number of parts per bin.

For example, a wiring harness can be very long and does not need much dunnage or protection, so it could be bulk loaded in a large container. However,

when packaging Class A parts, including mirrors, headlamps or decorative trim, we want to ensure we are protecting them with custom dunnage while increasing pack density.

Determining the right footprint

When designing a bulk container and determining how it can be packed out most efficiently, our engineering team also factors in different container sizes and footprints to optimize the space in a standard 53-ft (16 m) trailer. The goal is to maximize the number of parts per bin and bins per truck to help customers save logistics costs and avoid "shipping air." For return trips to the supplier for part replenishment, empty bins collapse to save space.

When it comes to the automotive industry, 48 in x 45 in (122 cm x 114 cm) bulk containers are the standard for a large majority of parts and products, with consistent and predictable capacities. Extended footprints are used for larger, bulkier parts, including a variety of standard footprints, from



Chad Mosley, Senior Product Manager, ORBIS Corporation.

32 in x 30 in (81 cm x 76 cm) to 78 in (198 cm) x 48 in (122 cm) and in heights from 18 to 50 inches (46 cm to 127 cm). Bulk containers can also be custom-designed and fabricated for specific application requirements.

Taking ergonomics into account

Understanding how the workforce interacts with parts on the assembly line also plays a role in container design. We consider ergonomics early in the process, looking at the container size, height, number of access doors, door width and door configuration. We always try to maximize door size, so it is easy for a worker to reach in for parts at the line.

One OEM had a 48 in x 45 in x 34 in (121 x 114 x 86 cm) container and found it was more ergonomically friendly to have doors on all four sides to access parts. Additionally, well-designed containers can have easy-to-grab sidewalls and latches, so they are easy to assemble and collapse.

Accounting for the load rating

When designing bulk containers, engineers should seek to understand the application requirements and how the bin is used, racked, stacked, and shipped. For example, designers at ORBIS use Automotive Industry Action Group (AIAG) standards to design for

load capacity. Generally, bulk container load ratings range from 1,000 to 2,500 lbs (450 to 1,150 kg) per container.

Selecting the right bulk packaging style

Collapsible bulk containers are available in a range of styles and capacities. Container selection depends largely on the load weight and part size. Sleeve pack solutions, comprised of a pallet, sleeve and top cap, are ideal for lighter-weight loads like automotive seat foam. Rigid structural foam containers are typically used for medium to heavy applications up to 2,500 lbs. (1134 kg). For loads above 2,500 lbs., custom-fabricated metal racks are recommended.

OEMs also have different mindsets about how they want to package and ship parts. OEMs determine whether to use hand-held totes or bulk containers based on their part packaging strategy and the specific demands of their production flow and lineside assembly processes.

Material matters

Reusable bulk containers play an important role in helping OEMs and tier suppliers meet sustainability goals. They support the circular economy by traveling hundreds of trips over their lifetime and when they reach end-of-life, containers are recovered and reprocessed

into new products using recycled resin. More OEMs are asking for packaging made from post-consumer recycled (PCR) content and suppliers should work with them to determine the right PCR levels, while maintaining container durability and performance.

Designing for automated systems and equipment

According to **Cyngn**, more than 45% of manufacturing leaders cite automation as their top investment priority in 2026. Product engineers should design with automation considerations in mind to ensure that bulk containers interface seamlessly with new automated equipment. This might include changing or modifying standard bulk containers or potentially building a new container for a new automated system. Bins can be molded for dimensional consistency to ensure repeatable performance within automation, with smooth surfaces for tags and labels that can be easily read by vision systems.

Establishing checkpoints along the way

As OEMs launch new vehicles and suppliers design new parts, planning new packaging is often required. Container suppliers should work closely with customers to design the right solution and plan a pilot program to ensure a successful launch. Companies that can create prototype bins and dunnage solutions for on-site customer approval can ensure that part fit, protection and density all meet expectations. This feedback loop is crucial to be responsive to customers.

Ultimately, engineering a standard bulk container for the automotive supply chain involves a balance of part protection, lineside requirements, and logistic demands while supporting modern manufacturing environments that are increasingly relying on automation. As automotive requirements continue to evolve, thoughtful engineering will help ensure reliability, efficiency and long-term value across the supply chain.

Chad Mosley is senior product manager for the ORBIS Corporation and wrote this article for SAE Media Group.

MANUFACTURING

The dawn of agentic autonomy in factories

The global automotive industry has reached a new era. If 2025 was defined by the cautious exploration of “experimental pilots” and the collection of vast data lakes from connected vehicle fleets, 2026 marks the year that data finally gains a mind of its own within the assembly plant.

We are witnessing a transition from passive automation to integrated, agentic autonomy. This is a shift that moves beyond simple programmed robotic arms and toward systems capable of independent reasoning and real-time optimization. This evolution is not just a technical upgrade; it is a fundamental restructuring of how vehicles are built, de-risked, and scaled in an increasingly volatile global economy.

From assembly lines to agentic reasoning

For decades, automotive automation was a linear affair. Robots followed

rigid, pre-set instructions to weld, paint, and assemble chassis. Even early AI integrations were largely diagnostic, alerting human operators to a misalignment in a door hinge or a temperature spike in a battery-bonding machine. Importantly, they required a human to intervene and “fix” the problem.

In 2026, the arrival of “Agentic AI” has rewritten this script. These systems function as intelligent agents that don’t just flag a delay in the semiconductor supply chain; they independently reason through the implications. If a shipment of sensors is delayed, the AI agent doesn’t just send an alert; it analyzes the current production queue, identifies which trim levels can be completed without that specific component, and automatically re-optimizes the production schedule for the next 48 hours.

By shifting from “human-in-the-loop” to “human-on-the-loop,” automakers are achieving a level of operational fluidity

that allows the factory floor to adapt to chaos in real-time.

The Industrial Metaverse: the automotive operating system

The 2026 smart factory is inseparable from the Industrial Metaverse. This is no longer a buzzword or a simple 3D visualization for board meetings; it is the operating system of the plant. High-fidelity digital twins of the entire assembly line, from initial stamping to the final quality inspection, allow for real-time simulation and “what-if” scenarios.

Automotive leaders are leveraging these twins to bridge the gap between digital design and physical reality. For example, when a manufacturer introduces a new EV battery chemistry, the digital twin simulates the exact thermal and physical stresses on the assembly robots before a single piece of hardware is moved. This “software-defined” approach allows manufacturers to:



GridRaster refers to its AR platform as special intelligence that can transform manufacturing and the training of factory workers.



A factory employee works with an augmented reality training platform developed by GridRaster.

- De-risk EV transitions: Virtually testing the conversion of internal combustion engine (ICE) lines to electric vehicle (EV) hubs without stopping output.
- Optimize SDVs: Simulating how over-the-air (OTA) updates will interact with hardware as the car moves through the final stages of assembly, ensuring the “digital soul” of the car matches its physical body.
- Use predictive energy management: Using AI agents to shift energy-intensive paint shop processes, which can account for up to 70% of a plant’s energy use, to off-peak hours, stabilizing the grid and lowering costs.

Capturing tacit knowledge: the race against retirement

As 2026 progresses, the automotive industry faces a knowledge chasm. With tens of thousands of veteran technicians and master mechanics reaching retirement age, legacy automakers risk losing decades of institutional memory. This is the subtle, unwritten knowledge

of how a specific machine “feels” when it’s about to fail or the nuance required in complex wire harness installation.

In response, 2026 will see the rise of Spatial Intelligence tools. Using AR and agentic systems, factories are now capturing this tacit knowledge in real-time. AI agents observe master technicians, document their movements, and translate that expertise into interactive, spatial instructions for a younger, “software-literate” workforce. This ensures that the expertise of the past becomes the digital intelligence of the future, preventing a drop in quality during the generational workforce transition.

The rise of the software-defined factory

The automotive factory of 2026 has essentially become a giant, physical computer. In this software-defined environment, the physical hardware is increasingly agnostic. Just as a smartphone can run different apps, a software-defined assembly cell can be repurposed from

assembling seat frames to installing dashboards simply by updating its agentic software layer.

This flexibility is the ultimate defense against market volatility. If consumer demand shifts overnight from sedans to SUVs, or from hybrid to full-electric, the agentic factory can reconfigure its own logic and workflows with minimal downtime. The physical infrastructure remains, but the intent of the factory is updated through code.

Sustainability through precision

Finally, 2026 will mark a turning point for so-called green factories. Agentic systems are now capable of predictive, AI-timed power consumption. By analyzing regional energy grid demands and internal production requirements, these systems can throttle energy usage in real-time.

Furthermore, the Industrial Metaverse allows for zero-waste prototyping. By perfecting the assembly process in a virtual environment first, automakers are drastically reducing the physical scrap and carbon footprint associated with traditional trial-and-error manufacturing.

Building a resilient future

Ultimately, the transition we observe in 2026 will represent the birth of a more resilient, software-defined industrial base. The competitive advantage of an automaker is no longer determined solely by raw labor costs or the size of the plant, but by the sophistication of its human-machine collaboration.

By embracing agentic autonomy and the industrial metaverse, manufacturers are creating a reduced-risk environment that can withstand global supply shocks, labor shortages, and the rapid pace of technological change. The automotive factory of today is not just a place where cars are made; it is a dynamic, learning organism. It is a space where “grease meets code” to build a more stable and prosperous future for the entire industry.

Dijam Panigrahi is co-founder and COO of GridRaster Inc. and wrote this article for SAE Media Group.

GRIDRASTER

ELECTRIFICATION

Some automakers retreat from North American EV market

A canceled vehicle is a pricey endeavor for an automaker. There are sunk costs (R&D, factory tooling, marketing, etc) that are likely never fully regained. Even if a vehicle enters the market as a hit, it might be years before that car, truck, or SUV truly turns a profit for the automaker. Now imagine if that vehicle is killed before ever rolling off a factory floor.

That's the case with **Honda's** 0 series EVs. The Japanese automaker canceled development of three EVs slated for North America. The trickle-down effect resulted in **Sony's** EV plans being dashed with the additional cancelation of the slightly odd Afeela sedan, and the recently unveiled SUV, which were to be built by Honda at its Ohio facility.

Honda is quick to point out that this

news only affects North America. The automaker has joint ventures in China to build EVs and already has EVs on the market in Japan. More importantly, the company will continue to develop its solid-state battery for vehicles and other items manufactured by Honda.

For other automakers, some of their offerings just never caught on. For example, **Hyundai** announced that the Ioniq 6 will be pulled from the US market. The styling never quite caught on, and while the Ioniq 5 continues to garner impressive sales, the weirdly shaped sedan became stagnant. The Ioniq 6 N will stick around, but if you want a car that looks like a speedbump, you should move quickly.

Meanwhile, **Ford** could never quite figure out what to do with the F-150 Lightning. Multiple price changes and

marketing a full-size pickup to an audience that enjoys talking about gas engines didn't help the pickup's sales in the long run. Instead, Ford is now working on a mid-size electric pickup that the company has said will cost \$30,000 at launch.

Meanwhile, **Volvo's** long-delayed EX30 was finally put to rest after coming to market with a larger-than-anticipated price tag and a host of software bugs. Volvo says that the electric EX60 and EX90 are still coming to North America.

For some of these vehicles, an administration hostile to EVs and a whirlwind of confusing tariffs led to their downfall. Suddenly, a potentially profitable vehicle was unprofitable. For others, the market just shrugged and made different choices.

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While some headlines construct a narrative of doom and gloom for EVs, the reality is far more nuanced. The relatively inexpensive **Chevy Bolt** is back (although weirdly for only 18 months, maybe) and, like the new **Nissan Leaf**, has garnered mostly glowing reviews. **Rivian's R2** will come to market soon. **Lucid** is already showing off future models, and **Slate** seems to be on track for production of its mid-\$20,000 pickup for the end of the year.

Let's not forget **Toyota** (see page 39). A company that just a few years ago didn't seem very happy to be selling EVs just dropped three on the market (bZ Woodland, C-HR, and Highlander EV), joining an updated bZ.

New EV sales have fallen, compared to 2025, by a whopping 28 percent during the first quarter. Many bought EVs sooner than anticipated ahead of the expiration of incentives late last year. There might be a rebound, but economic headwinds have also affected gas car sales, which are also down from Q1 2025 by 6.3%.

Meanwhile, used EV sales are up 12% from Q1 2025. The demand seems to be there when the economics make sense.

The EV market is more challenging than ever, and that's led to some tough decisions by automakers. Yet for every canceled vehicle, a new vehicle is announced and headed to the market. Electrification is a long game. Some automakers are just playing it better than others.

Roberto Baldwin

TESTING

Enabling certified GoogleTest for safety-critical embedded software

Software is driving major changes in automotive design. The rise of the software-defined vehicle, combined with increasing automation, is dramatically increasing software complexity. Automotive teams must deliver larger volumes of safety-critical code on tighter schedules while maintaining strict compliance with functional safety standards.

In this environment, effective testing and verification are more important than ever. Development teams are increasingly adopting shift-left testing strategies, where defects are identified early at the unit level before software progresses down the development pipeline. Detecting issues earlier reduces risk, lowers remediation costs, and improves development velocity.

GoogleTest, originally released as open source in 2008, has become one of the most widely used frameworks for unit testing C++ software and is preferred across industries building embedded software systems. Developers value GoogleTest for its flexibility, clear test structure, and ability to integrate with complex embedded environments, including cross-compilation toolchains and HIL testing setups.

