AUTOMOTIVE ENGINEERING

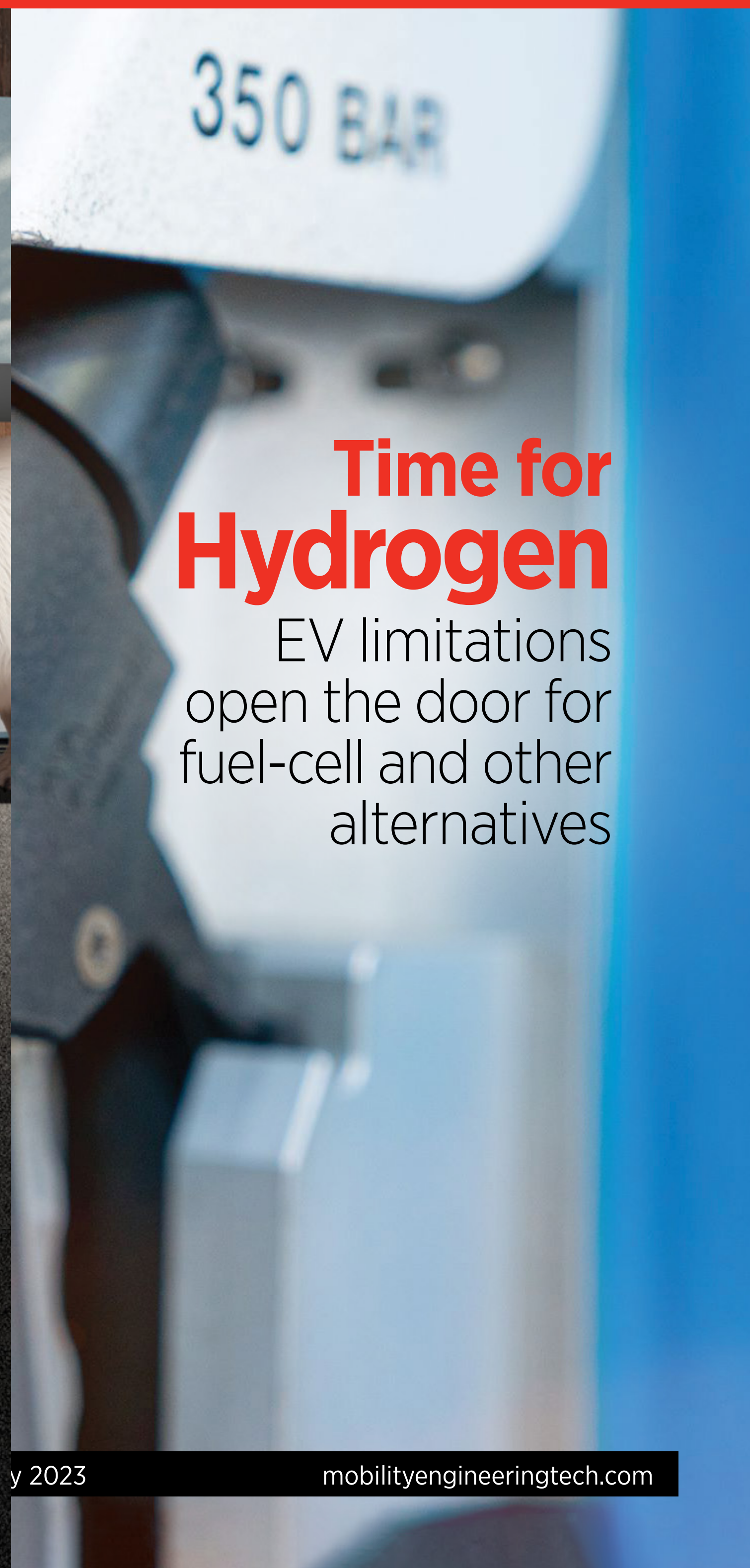
SAE