However, safety-critical industries such as automotive, medical devices, industrial automation, rail, and aerospace, must comply with functional safety standards including ISO 26262, IEC 61508, IEC 62304, and EN 50128. These standards require that the software tools used in development and verification can be trusted when applied to safety-related software.

If a testing tool can introduce errors or fail to detect defects, the reliability of the software under development may be compromised. Therefore, standards for safety-critical systems require assurance that such tools perform their intended functions correctly, often established through independent third-party assessment.

For development teams using open-source frameworks like GoogleTest, this requirement historically introduced an additional challenge. While the framework itself provides powerful unit testing capabilities, organizations are responsible for demonstrating that the tool can be safely used within a safety-critical development process. Independent certification offers one practical way to address this requirement and provide justification during safety audits.

When a recognized third-party organization like TÜV SÜD assesses and certifies a testing toolchain, development teams gain assurance that the tool has been independently evaluated for safety-related software development.

Parasoft provides this capability through C/C++test CT, a TÜV SÜD-certified solution for functional safety standards including ISO 26262, IEC 61508, IEC 62304, and EN 50128. C/C++test CT does not replace unit testing frameworks but integrates with widely used frameworks like GoogleTest to provide additional capabilities required for safety-critical development.

Importantly, C/C++test CT's TÜV SÜD certification includes the integrated GoogleTest framework within the certified toolchain configuration, enabling GoogleTest to be used for

safety-critical software development.

Within this workflow, developers write unit tests using familiar GoogleTest constructs while C/C++test CT provides structural code coverage, automated requirements traceability, and compliance reporting.

The result preserves the flexibility and productivity of open-source unit testing while satisfying safety-critical standards. Developers benefit from the widely adopted GoogleTest framework, while organizations gain the assurance of independent certification.

Modern development practices, such as continuous integration pipelines, automated verification, and emerging techniques like AI-assisted code analysis, can further enhance efficiency. However, the foundation remains a reliable, independently certified testing toolchain that supports early verification of software behavior.

By combining GoogleTest's flexibil-



ity with a TÜV SÜD-certified testing toolchain, development teams can confidently adopt the open-source framework in safety-critical projects, accelerate shift-left verification, and deliver high-quality embedded soft-

ware while meeting strict regulatory requirements.

Ricardo Camacho, director of product strategy for embedded and safety critical compliance at Parasoft, wrote this article for SAE Media Group.

PARASOFT

PODCAST

V2X VEHICLE COMMUNICATIONS

In a world where nearly every device talks to nearly every other device, it's no surprise that vehicles talk to one another and to the cloud. While mapping software has long used networked devices to help drivers find the quickest route to their destinations, vehicle communications go well beyond simply getting you from point A to point B.

In this episode, editors from *Automotive Engineering* talk to Honda chief engineer Sue Bai about Ohio's proactive roadway maintenance system and to Miovision VP of V2X sales Thomas Bauer about how traffic lights can talk to your vehicle.

sae.org/podcasts/AE-Podcast-7



Episode guests:



Thomas Bauer
VP of V2X Sales,
Miovision



Sue Bai
Chief Engineer,
Honda

Hosted by:



Forvia Hella ready to light the night with ADB, but NHTSA test stands in the way



Forvia Hella's adaptive driving beam (ADB) headlight system can use individual pixels to display information on the road ahead of the vehicle. In this instance, an icy-conditions warning.

A demonstration ride shows the glare-free, game-changing power of adaptive driving beams, already available in Europe. An approval test from NHTSA is proving difficult for OEMs to pass.

by Chris Clonts

I'm riding in the second row of a **Lincoln Navigator** fitted with **Forvia Hella's** adaptive driving beam (ADB) headlight system. The low- and high-beams are on, blasting everything in front of us for between 350 and 500 feet (122 and 152 m) with a bright, daylight-temperature LED light. Even traffic and street signs at the edges of the road, which normally aren't as well illuminated, are bathed in brightness.

A car pulls out in front of us, and the system instantly adjusts, creating a tunnel of unlit space on and just next to the vehicle ahead. So even though we still have high beams on the rest of the road, that driver isn't facing the harsh glare that is the No. 1 complaint about today's high-intensity headlight systems.

Automotive lighting fans have waited for systems like this to come to the U.S. since they were approved in Europe in 2006 and started appearing on vehicles there in 2012. Currently, only **Tesla** and **Rivian** have such systems in vehicles sold in the U.S. We'll get into why below.

Hella's system uses real-time data from cameras already on a vehicle to detect other vehicles in real time, said Aaron Knettle, a Hella lead development engineer. "We control our own software for object detection and how to respond to that," he said, adding that the system can track and react to up to eight objects simultaneously, including pedestrians and cyclists. Knettle said whether the system blacks out only vision areas, such as rear- and side-view mirrors or an entire vehicle, is a decision made by the OEM.

The headlights can be made up with as few as 48 or as many as 16,000 LEDs. I got to see both extremes on the demo ride in the Navigator. Perhaps surprisingly, the system with only 48 beams performed nearly as well in creating the shadow for cars ahead (the system works for oncoming cars as well). The 16,000-LED headlights drew, of

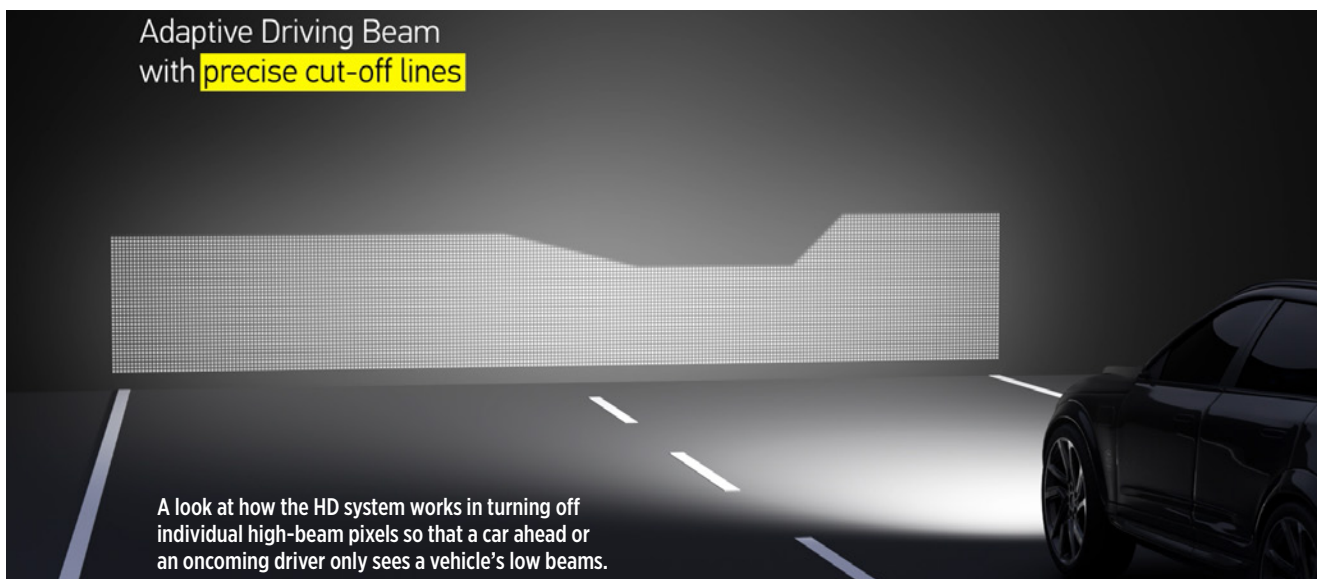
course, a sharper edge between light and dark. Forvia Hella calls that upper end their SSL/HD system and it comes with the ability to project things on the road ahead of the vehicle. For instance, warnings of railroad crossings or icy conditions ahead. The system includes an LED chip mounted directly on the driver/integrated circuit. What makes the shadows on oncoming cars happen is pulse width modulation on an individual pixel level, engineers said. The aesthetic result is that extremely slim headlamps are possible due to reduced lens-dimension requirements.

A common misconception about ADB systems is that when they "black-out" oncoming cars or, especially, pedestrians, is that it makes them more difficult to see. Only the high beam is affected, so what's shining on the object is still the full light of a low beam.

The only added requirement for the HD system is that more individual LEDs call for progressively higher compute. In case of an ADB software failure, the systems revert to normal low beam/high beam operation.

The holdup? Testing

In 2016, SAE's vehicle lighting committee issued J3069, which outlined test procedures for ADB headlight systems. It updated the standard in 2021, changing things such as light/shadow boundary requirements due to the changing abilities of new systems.



In 2022, after discussions with suppliers, OEMs and the J3069 team, the National Highway Traffic Safety Administration (NHTSA), updated the Federal Motor Vehicle Safety Standards (FMVSS) No. 108, which governs all automotive lighting, to allow ADB headlights in America. NHTSA's test came with two problems.

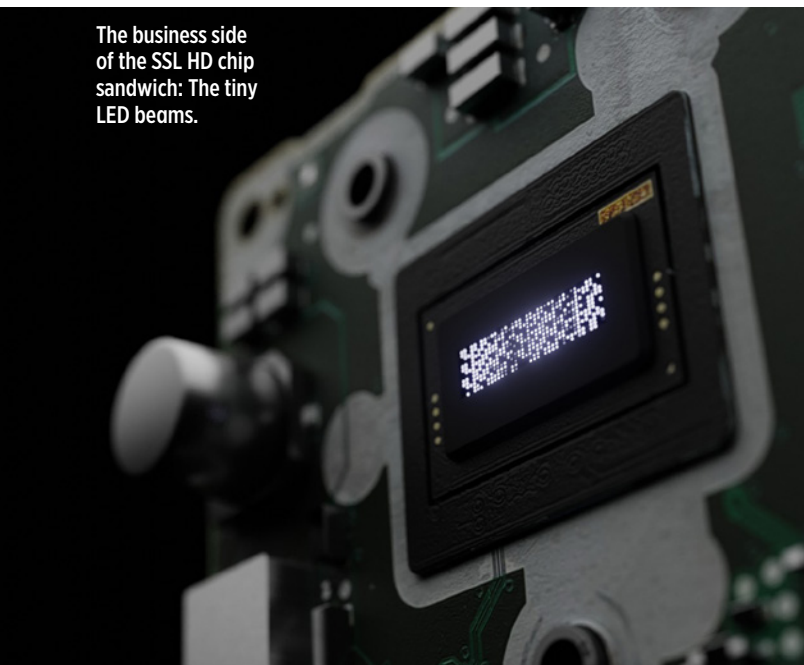
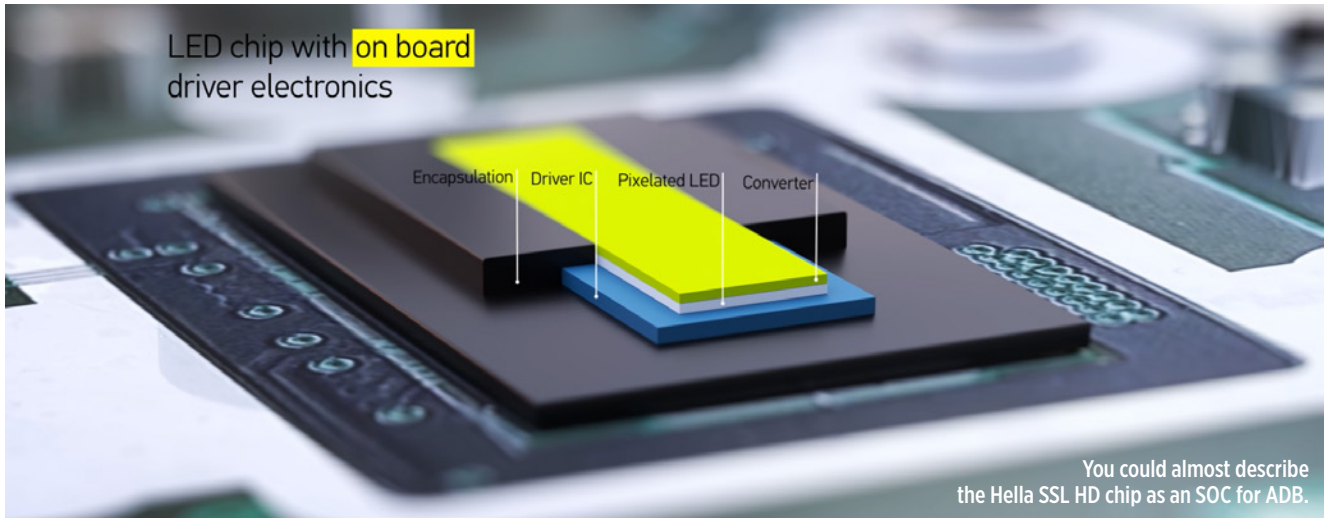
Problem one: "The OEMs must pass the test based on the vehicle," said Antonio Pantoja, HELLA Hella Vice President Tech Center, USA Lighting & Innovation Americas. That's as opposed to Europe, where the approval comes at the headlamp (supplier) level, which means any vehicle with that system is approved. Here, every make/model is approved separately. So, if **Cadillac**, for instance, wants to put Hella's system on

the CT5 and the Escalade, both cars must test separately. Europe has always placed a premium on lighting, though. The U.S. maximum for light from a high beam is 75,000 candela per lamp. In the EU, it's about 200,000.

Problem two: "The test is difficult to pass. It's very stringent," said Carissa Silas, Forvia Hella manager of marketing and communications.

Michael Larson, a lighting Engineer with **General Motors** who was chair of SAE's ADB task force, agrees with that assessment. He said the organization had been talking with the NHTSA for 10 years. Since the task force knew the NHTSA wanted a vehicle-level test, it came up with a set of tests that would allow European systems already on the road there to pass here. "Maybe there would have been some software updates because of some of the special things here in the U.S.," he said. "Well, NHTSA, they went a different way."

Forvia Hella ready to light the night with ADB, but NHTSA test stands in the way



He said the NHTSA tests call for multiple sub-tests on “curves and straightaways and different speeds and things like that.” He said it was more testing than J3069, which the industry can deal with. “The problem,” he said, “is they came out with really restrictive glare requirements. So much so that low beams of today (on non-ADB vehicles) wouldn’t pass the new test.”

Since most ADB systems keep the low beams and high-beams on at the same time (thus the enhanced driver vision), “this makes it so we have to do something different for low beams to get ADB to pass and then we also have a lot of things to do with the shadow to meet the requirements,” he said. “It’s really difficult.”

Hella VP Pantoja said it’s the sheer number of variables that also

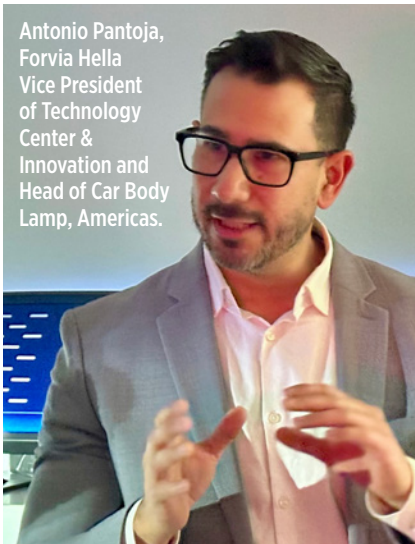
make the test difficult. “Different drivers or suspension settings can affect it,” he said.

SAE Media reached out to the NHTSA and did not receive a response. It’s possible the agency feels caught between two competing goals: the Insurance Institute for Highway Safety, seeing the sad state of U.S. automotive lighting, began testing new vehicle headlights and publishing the results in 2016. Originally, the goal was to drive overall night vision improvement. But as LED headlights became increasingly popular as costs fell, IIHS also tested for what had become a rampant complaint from drivers, especially older ones: blinding glare of LED headlights that were either aimed badly or had low beam cutoff points that were too high.

“So, really what happened is that NHTSA basically made ADB a glare prevention device, not an enhanced visibility device,” Larson said. “It’s still going to be a benefit. But NHTSA is getting a lot of complaints about glare, so they’re very sensitive to it.” Still it’s basically a

CLOCKWISE FROM TOP LEFT: FORVIA HELLA; CHRIS CLONTS; FORVIA HELLA

Antonio Pantoja,
Forvia Hella
Vice President
of Technology
Center &
Innovation and
Head of Car Body
Lamp, Americas.



zero-tolerance policy for glare.

The test itself is done with photocells, which stand for an oncoming driver's eyes and are placed on a track, in curves and straightaways and at the tops of hills. Then the brightness is measured. Larson said, though, that the restrictive glare levels were derived from very low-mounted headlamps.

"Like headlamps we don't even mount – nobody mounts them this low anymore – at 620 mm (2 ft)," he said, adding that was probably the standard height 30 years ago. "Things are higher now, and drivers' eyes are higher, also."

In a speech at SAE International's World Congress in April, NHTSA Chief Counsel Peter Simshauser said the agency was open to negotiated rule-making on some issues. That more collaborative process differs from notice-and-comment rulemaking, which can be more adversarial. However, Simshauser did not address ADB regulations directly.

"We'll get there."

HELLA's Pantoja said that it would be ideal if NHTSA were open to discussing possible changes to FMVSS No. 108. But Larson said that's not likely, citing the administration's negative response to petitions from automakers and lighting suppliers urging reconsideration of the final



The complete headlamp module with chips and LEDs enclosed.

rule and even the adoption of SAE J3069.

The history of the auto industry, though, is one of adapting and overcoming regulations and test requirements. When the IIHS introduced side-impact testing in 2003 (and NHTSA updated FMVSS No. 214) that showed severe intrusion and damage on vehicles, many OEMs claimed the test was too difficult. But engineers redesigned door beams and made other structural changes that passed easily.

And so it should be with ADB headlamps. Forvia Hella engineers said they are working with customers on passing the FMVSS No. 108 standard. And GM's Larson said engineers are up to the challenge. "We're very resourceful. We will figure it out. More automakers are going to bring out vehicles. It just takes time and money and resources and all this time people aren't enjoying the benefit of ADB," he said. "We'll get over the hurdle, but it's maybe a hurdle that we didn't have to get over." ■

For more information about ADB headlights and lighting systems overall, find the following white papers at SAE.org:

- *The Balance of Illumination and Glare Prevention of Upward Directed Lighting.*
- *Investigation of a System for Headlight Glare Control Based on Photometric Zones.*
- The current SAE J3069 standard.

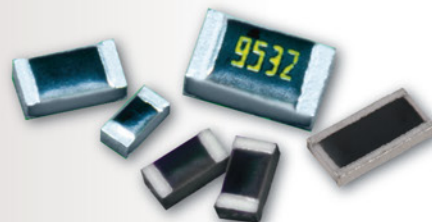


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CERTUS was validated using a production-intent automated driving feature on a Polestar 2 platform. For the OEM, this approach reduced redundant testing, shortened iteration cycles, and provided clear insights into where valuable development effort should be focused.

How CERTUS reshapes AV testing

by Michael Orgill

For automated driving system (ADS) engineers, verification and validation (V&V) are no longer a downstream activity and has increasingly become the program driver. Across the industry, validation costs and duration are now shaping product strategy. Independent analyses have suggested that up to a third of Level 4 vehicle development costs can sit within V&V. Physical mileage accumulation alone demands hundreds of millions, if not billions, of miles to achieve statistical confidence. That level of effort stretches timelines, absorbs engineering resources, and risks making higher levels of autonomy commercially unviable. The core problem is not a lack of testing. It is inefficiency in how testing is structured and how results are interpreted.

Mileage accumulation remains necessary, but it is a blunt instrument. It repeatedly samples nominal conditions and under-represents rare, safety-critical edge cases. It generates volume, not necessarily safety insights. As the complexity of the driving scenarios that must be tested grows – expanding combinatorially as parameters are added for speed, numerous actors, realistic weather, road geometry, and behaviors – brute-force approaches don't scale.

HORIBA MIRA, a Europe-based automotive engineering consultancy, has developed a tool chain alongside industry partners to address this imbalance. CERTUS provides solutions to answer three practical engineering questions: What should we test? How should we test it? And when can we stop testing? The result is an intelligent, scenario-based approach designed to reduce the burden of brute-force testing and increase statistical confidence in system performance to ultimately deliver reductions in the time and cost burden of the V&V process.

Moving beyond mileage accumulation

Traditional validation strategies rely on public road mileage accumulation. While forming one component of the V&V mix when used alone, it is inefficient for exploring the full scenario of an ADS operating within a defined operational design domain (ODD). Even a relatively simple pedestrian scenario can yield tens of thousands of test combinations when vehicle speed, actor trajectories, and real-world environmental factors are accounted for.

CERTUS embraces a scenario-based testing paradigm that complements mileage accumulation. Rather than attempting full factorial coverage – which is not practicably feasible – it defines cascading sets of:

- Functional scenarios, which describe driving events and intended ADS responses, behaviors, and outcomes
- Logical scenarios, which bound parameter ranges and resolutions using statistical distributions
- Concrete scenarios, which serve as specific test cases and are selected to sample the scenario space.

Following a minimal initial sample of concrete scenarios chosen to maximize their coverage, all subsequent iterations use search space optimization and parameter sensitivity analysis to focus tests on regions



To assess safety, metrics such as time-to-collision, time headway, lane offset, and road-rule compliance are weighted and fused algorithmically.

where performance uncertainty is highest or where ADS behavior approaches minimum acceptable thresholds. We can optimize the selection of tests according to any chosen objective function. This 'seek and refine' loop allows engineers to concentrate on

the areas of greatest safety relevance, rather than revisiting well-understood cases.

In one comparative evaluation, a conventional statistical spread of 2,500 scenarios yielded a 56% confidence rating in system performance. Using the CERTUS methodology, 550 scenarios increased

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Sharper validation without **BRUTE FORCE**



One of the most difficult decisions in ADS validation is determining sufficiency. How much testing is enough to robustly prove safety?

that confidence rating to 77%. Fewer tests delivered greater assurance because each scenario was selected for its informational, evidential and safety value.

Oracles: from raw data to engineering objectivity

A key enabler within CERTUS is its use of automated performance scoring algorithms, known as oracles. Conventional testing often reduces results to binary pass-fail criteria using individual KPIs. That approach ignores context. An unavoidable collision triggered by extreme circumstances may be judged as a failure, even if the system behaved optimally within physical limits. The CERTUS oracles combine multiple time-series and event-based metrics into a single contextualized score. To assess safety, metrics such as time-to-collision, time headway, lane offset, and road-rule compliance are weighted and fused algorithmically. To assess progression, measures such as mission time efficiency and goal completion rate are incorporated.

This multi-dimensional evaluation enables engineers to assess whether the ADS behaved safely and appropriately given the scenario, rather than simply whether an arbitrary threshold was exceeded. The output is a set of scores accompanied, by quantified levels of confidence in each. That distinction is critical when engaging with regulatory authorities.

Residual risk and the question of ‘when to stop’

One of the most difficult decisions in ADS validation is determining sufficiency. How much testing is enough to prove safety? CERTUS addresses this through residual risk estimation techniques grounded in statistical methods that align with ISO 21448 SOTIF principles. Rather than relying on subjective engineering judgment or arbitrary mileage targets, we estimate the rate at which defined risk-acceptance criteria are violated by the ADS.

These risk estimates account for both aleatoric variability and epistemic uncertainty. The level of statistical confidence is reported alongside each estimate, allowing engineers to determine whether further sampling could reduce uncertainty, or whether they have entered the territory of diminishing returns. This quantitative risk evidence directly supports the development of a traceable and

defensible safety case for the ADS. In parallel, it aligns with evolving regulatory thinking that scenario-based evidence and analyses should underpin pre-market approval.

Recent regulatory analysis from HORIBA MIRA highlights the impracticality of requiring statistical equivalence to a ‘careful and competent driver’ prior to ADS deployment. Instead, regulators are expected to define high-level safety goals – from which safety engineers can derive quantitative risk acceptance criteria – and then require evidence-based demonstration of compliance. Scenario-based testing, intelligent test selection, and statistically sound interpretation of test evidence are all central to that framework.

Multi-modal correlation: simulation with physical grounding

The efficiency gains achieved by CERTUS rely heavily on simulated testing. However, simulation alone cannot constitute evidence of safety without validation. The CERTUS workflow integrates virtual, physical, and mixed-reality tests within its multi-pillar strategy. Simulation enables rapid scenario iteration. Physical tests executed on HORIBA MIRA’s ASSURED CAV proving ground validate model fidelity and corroborate the outcomes of high-priority scenarios using robotic actors and controlled environments.

Analyzing the correlation between paired physical and virtual scenarios gives insight into the degree of inter-modal reproducibility. Once sufficient correlation has been demonstrated, simulation data can be used as evidence to support a safety case. Mixed-reality testing serves as a complementary intermediate layer. Physical vehicles interact with both real and simulated actors simultaneously, enabling complex multi-actor scenarios to be executed safely and repeatably. During junction testing, for example, real vehicles and robotic soft targets can be combined with simulated traffic to stress perception and planning stacks.

The core problem is not a lack of testing. It is inefficiency in how testing is structured and how results are interpreted.

Polestar case study: Validating a production-intent feature

CERTUS was validated using a production-intent automated driving feature on a **Polestar 2** platform. The objective was not to demonstrate headline autonomy, but rather to assess how efficiently and robustly our methodology could characterize system performance.

Functional scenarios and behaviors were defined through an initial ODD analysis. Logical scenarios were constructed to capture junction negotiation, actor interaction, and rule compliance. Intelligent sampling iteratively refined the choice of concrete scenarios. Oracles assessed the quality of performance. Residual risk analysis quantified confidence and coverage.

The result was a traceable evidence base that supported engineering decision-making. Instead of relying on undifferentiated mileage, the program generated robust, statistically rigorous data tied directly to scenario coverage. For the OEM, this approach significantly

reduced redundant testing, shortened iteration cycles, and provided clear insights into where development effort should be focused.

Rebalancing the V&V equation

As ADS capability and complexity increase, validation costs risk scaling non-linearly. Without methodological change, V&V could become the limiting factor in program viability. CERTUS demonstrates that brute-force mileage accumulation is not the only path to assurance. By combining intelligent scenario selection, contextual performance assessments, and residual risk quantification with validated simulations, it is possible to increase confidence while limiting test burdens.

For engineers working on Level 3 and Level 4 automated systems, the implication is clear: the validation process must become as data-driven and as optimized as the ADS perception and planning stacks that it seeks to assess.

The future of automated driving will depend on how efficiently we can prove will make safe decisions. ■

Michael Orgill is project engineer for connected and automated vehicles at HORIBA MIRA and wrote this article for SAE Media Group.

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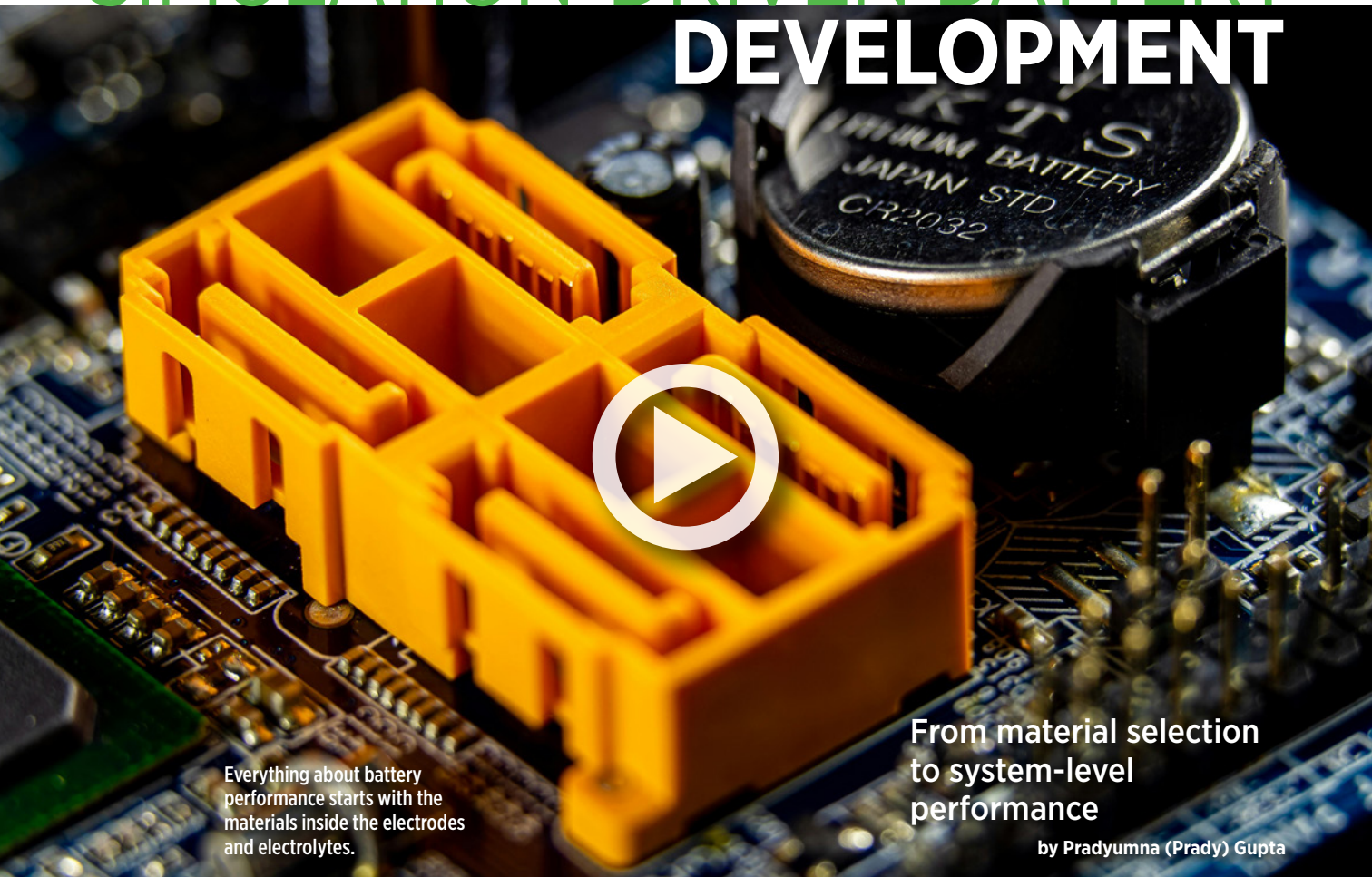
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SIMULATION-DRIVEN BATTERY DEVELOPMENT



Everything about battery performance starts with the materials inside the electrodes and electrolytes.

From material selection to system-level performance

by Pradyumna (Prady) Gupta

Transportation's shift toward electric power – whether cars, planes, or big trucks – has made battery engineering a pretty wild, multidisciplinary puzzle. It's not just about coming up with a prototype anymore. To hit the right mix of energy density, power, safety, cost, and longevity, teams need to rethink how they design these systems.

Enter simulation and modeling tools. Engineers now use these digital tools to blend electrochemistry, thermal management, materials science, and whole-system design. Instead of jumping straight to building, they try out battery ideas in the virtual world first, speeding up how long it takes to figure out what works and what doesn't and boosting the reliability of those batteries in the real world. Today, battery simulation spans multiple scales from the behavior of active materials within electrodes to the thermal dynamics of the entire battery pack as integrated into a vehicle.

The shift toward virtual battery development

In the past, battery development included a lot of trial and error. Engineers pushed their physical prototypes through the toughest conditions to see how they'd hold up. While hands-on work is crucial to ensuring batteries actually work, it eats up a ton of time and money. Things move faster in simulation-driven test cycles. Instead of building every single idea, engineers run virtual experiments, testing out hundreds of designs to predict how a battery will perform, spot potential weak points,

and fine-tune designs before anyone picks up a tool.

In high-performance electric systems where batteries must withstand extreme acceleration, rapid discharge, and intense thermal loads, simulation also reduces development risk by identifying failure modes early in the design cycle.

Modeling across the battery development stack

A defining characteristic of simulation-driven battery engineering is its multiscale nature. Each stage of development requires different modeling techniques and levels of abstraction.

1. Material and electrode-level characterization

Everything about battery performance starts with the materials inside the electrodes and electrolytes. Here, simulations drill down into how lithium ions move through electrode particles, how charge transfers at the electrode-electrolyte interface, what happens as the solid-electrolyte interphase (SEI) forms, and the mechanical stress as the battery expands and contracts during use.

Researchers lean on physics-based models, often building on the Doyle-Fuller-Newman framework, to see how factors such as particle size, material porosity, and electrode thickness shape the battery's energy density and power. These kinds of models make it easier to understand new materials like silicon anodes or solid-state electrolytes, especially when issues like diffusion-driven stress or cracks in the particles start to cut battery life short.

2. Cell-level electrochemical modeling

After engineers select the electrode materials, they begin simulating the entire battery cell. This helps them understand how the battery behaves under varying conditions. They monitor factors such as how the voltage changes during charging, how much capacity is retained through each cycle, and whether internal resistance increases. Additionally, they examine the battery's performance during charging and discharging at different rates, known as the C-rate.

The C-rate basically tells you how fast a battery is loaded or drained compared to its size. Using simulation, engineers test what happens when they push those discharge rates: does voltage drop, does the battery heat up, does capacity fade faster? These models help reveal the classic tug-of-war between energy density and power density. If you want a battery to pack more energy, you make the electrodes thicker, which is good for storage, not so great for delivering quick jolts of power. If power is your game, you go with thinner electrodes so ions can race through and resistance stays low.

Some applications, like electric planes, racing cars, or big trucks, need both sides of that equation. That's really where simulation shines: it helps engineers find the sweet spot in design, so batteries perform just right for whatever they're powering.

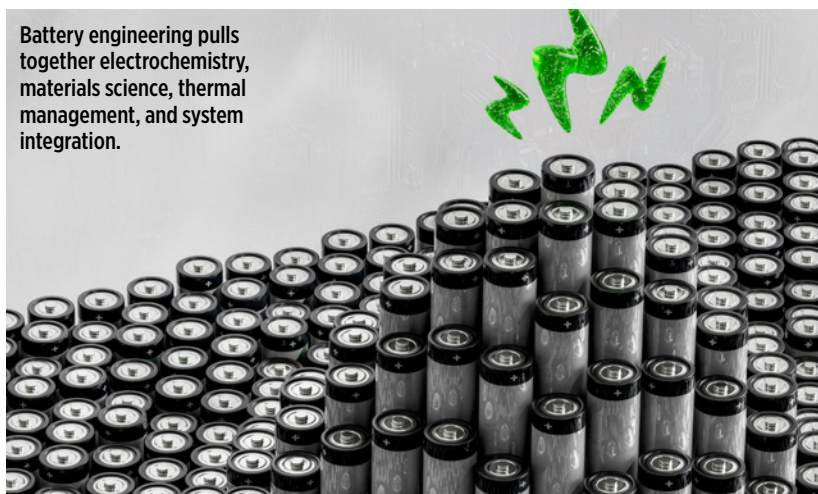
3. Thermal and mechanical behavior

Temperature plays a huge role in how well a battery works. When things get too hot, batteries wear out faster, lose some of their punch, and there's a higher risk of dangerous events like thermal runaway.

To stay ahead of these problems, engineers run thermal simulations. This lets them see how heat appears and moves within a battery cell or module. The models usually look at a few main things: heat generated by electrical resistance (that's Joule heating), heat released during electrochemical reactions (that's entropic heat), and how well heat dissipates through cooling systems or special materials that absorb heat. They also pay close attention to temperature differences inside battery modules and packs.

By using models that link the battery's thermal and electrochemical behavior, engineers can identify the

Battery engineering pulls together electrochemistry, materials science, thermal management, and system integration.



conditions that cause hot spots. That gives them a chance to tweak the cooling setup or even change how the cells are arranged to keep things safer and running smoothly.

It's not just heat that's a concern; mechanical modeling is getting more important, too. This is especially true for new battery types like solid-state designs.

4. Pack-level system modeling

At the vehicle level, battery design becomes a complex integration problem involving electrical, thermal and structural systems. Simulation platforms allow engineers to build system-level models that include:

- Cell-to-cell electrical balancing
- Thermal propagation between modules
- Battery management system (BMS) control strategies
- Vehicle duty cycles and real-world operating conditions

Multiphysics modeling tools integrate these domains to evaluate performance under realistic load profiles such as acceleration, regenerative braking and fast charging. These models are also essential for assessing system safety, including failure propagation scenarios and abnormal operating conditions.

Predicting degradation and lifecycle performance

One of the most valuable applications of simulation is predicting battery degradation.

Lithium-ion batteries degrade through multiple interacting mechanisms, including:

- Growth of the solid-electrolyte interphase
- Lithium plating during fast charging
- Particle cracking and loss of active material
- Electrolyte decomposition

Physics-informed degradation models can simulate how these mechanisms evolve over thousands of cycles. By linking them to



Pradyumna (Prady) Gupta is founder and chief scientist at Infinita Lab and founder and CEO at Infinita Materials.

operational parameters such as temperature and C-rate, engineers can estimate capacity retention and state of health over time. This capability allows battery designers to evaluate long-term performance under different usage scenarios, such as aggressive driving patterns or repeated fast-charging events.

Surrogate models and AI in battery simulation

While detailed electrochemical models provide high accuracy, they can be computationally demanding. For large design studies or system-level simulations, engineers often rely on reduced-order or surrogate models. These models approximate the behavior of complex physics-based simulations while requiring significantly less computational time. Machine learning techniques are increasingly used to generate such surrogate models by training algorithms on large simulation datasets. The resulting models enable real-time

battery performance prediction within design tools, digital twins, or vehicle control systems.

Virtual validation before physical prototyping

Perhaps the most significant impact of simulation-driven battery development is the shift toward virtual validation. Rather than building numerous physical prototypes, engineers can evaluate design variations digitally, narrowing down promising configurations before manufacturing test samples. This approach can dramatically shorten development timelines while reducing cost.

For example, advanced simulation tools have allowed engineers developing high-performance electric vehicles to compress battery pack design cycles from months to just a few weeks by optimizing designs in a virtual environment. Physical testing remains essential for final validation, but simulation ensures that prototypes are already close to optimal designs.

Toward digital twins of battery systems

The next evolution in simulation-driven engineering is the development of digital twins, dynamic virtual representations of physical battery systems. A digital twin combines real-time sensor data with physics-based models to monitor battery performance during operation. Such systems can:

- Predict remaining useful life
- Optimize charging strategies
- Detect early signs of degradation or failure

As vehicles become increasingly software-defined, digital twins may play a key role in battery management systems, enabling adaptive control strategies that maximize performance and extend battery lifetime.

Conclusion

Battery engineering pulls together electrochemistry, materials science, thermal management, and system integration. It's not just that these fields bump into each other, they're tangled up, making simulation-driven design a must, not just a nice-to-have. By connecting models ranging from tiny electrode materials to full vehicle systems, engineers get a clearer picture of how batteries work, what sacrifices they're making for performance, how they age, and how to tweak designs before they're stuck with expensive prototypes.

As electrified mobility continues to expand across automotive, aerospace and industrial applications, simulation will remain a critical enabler for the next generation of high-performance, safe, and durable energy storage systems. ■

Pradyumna (Prady) Gupta is founder and chief scientist at Infinita Lab and founder and CEO at Infinita Materials and wrote this article for SAE Media Group.

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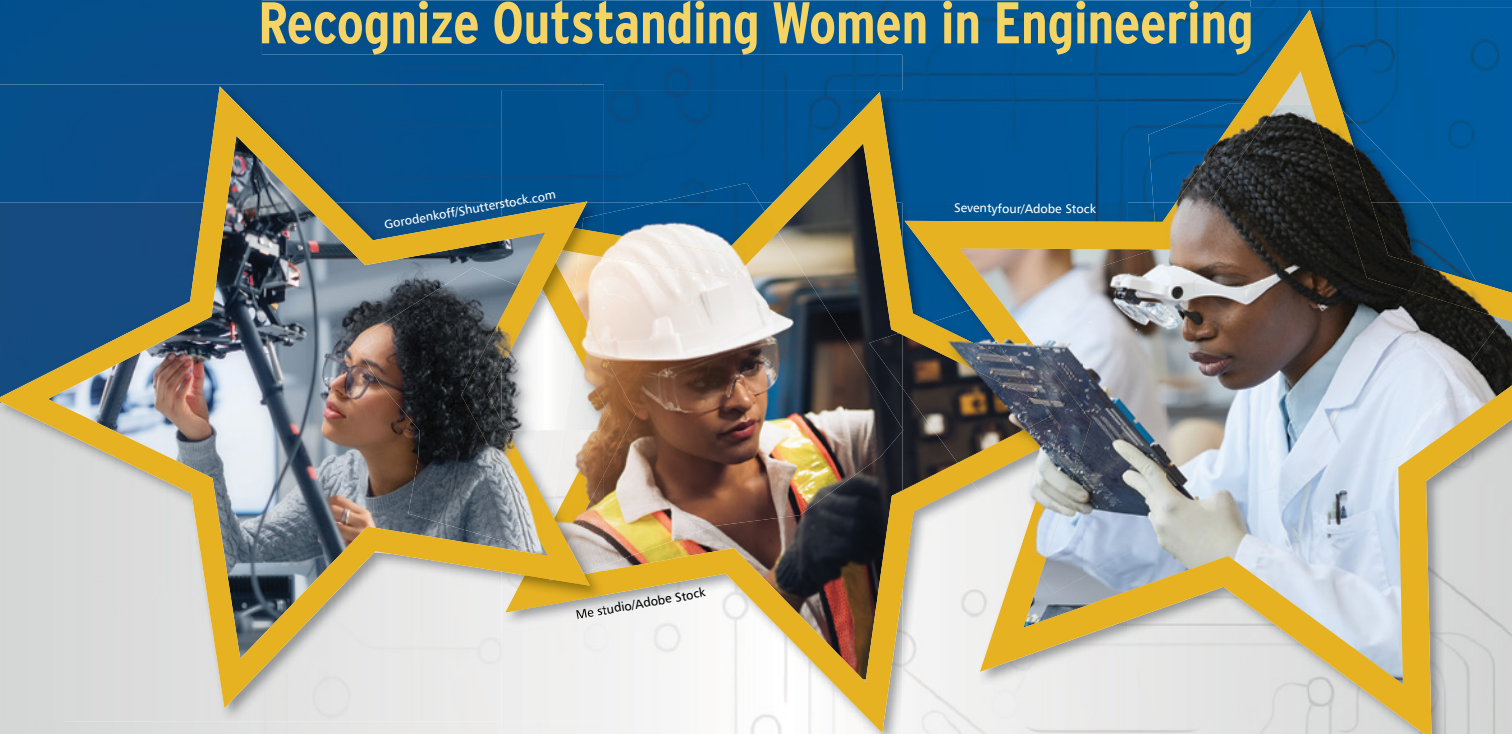


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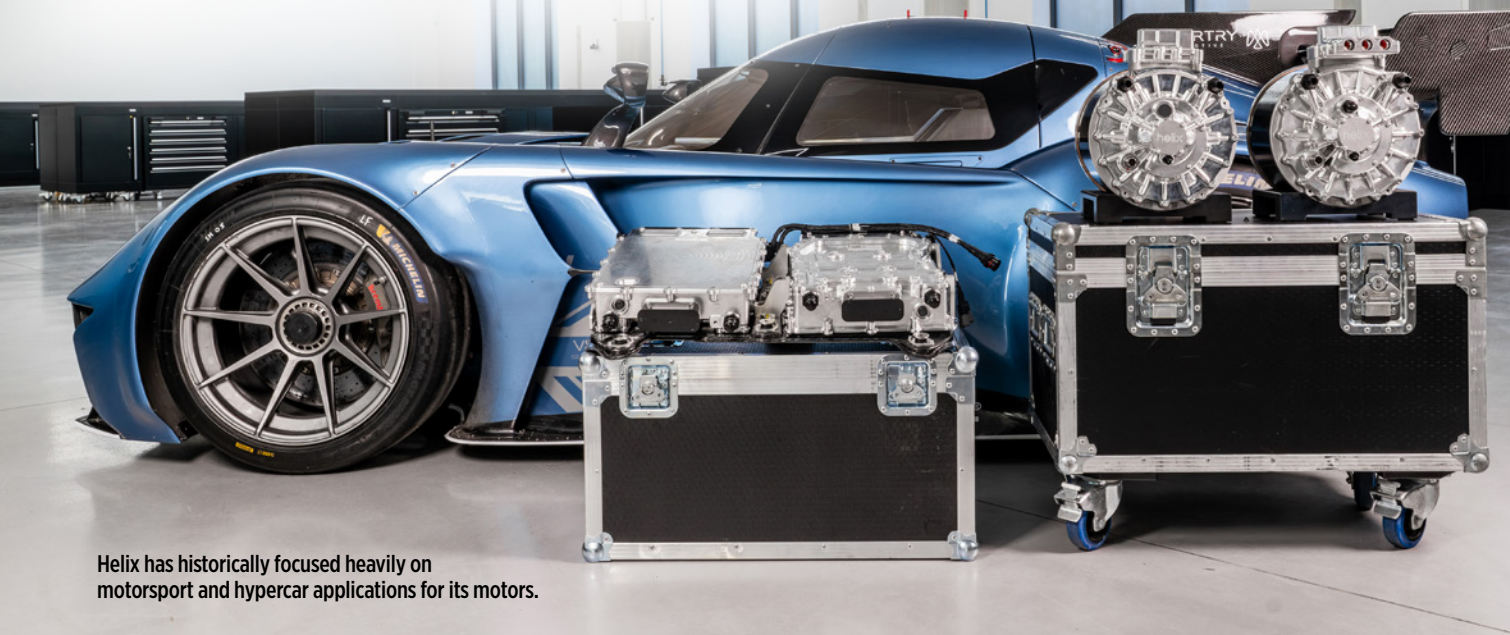
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How simulation unlocks efficient and innovative **MOTOR DESIGN**



Helix has historically focused heavily on motorsport and hypercar applications for its motors.

Engineers are still at the heart of the development process as simulation tools become great levelers.

by Alex Morley

Time has always been a valuable currency in engineering, and many projects live or die based on how fast their teams can bring products to market.

Motor development may be one of the best examples of this truism in practice. Along with the motor itself coming with significant electronic engineering and thermal management challenges, it often needs to be developed with wider system considerations in mind, which can make product development extremely complex. After accounting for traditional prototyping cycles – with all the material, manpower, and time they require – motor development projects are often difficult and high-risk, owing to the sheer amount of up-front investment and resources required to develop a new system.

Historically, this has been a real constraint on the spread of e-mobility, since complex applications that push the boundaries of motor technology have traditionally been too risky and resource-heavy to justify the investment. For many motor engineering houses, the sheer number of parameters and unknowns have made even scoping out projects relatively unattractive.

This is where sophisticated simulation has increasingly come into play and has helped accelerate the rollout of e-mobility. Whereas once scoping out a project would have required many days of engineering time to determine initial design candidates, modern electromagnetic simulation software can now produce potential specifications in just several hours of computing time. Simulation suites can now take a bundle of initial parameters and produce some prospective magnet sizings, stator dimensions, winding selections, and

more. From there, it's possible to develop reasonable estimations of system performance, costs, and project timelines.

For many customers, providing a realistic set of prospective solutions is the ideal launching point for a project. This is especially the case in complex e-mobility projects, where deep supplier-customer collaboration is required. By radically reducing the friction on the supplier-side to providing these options, modern simulation techniques provide an ideal launching point for these relationships. Before, many of them wouldn't have been able to get off the ground without significant investments of senior engineering time.

Computing limits

Simulation capability alone does not solve everything. In practice, the performance and predictive power of any finite element analysis is going to be limited by the amount of data that it has access to. Configuring a simulation run can take considerable time, with processing often requiring an overnight window for the computing to be done. And then there is the matter of interpreting and presenting the simulation results, which requires considerable subject-level expertise to ensure that engineering and customer teams can have



Motor simulation suites today can take multiple initial parameters to produce prospective magnet sizings, stator dimensions, winding selections, and more.

confidence in what they are presented.

This all means that teams need to invest considerable time in converting historic datapoints on motor performance and characteristics into machine-readable datapoints, and maintaining a consistent regime of converting results from live projects into data for model inputs. This demands a strong relationship between analysis teams and other engineering functions, both in maximising the amount of input data but most crucially its variety: for many projects that advance the state of the art, useful and predictive simulation can risk being constrained by the amount of data points at the “frontiers” of motor performance and characteristics.

To help with this communication and to provide an “intermediate” step between complete analysis and “back of the envelope” calculations, our team at Helix developed an in-house deterministic tool that provides initial rough approximations to 95% certainty of the configurations required. Using regressions of traits, this allows us to use our wealth and variety of data to provide rapid initial estimations of system topology and performance to engineering and customer teams within fifteen minutes. This earlier phase allows us to ensure that more detailed simulations make the most use of analyst resources and computing time,

preventing a bottleneck at this phase.

Simulation is the first part of a conversation with any new customer, as it allows engineers and customers to clearly communicate expectations and requirements. But its application continues long after the initial prototyping phases have concluded, being employed throughout the development cycle as a system transitions from concept to production.

While simulation plays a critical role in the post-design phase by helping teams optimise production processes and tooling, speed of delivery usually takes a backseat to precision at this point. This means that the early-stage scoping simulations operate under very different constraints to simulations at later stages.

Since early-stage simulations for complex motor systems need to be both rapidly delivered and compellingly accurate, quality pre-prepared data becomes critical for success. In contrast to later-stage simulations, where time can be afforded to manually treat data, early-stage simulations depend on a team being able to quickly tap pre-existing data that covers a quantity and variety of configurations.

Accuracy needs quality data

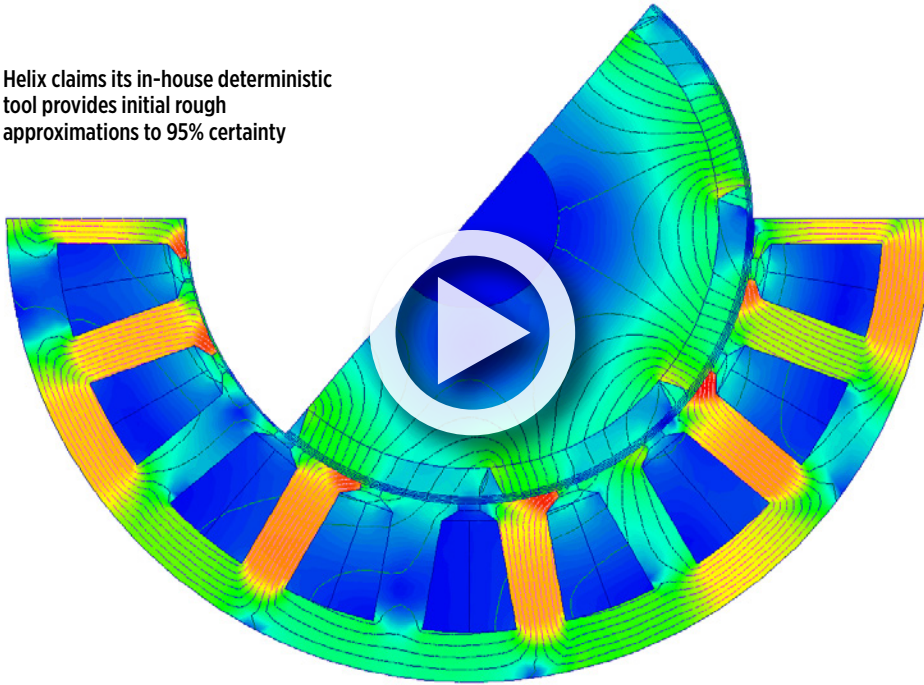
While speed of delivery is key, it means nothing without accuracy. The key to accuracy in many complex motor simulations is quantity and variety of data, which in turn is a function of the quantity and variety of work undertaken by a particular team or organisation.

In practice, this poses a significant opportunity for organisations

How simulation unlocks efficient and innovative MOTOR DESIGN

SIMULATION FOR PRODUCT DEVELOPMENT FEATURE

Helix claims its in-house deterministic tool provides initial rough approximations to 95% certainty



Being able to leverage the variety of historic data at hand to simulate solutions for these spaces, which are largely early in their electrification journeys, we've found ourselves first-to-market in developing compact, power-dense solutions.



Alex Morley is team leader, analysis, at Helix.

that have a strong legacy of motor development, allowing them to turn historical projects into powerful datapoints to give them an advantage during the simulation phase. But it is particularly an opportunity for smaller organisations that have traditionally focused on niche, low-volume motor applications: in practice, an organisation with dozens of production runs of a range of niche motors will have more data variety than one that has only a few mass production runs in a narrow performance window.

For our team at **Helix**, this has opened up a considerable opportunity. While we've historically focused heavily on motorsport and hypercar applications for motors, the sheer variety of data we have has allowed us to make a radical pivot in recent years into the aerospace, marine, industrial, and defence spaces. By being able to leverage the variety of historic data at hand to simulate solutions for these spaces, which are largely early in their electrification journeys, we've found ourselves first-to-market in developing compact, power-dense solutions in these application spaces.

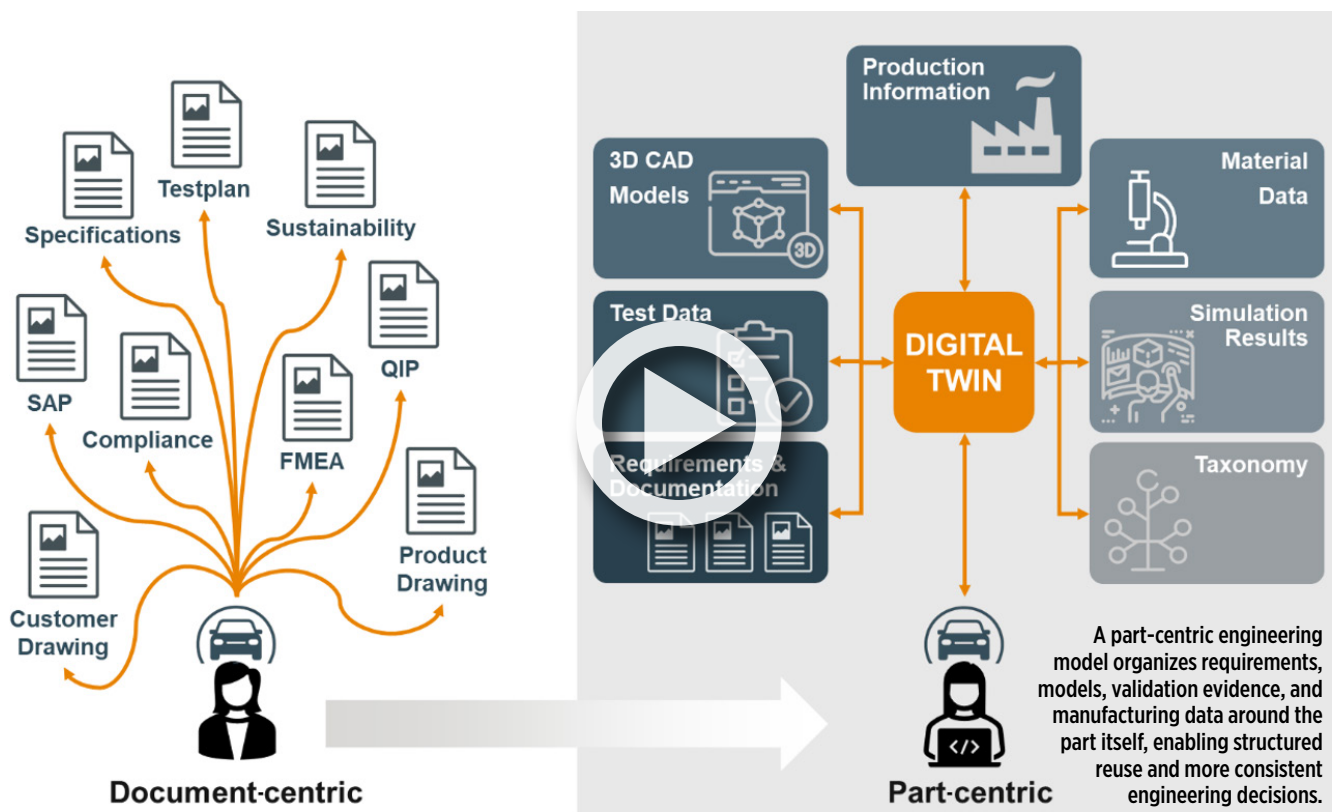
Engineers are still at the heart of the development process. Results are manually checked, and parameters selected by experts in their fields who can suggest the best factors and priorities for any application. Every project becomes part of a continuous learning loop, strengthening the dataset and enhancing future accuracy. In this way, simulation has become a great leveller and a means to radically improve the quantity and variety of solutions that we and the industry can offer these markets.

From the first conversation to the final validation step, simulation is the connective tissue that holds modern motor development together. It reduces waste, accelerates timelines, improves accuracy, and unlocks creativity that was previously bottlenecked by investment- and resource-intensive design and prototyping phases. As our own journey has shown, with the right tools, data, and expertise, simulation doesn't just support motor innovation – it powers it. ■

Alex Morley is team leader, analysis, at Helix and wrote this article for SAE Media Group.

BOTH IMAGES: HELIX

Engineering in the second quarter of the 21st Century



Building a trusted digital twin and decision-centric simulation ecosystem

by Jeremy Patterson

The automotive industry has been experiencing significant change and transformation. Electrification, software-defined vehicles, advanced driver assistance systems, and increasing electrical system integration are fundamentally reshaping how vehicles are designed and validated. As integration complexity continues to increase, the expectations for design cycle times are being compressed. Programs that once relied on extended validation timelines are now expected to deliver the same level of confidence in a fraction of the time.

Traditional engineering workflows were built around sequential design phases, iterative simulations, and heavy reliance on physical validation. Design concepts were documented, prototypes were constructed, tests were performed, and results were compiled in reports and specifications that informed the next iteration. That approach worked well when systems were less complex and product life cycles were longer. In recent years, the volume of data, the speed of development, and the interconnected nature of modern vehicle architectures demand a different approach.

Today, the conversation often turns to AI, digital twins, and automation as the mechanisms that will enable this shift. These technologies are extremely powerful, but they are not substitutes for engineering

discipline and rigor. More tools do not create better outcomes. Real progress comes from rethinking how engineering work is structured so that digital capabilities become trusted, repeatable, and scalable.

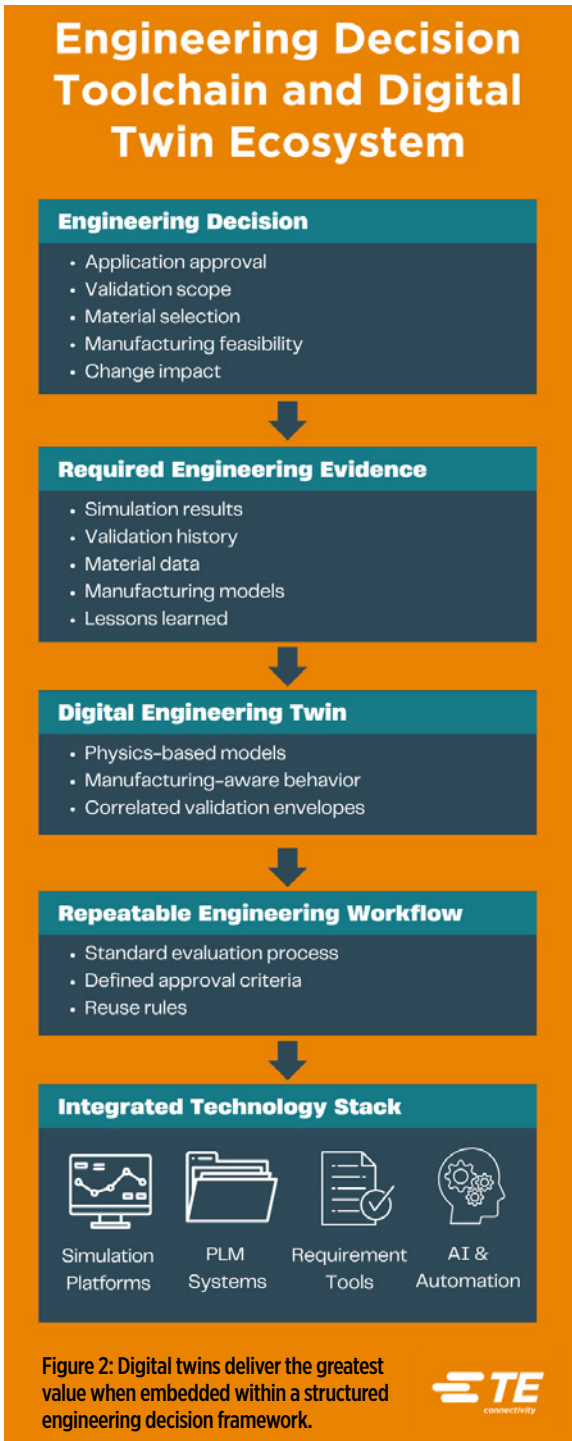
The shift from document-centric to part-centric engineering

For decades, engineering knowledge has been captured primarily through documents and disconnected systems. Drawings, CAD models, test reports, FMEAs, simulation files, spreadsheets, and presentations became the system of record. While these artifacts were valuable, they also introduced structural complications. Engineers often had to reconstruct the context of previous programs by reviewing large volumes of information across various tools and repositories. The quality and organization of the data often depended on how it was originally captured.

This approach limits the reuse of valuable engineering data. Simulations may exist, but they are not always structured for efficient retrieval. Validation evidence is often distributed across various reports and systems. As a result, engineering teams can find themselves repeating work that has effectively already been done, simply because the underlying information is difficult to access or interpret.

The shift toward part-centric engineering has been underway for some time, but recent advances in system integration, API maturity, and cloud-based computing power are accelerating it. In a part-centric engineering organization, requirements, design intent, simulation models, validation evidence, material data, and manufacturing

characteristics are linked directly to the part in a structured and traceable way. This allows the engineering context to persist rather than be constantly recreated. Evidence becomes reusable, decisions more consistent.



Defining the engineering digital twin

The term digital twin has gained widespread attention across many industries, and its meaning varies significantly depending on the technology. In the energy sector, a large generator may have its own digital representation or twin that continuously receives telemetry from sensors operating in the field. This allows engineers to monitor the performance of the system, conduct predictive maintenance, and simulate adjustments to the digital twin before modifying the actual system in the field. This approach works well for high-value systems produced in small quantities.

Automotive component engineering presents a different challenge. Many components are produced at very high volumes, where continuous telemetry data may not be available. In this environment, the engineering digital twin is defined as a validated digital representation of product behavior and manufacturing variation across defined operating conditions. An engineering digital twin is not simply a geometric model. It represents a culmination of physics-based simulation models, material characterization, manufacturing process assumptions, inspection data, and correlated validation results. Collectively, these elements define the performance envelope of a component or system.

Because engineering digital twins incorporate both product design and manufacturing behaviors, engineers can evaluate how a product will perform not only in theory but also when produced at scale. This capability is extremely important for high-volume components where manufacturing variation can strongly influence real-world performance.

When properly structured, the engineering digital twin evolves continuously as each program contributes new data, additional simulation correlation, and updated validation evidence. Over time, this accumulation of knowledge improves model fidelity and strengthens confidence in digital evaluation.

The engineering decision toolchain

Engineering digital twins deliver their full potential when embedded within a structured engineering decision framework or model. This framework is best described as the engineering decision toolchain. The toolchain defines the key decisions that shape product development, the evidence required to support those decisions, and the workflows that ensure decisions are executed consistently.

Examples of decisions within the engineering decision toolchain include requirements integration and interpretation, material selection, design reuse eligibility, manufacturing feasibility, lessons-learned integration, and determination of virtual versus physical validation scope. By explicitly defining these decisions and the evidence needed to support them, organizations create a consistent engineering process that is repeatable across programs and trusted by customers.

Decades of historical data and experience build the foundation of this system. Validation results, simulation correlation data, material performance information, and accumulated lessons learned form the evidence base that supports trusted engineering decisions. Engineers pull from this structured knowledge foundation to evaluate new designs at an unprecedented speed while maintaining confidence in performance and reliability.

In practice, when digital twins are integrated into this decision framework, simulation results and validation data becomes reusable assets

rather than isolated program outputs. Engineers can determine whether new design changes fall within previously validated envelopes or require additional physical testing. This structured reuse approach significantly improves engineering efficiency while preserving technical rigor.

Discipline should come before tools. Once the engineering decision framework is clearly defined, automation and artificial intelligence can be introduced in a controlled way. AI-enabled engineering systems can assist by retrieving relevant historical evidence, automating repetitive analytical tasks, and accelerating evaluation cycles. The intent is not to replace engineering judgement and creativity, but to ensure that engineers consistently have the right information available when making critical decisions.

The infrastructure that supports this system or approach forms the technology stack of the engineering decision toolchain. The tech stack architecture integrates simulation platforms, requirements management systems, product lifecycle management environments, manufacturing data, and AI-assisted workflows. When these systems operate together within a disciplined framework, they enable the toolchain to scale across various programs and product lines.

Simulation as strategic infrastructure

In the decision-driven engineering environment, simulation departments are no longer a support function. Digital twins and the engineering decision toolchain rely on simulation to provide the structured evidence that supports key engineering decisions such as material selection, validation scope, design reuse, and manufacturing feasibility.

The real power of digital engineering does not come from any single tool, but from the integration of product simulation, manufacturing process models, inspection data, and physical validation into a continuously improving digital twin. Each program contributes new knowledge that strengthens the accuracy and credibility of future engineering decisions.

Product simulations evaluate functional performance across electrical, thermal, and mechanical domains, while manufacturing process simulations predict how production methods influence geometry, stress distribution, and material behavior. Inspection data such as CT scanning or dimensional metrology shows how the real part differs from the design, while physical validation confirms model accuracy and helps identify conditions that fall outside of expected behavior.

When these elements operate together within the engineering decision toolchain, simulation becomes part of a structured feedback loop linking design intent, manufacturing reality, and validation evidence. Over time, this naturally leads to a more reliable digital twin, where product models predict behavior, process simulations capture manufacturing effects, and validation data helps refine and improve model accuracy.

As correlations improve and digital twins mature, engineering teams can move much faster through design iterations and evaluate performance with a high level of confidence. What once required months of iterative testing can now be addressed in days through structured digital evaluations, with physical testing used to confirm the areas that truly matter. Physical testing remains essential for correlation, discovery, and understanding edge-cases, but in a disciplined digital environment, it becomes focused on areas of uncertainty rather than repeating work that has already been validated.



Linking product simulation and manufacturing reality in an engineering digital twin.

Re-engineering engineering

Technology alone will not deliver the transformation or digital capabilities needed to compete in an AI-driven world. It must be paired with strong organizational discipline and a redesigned approach to engineering. Engineering teams must define how decisions are made and what evidence supports them, while digital platforms and tools enable these standards to operate efficiently at scale.

Artificial intelligence and advanced simulation technologies will continue to expand what is possible in engineering. However, the real transformation comes from redesigning how engineering knowledge is structured and subsequently applied. By shifting from document-centric to part-centric knowledge, embedding validated engineering digital twins within a structured decision toolchain, and treating simulation as strategic infrastructure, organizations can unlock speed, efficiency, and innovation capacity.

The future of automotive engineering will belong to organizations that build trusted digital ecosystems where knowledge compounds over time and engineering decisions are supported by structured evidence. In that environment, engineers spend less time reconstructing the past and more time shaping the next generation of mobility solutions. ■

Jeremy Patterson is vice president and CTO, EMIA Automotive, TE Connectivity and wrote this article for SAE Media Group.

INDEPENDENT MATERIALS TESTING for OEM validation



OEM-approved independent laboratories validate compliance with internal material specifications. These laboratories support suppliers during development and production approval by providing testing aligned with OEM standards.

How validated data provides the foundation for approved components.

by Kurt Kelley

As vehicle architectures evolve toward electrification, increased functional integration, and aggressive lightweighting targets, the performance requirements placed on materials used in automotive systems continue to grow. From structural polymers and coated metals to interior surfaces and functional elastomers, materials must maintain performance across increasingly demanding environmental and mechanical conditions.

To ensure these materials meet durability, safety, and performance requirements, automakers rely on OEM-approved independent laboratories to validate compliance with their internal material specifications. These laboratories support suppliers during development and production approval by providing testing aligned with OEM standards.

Volkswagen AG maintains a global network of approved testing laboratories capable of performing materials testing to its internal specifications. Recently, **Element Materials Technology** received Volkswagen accreditation for materials testing at its labs in Warren and Plymouth, Michigan, expanding the approved testing capacity for VW suppliers.

For engineers responsible for component development and supplier validation, access to accredited independent laboratories can help streamline the process of verifying materials against OEM specifications during both early design validation and production readiness.

The role of independent materials testing in automotive development

Modern vehicle programs rely on increasingly complex materials. Interior components often combine polymers, textiles, adhesives, and coatings, while structural components incorporate advanced steels, aluminum alloys, and engineered thermoplastics. Each of these materials must meet strict OEM requirements addressing:

- Long-term environmental durability
- Mechanical integrity under operational loads
- Resistance to fluids, chemicals, and UV exposure
- Surface performance and appearance retention
- Flammability and safety performance

To ensure consistency across the supply chain, OEMs require materials testing to be conducted according to standards they define. These specifications typically refer to standardized tests derived from organizations such as SAE International, ISO, ASTM International, and DIN. Independent labs provide controlled environments and specialized instrumentation

to perform these tests while ensuring traceability and repeatability through accredited quality systems.

Materials validation within the supplier approval process

Materials testing plays a critical role in several stages of the automotive development process. During early development, suppliers must demonstrate that candidate materials meet baseline performance requirements. Later, testing data is used to support production approval documentation. Within the automotive supply chain, this process often aligns with the Production Part Approval Process (PPAP), where suppliers must verify that materials and processes consistently meet engineering requirements. Testing data generated by accredited laboratories supports multiple validation activities, including:

- Design validation
- Process qualification
- Supplier approval documentation
- Failure analysis and corrective action investigations

For engineers working within Tier 1 and Tier 2 suppliers, access to approved labs capable of performing OEM-specific testing helps ensure that materials data will be accepted during OEM validation reviews.

Mechanical performance testing

Materials validation encompasses a wide range of test disciplines designed to replicate the environmental and operational conditions encountered during vehicle life. Mechanical performance testing, for example, evaluates the ability of materials and assemblies to withstand operational stresses while maintaining structural integrity. Typical methods include tensile testing, compression testing, flexural strength measurement, and fatigue evaluation. These tests are critical for materials used in load-bearing applications such as brackets, structural reinforcements, and composite assemblies. Testing may also include creep and stress relaxation studies, particularly for polymeric materials subjected to long-term mechanical loads at elevated temperatures.

Environmental durability and aging

Vehicle components experience significant environmental variation, including extreme temperatures, humidity exposure, and thermal cycling. Environmental testing simulates these conditions and evaluates long-term material performance. Common environmental tests include:

- Thermal shock and thermal cycling
- High-temperature aging



A salt spray test (also called salt fog testing) uses high-saline environments to measure the corrosion resistance of products, paints, and coatings over extended periods.

- Humidity exposure testing
- Water immersion and condensation testing

These tests help engineers evaluate potential degradation mechanisms such as polymer embrittlement, adhesive failure, and dimensional instability. Environmental durability testing is particularly important for materials used in battery systems, under the hood, and exterior components.

Surface and coating performance

Coatings and decorative finishes are used throughout interiors and exteriors to provide corrosion protection, appearance, and wear resistance. Testing methods used to evaluate these systems typically include:

- Abrasion and scratch resistance testing
- Adhesion testing of coatings and paint systems
- Chemical resistance testing against automotive fluids
- Weathering and UV exposure testing

These tests are especially important for interior trim components, touch surfaces, and painted exterior parts where both performance and appearance must be maintained over the vehicle lifecycle.

Flammability and interior safety requirements

Interior materials must meet strict flammability requirements to ensure passenger safety. Testing methods evaluate ignition resistance and flame propagation behavior under defined conditions.

Flammability testing is typically applied to:

- Interior plastics
- Upholstery materials
- Textiles and foam systems
- Insulation materials

INDEPENDENT MATERIALS TESTING for OEM validation

ZERO PROTOTYPING | TESTING FEATURE



Corrosion tests are especially important for interior trim components, touch surfaces, and painted exterior parts where both performance and appearance must be maintained over the vehicle lifecycle.

Increasing materials complexity in EVs

The rapid growth of electrified vehicles has introduced additional challenges for materials engineers. Battery systems, high-voltage components, and thermal management systems require materials capable of withstanding demanding electrical, thermal, and chemical environments. These systems introduce new validation challenges, including:

- Exposure to aggressive electrolytes
- Thermal gradients during fast charging and discharge cycles
- High-voltage insulation requirements
- Fire propagation mitigation

As a result, testing programs are expanding to include specialized evaluations focused on electrical insulation performance, thermal stability, and chemical compatibility. Independent labs play an important role in supporting these evaluations by providing the instrumentation and environmental chambers required to simulate these complex conditions.

Independent laboratories as an extension of OEM engineering capability

For OEMs and suppliers alike, independent laboratories serve as an extension of internal engineering and validation teams. By providing accredited testing aligned with OEM specs, these labs help ensure consistency and reliability across global supplier networks. Independent testing capacity can also help address several challenges frequently encountered during vehicle development:

- Limited internal OEM laboratory capacity
- Increasing complexity of materials systems
- Accelerated development timelines



Kurt Kelley is the department manager of Materials Testing for Element Materials Technology.

- Global supplier networks requiring standardized validation

By generating repeatable and traceable test data, accredited laboratories help engineering teams make informed decisions regarding material selection, component design, and long-term reliability.

Materials testing as a foundation for vehicle reliability

Ultimately, the long-term durability and safety of automotive systems depend heavily on the performance of the materials used in their construction. Materials testing provides the data needed to understand how these materials behave under real-world conditions, including mechanical stress, environmental exposure, and chemical interaction. For engineers responsible for developing next-generation automotive systems, validated materials data provides a critical foundation for designing components capable of meeting the durability expectations of modern vehicle platforms.

As vehicle architectures continue to evolve, particularly electrified powertrains and advanced materials, the role of independent testing labs will continue to expand, helping suppliers demonstrate compliance while supporting the development of reliable and safe automotive systems. ■

Kurt Kelley is department manager of Materials Testing for Element Materials Technology and wrote this article for SAE Media Group.

BOTH IMAGES: ELEMENT MATERIALS TECHNOLOGY

Toyota expands all-electric bZ ‘family’



“The customer who drives a Camry and switches to the Tesla Model 3 or something, probably this customer will be confused. But going from the Camry to the bZ, this customer doesn’t feel any confusion. It’s a normal car.”

Toyota continues to shift gears out of sync with other OEMs when it comes to building and selling all-electric vehicles. After years of down-playing EV sales in favor of hybrids and PHEVs, Toyota is instead expanding its all-electric line-up of vehicles just as other automakers are canceling or scaling back multiple EV projects (see page X). Just don’t go looking for a bunch of new bZ models on dealer lots.

As part of this strategy, Toyota unveiled its largest EV yet, the 2027 Highlander, in February. Applying the name of a popular three-row SUV to what is now an electric-only model is surprising, but the new Highlander should have the performance figures to live up to the name. Toyota will sell two trims, the Limited and XLE, which both use a 95.8-kWh battery to provide an estimated 320 miles (515 km) of range and which can provide off-

board power in emergency situations. Available with front- or all-wheel drive, the new Highlander will offer up to 338 combined system hp (252 kW) and 323 lb-ft (438 Nm). The vehicle will also boast seating for seven, more than 45 cu ft of rear storage (with the third-row seats folded down) and the latest versions of Toyota’s infotainment and Safety Sense Systems. The Highlander will be assembled at Toyota Motor Manufacturing Kentucky while the battery modules will be assembled at the Toyota Battery Manufacturing North Carolina (TBMNC) Battery Plant and at partner suppliers in the U.S.

The all-electric Highlander joins the C-HR in getting an all-electric remake in the U.S. While Toyota has sold ICE, hybrid and PHEV versions of the C-HR around the world in recent years, the compact SUV hasn’t been offered in the U.S. since the 2022 model year,

when the gas-only version was discontinued here. For 2026, Toyota is reintroducing the C-HR as a battery electric model. The fact that the Highlander and C-HR are keeping familiar names says a lot about where Toyota sees EVs going in the near term. Even though the C-HR is technically not a part of the bZ family – otherwise, it could have been called the bZ Sport – in engineering terms, it’s sort of a distant relative, Toyota chief engineer Masaya Uchiyama told SAE Media.

“The bZ name was kind of a starting point for Toyota,” Uchiyama said. “After that, we decided on the pathway approach, and battery EVs are getting more normal, so it’s better to have an existing name. That’s why we are using C-HR and [Highlander] instead of bZ Big or something like that.”

Naming differences aside, Toyota’s current EV models share plenty of



The 2026 Toyota C-HR uses a 74.7-kWh battery, a 167 kW front motor and a larger, 167-kW rear motor for what the automaker calls a sophisticated feel on the road.

technical details. The current bZ, the bZ Woodland and the C-HR all use similar batteries and motors, Uchiyama said, but the Woodland trim adds specific AWD control while the C-HR was tuned with a specific suspension for a more emotional driving feel. That makes the bZ Woodland its own beast, perhaps roughly comparable to a RAV4 Woodland trim with all-terrain tires. The EV's AWD system uses two motors that each produce 167 kW and 198 lb-ft (268 Nm) for a combined net output of 375 hp (280 kW) and a 0-60 time of 4.4 seconds. The C-HR is similar in most regards, with the same 74.7-kWh battery and charging features, but the C-HR also offers AWD, even though the rear motor is smaller (the front motor is still 167 kW) and only produces 87 kW and 125 lb-ft (169 Nm). Overall power output is 338 hp (252 kW). Both the bZ Woodland and the C-HR have independent MacPherson strut-type front suspensions and multi-link rear suspensions, both with stabilizer bars. On the bZ Woodland, the suspension provides

8.4 in (21 cm) of ground clearance. All of them use a 400-volt architecture, which Uchiyama said was the sweet spot for today's EVs

"We see, currently, the 400-volt system as kind of practical for many people," he said. "If we can switch to 800 volts, it's going to be very expensive."

The main thing that would prompt Toyota to shift to an 800-volt system, Uchiyama said, would be a major reduction in those costs, along with more 800-volt-ready charging infrastructure and improved battery cells. He wouldn't say what chemistry that might be, but did say that Toyota is "doing a lot on the R&D side" and that when it comes to when an 800-volt future will make sense, Toyota is studying the possibility, but hasn't decided anything yet.

Feeling the improvements on the road

Toyota might be keeping its "beyond zero" branding around for its marquee EV, but the changes the company made in the new bZ Woodland trim

should legitimately make people forget the critical and commercial disdain that the original bZ 4X received. Toyota has reworked the entire bZ formula, taking advantage of improved technologies throughout, and made a normal-looking and -acting SUV that happens to be all-electric. Uchiyama said the engineers heard loud and clear that they needed to provide a better EV if Toyota wanted to actually compete at dealerships.

"We heard a little voice from the market about the range and also the charging speed, and also the information about the [range display]," Uchiyama said, laughing. "To do that, we improved the battery, we have a bigger battery size now, and also we completely changed motors, and also the charging system, and the heating system, and then we put battery preheating into the new bZ." Uchiyama said Toyota improved the efficiency of the electric system and the motor's efficiency, and upgraded some power electronics from silicon to silicon carbide.



The new Toyota Highlander shifts to an all-electric powertrain for the 2027 model year, one of many signs that the automaker is rethinking its EV strategy.

These improvements mean the new bZ Woodland has options the original model never dreamed of. That's why, given the potential for off-roading, the bZ Woodland has a special AWD control system that monitors the rotational speed of the inside and outside wheels, similar but different from torque vectoring. Depending upon wheel speeds, the system can transfer torque between front and rear (but not left to right), giving the car better understeer and oversteer control.

Driving the bZ Woodland is nothing like the original bZ. It's tough to understate how much better the acceleration is now and how the increased power gives the EV a true sense of purpose, even if it isn't going to be anything close to the quickest EV on the block. Toyota has built a confident EV that's quiet on the highway and totally capable of driving a few adventurous miles into the back country, if the trail is right. What's perhaps most notable about the bZ Woodland – and the CHR, which swaps out the off-roading

features for a more sophisticated feeling on the road – is that these are Toyotas through and through from behind the wheel, falling comfortably in that comfortable space where a car does what it's supposed to do without offering flashy tricks, like a tank turn or ludicrous speed.

For all of Toyota's newfound dedication to EVs, this is still a company that's adapting at a slow pace. This is how its customers want it, apparently, as you might be able to guess by the fact that these EVs still do not have one-pedal driving. Uchiyama reiterated Toyota's stance that all Toyotas should behave in similar ways, whether they're battery-powered or use another fuel source.

"Whether you are off-road, on-road, wherever, we want you to have a more natural driving feel," Uchiyama said. "When we talk about EVs, everybody talks about acceleration or a peak kind of performance. We don't talk about that. It's okay that we want to have a more natural vehicle feeling, which gives the driver confidence." Unlike

competitors with RWD EVs that can provide a longer wheelbase and a bigger battery, Toyota's EVs are front-wheel-based, so they feel that little bit more like a "normal" vehicle with a traditional powertrain. Other automakers have made a splash with the aforementioned tricks, but Toyota believes EVs should drive like any other vehicle – whether ICE or hybrid or PHEV – because that will make a driver's eventual transition to electric power that much easier.

"[Driving our EV] feels close to those kinds of vehicles, and if we can have that, this customer is very easy to transfer to battery vehicles," Uchiyama said. "The customer who drives a Camry and switches to the Tesla Model 3 or something, probably this customer will be confused about where a switch is or something. It's a very different experience. But going from the Camry to the bZ, this customer doesn't feel any confusion. It's a normal car. That's the safe feeling we want them to have."

Sebastian Blanco

First Drive: 2026 Subaru Outback Wilderness

The Subaru Outback Wilderness tackles the muddy roads of NorCal.



The transformation of the Subaru Outback from wagon to SUV is complete. While the wagon was a perfectly capable off-road machine, the new Outback gets a boxier exterior (possibly an homage to the boxer engine) and Wilderness-trim level-first platform upgrade. During a recent drive program in Northern California, I had the opportunity to test the increased capability of the vehicle firsthand.

Rugged first

Subaru's Wilderness trim level adds additional off-roading capabilities to the automaker's lineup. The previous generation Outback had a Wilderness trim level, but this time Subaru developed the current Outback platform with Wilderness in mind. This means refined packaging and a vehicle that's ready to be upfitted for a more adventurous driver - or, at least, someone who needs to drive over and through deeper potholes.

To help traverse terrain, the Wilderness trim level increases the vehicle's clearance from 8.7 in to 9.5 in (22 to 24 cm). Subaru also increased the approach and departure angles from 18 to 20 degrees and 21.4 to 23.6 degrees, respectively. The result of these changes made themselves clear during the majority of my time behind the wheel of that vehicle on dirt roads in a Northern Californian ranch. Recent rains

created some deep sections of mud and exposed rocks and tree roots that crisscrossed the vehicle's path. At no point did the Outback feel like it was struggling to overcome any of the obstacles along the predetermined off-road course. It's not built for Moab, but it will deftly tackle most dirt roads even after days of rainfall.

The Wilderness sports the more powerful of the two engines available for the Outback. Under the hood lies a 2.4-L turbocharged 4-cylinder Boxer engine that produces 260 hp (194 kW) and 277 lb-ft

(375 Nm). It's 80 hp (60 kW) and 99 lb-ft (134 Nm) more than the standard engine. The extra torque is most noticeable while climbing, both off-road and on.

The trim level comes standard with electronically controlled dampers to keep the wheels planted onto the ground, and while in the rough bits, reduce some of the bumps encountered. But where it shines is on the twisties. The Outback Wilderness is a surprisingly fun vehicle to carve up the curvy asphalt you'll likely encounter during your drive to the trailhead.

A CVT gearbox is standard on all trim levels. The Wilderness does get a slightly increased gear ratio compared to the other trim levels to help it tackle tougher terrain. Helping drivers is the company's X-MODE system that tackles snow and dirt in one setting and deep snow and mud via another setting. I tested these settings and the vehicle's hill descent. While in those X-MODES, the hill descent is automatically enabled, which reduces the search for a button or control to turn it on, and it can be adjusted by increasing or decreasing the speed of the vehicle with the accelerator and brake. I found that to be a better solution than searching for a way to turn on hill descent while at the top of a stress-inducing incline.



The new front fascia design of the larger Outback.



The welcome sight of buttons.

Hard on the outside, soft inside

The new design of the Outback is reminiscent of the move by truck makers to lob off the nose of their vehicles and create a flat space to display their name. It's mostly flat, it's black, and it says "Subaru." The rest of the vehicle is a series of sharp edges. Some of the bits are quite useful. Along the back there's a nub to lean your snowboard and skis against so they don't go tum-

bling to the ground and scratch vehicle up while falling.

Inside, I found the seats to be comfortable, both front and back. I'm happy to report that the interior is full of actual buttons and knobs. Something that should be required by any vehicle that bills itself as an off-road vehicle. Tapping a screen while off-roading is a difficult proposition.

The rear cargo area with the rear

seats up is 34.6 ft³. With the seats down it increases to 80.5 ft³. The 60/40 split opens options for storage and passengers and for those looking for a vehicle to match their outdoorsy lifestyle, the Outback is primed with enough room for their gear.

If you need to drag something with you to a location, the towing capacity is 3500 lbs (1588 kg). To appease the overlanding folks, the roof weight capacity has a static load of 800 lbs (363 kg), while the on-the-go load is 220 lbs (100 kg).

The infotainment system is housed in a 12.1-in display and supports wireless CarPlay and Android Auto. Subaru's infotainment system feels very much like a tablet slapped onto the dashboard of a vehicle. It works fine. Most will pair their phones with it and be happy.

Unfortunately, there was very little time on the highway to test the driver assistance features. Subaru was keen to show off the vehicle's ability to tackle both mountain roads and its off-road course. In both instances, the vehicle's abilities were a delightful surprise.

The Outback Wilderness starts at \$46,445 (including \$1,450 destination fee) and is available now.

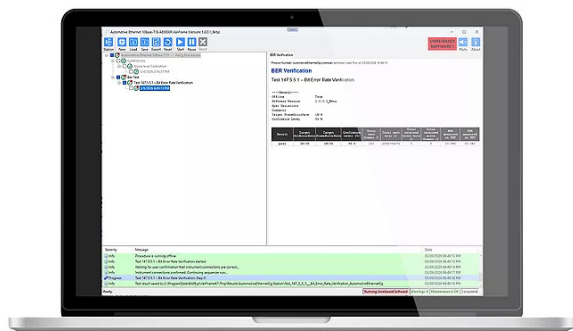
Roberto Baldwin



The rear cargo space.

SPOTLIGHT: TESTING & SIMULATION

Ethernet compliance testing



Keysight Technologies (Santa Rosa, California) offers a new automotive Ethernet receiver compliance test solution designed to support validation from 10BASE-T1S to 10GBASE-T1. Keysight states this solution enables auto-makers and suppliers to accelerate the transition to high-speed zonal architecture and software-defined vehicles. The solution supports emerging multi-drop 10BASE-T1S Ethernet architectures for zonal and edge-controller applications. This comprehensive automated receiver compliance test software executes receiver validation for PHY compliance with Open Alliance TC14 PMA Test Suite 5.2.1 specification. Supported oscilloscope models include Keysight DCA-M model N1092A/N1092C, with clock recovery via Keysight N1077B.

<https://www.keysight.com>

SPOTLIGHT: SEMICONDUCTORS

Semiconductor lubricants



IKO International (Morristown, New Jersey) has released its Liquid Crystal Lubricant as an alternative to traditional lubricating greases that are composed of base oils and thickeners. According to IKO, the molecules of those greases do not adhere well to metal surfaces and evaporate easily. Liquid Crystal Lubricant reportedly forms molecular aggregates whose layers easily slide past each other. This unique molecular structure adheres better to metal surfaces without releasing materials. The result is excellent lubrication characteristics where rolling contact occurs and low outgassing. When tested in various conditions, Liquid Crystal Lubricant exhibited very little detection in mass spectrometry at 10-5 Pa and high temperatures.

<https://ikont.com>

Push-on adapters

Connectronics (Edinburgh, Indiana) launched the SMP bullet, a subminiature push-on adapter designed to ensure reliable RF performance, especially in board-to-board or other gang-mating applications. The SMP Bullet supports both board-to-board and cable-to-board connections. Available for fixed and spring-loaded applications, it accommodates tolerance and misalignment issues during mating, prevents signal degradation and ensures consistent RF performance. The adapter has a high-density, small-form-factor design that supports dense interconnects in limited space while providing versatile board-to-board and cable-to-board connectivity. Each bullet is designed to minimize gaps and compensate for axial and radial misalignment, ensuring a consistently repeatable voltage standing wave ratio under compression.

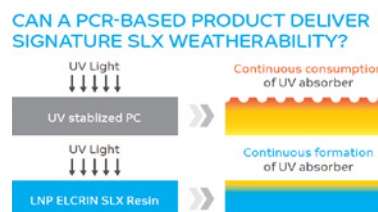


<https://www.connectronics.com>

Automotive compounds

SABIC (Riyadh, Saudi Arabia) launched the PIAE 2026 new LNP ELCRIN SLX compounds based on post-consumer recycled (PCR) content and new LNP KONDUIT WTF2C compound that supports thermal management in ADAS components.

SABIC states that these new compounds are made with 30% and 45% PCR content, respectively. They offer excellent weatherability and impact resistance to extend the life of high-gloss molded-in-color parts, thereby avoiding volatile emissions from painting, and to facilitate end-of-life recycling/recovery. The WTF2C compound can replace die-cast aluminum in housings for ADAS radar and electronic control units (ECUs) to increase design flexibility, cut weight, system costs and emissions.



<https://www.sabic.com>

TMMK president: Solar and bright, quieter factory floor help production

Kerry Creech, **Toyota** group vice president for Region 1 and president of **Toyota Motor Manufacturing Kentucky** — Toyota's largest factory in the world at more than 1,300 acres — is an executive with a story that is rare these days. He started at the Georgetown plant in 1990, working on the line in powertrain quality control.

SAE Media was part of a panel of journalists who sat down with Creech after a tour of the expansive plant that produces the Camry Hybrid, the RAV4 Hybrid, the Lexus ES 350 and 300h, as well as four-cylinder and V-6 engines. Soon it will be building the all-electric Highlander, including assembling the batteries on-site. Lines One and Three have been fully modernized, with AMRs carrying chassis through an open environment that is more efficient than the traditional front-to-back-end line full of switchbacks.

We've been seeing so many team members who have been here 20, 30 years. Personally, what has kept you all here for such a long time?

One of my favorite questions. I call TMMK a generational plant. And the reason why I call it a generational plant, and what I mean by that, is that there are sons, daughters, aunts, uncles, brothers, sisters that work here. And I'll ask you guys a question: Would you tell your son or daughter to come work at a place that you work if you didn't think it was a good company? That brings home more for most people than any other way that I can answer. That's exactly what happens here. There are a lot of relatives that work here.

Is it hard building sustainability into such a large plant? What are the biggest green programs?

There is a 50-acre solar farm that is on our campus. It's about a 16.3-megawatt facility that can produce enough clean, renewable energy to build about 20,200 vehicles a year. [The plant produced

450,000 vehicles in 2024.] And it offsets 100% of the electricity used by our stamping shop -- and we have a very large stamping shop.

Other than overall production and space efficiency, what do you think benefits the plant and employees the most?

I think that the clean, bright, and quiet, atmosphere of the plant helps us. And I'm going to give you some reasons why I think that is. There's a lot of tours that go through TMMK.

Many of those tours are high school students that come through and they get an impression of what manufacturing is like. And most of them, before they come here, believe that manufacturing is this dirty, dark building that you go in and you just get depressed by going in it. So when they go through at least Line One and they see the clean, bright, and quiet facility, we get a lot of feedback about how clean it is. What that does is it gives us a lot more high school students after they graduate interested in coming here or going to a trade school and working as a skilled team member. That's very important. And as I said, it's a generational plant. A lot of our other team members are referrals from other team members. It's one thing I tell other [executives] as they come through. Making things better for your team members is one of the most important things you can do.

It's apparent that a lot of the team members here have a better view of you than, say, the stereotypical executive-worker relationship. Can you explain that?

It's my goal when I retire — and I know you guys are going to think this may be crazy — but if I ever see a team member in Walmart or Target or some other store, I don't want to feel like I have to hide behind the shelves because I've done something to them.

Compiled by Chris Clonts. Some questions have been edited for space.



“[The 50-acre solar farm on our campus] offsets 100% of the electricity used by our stamping shop -- and we have a very large stamping shop.”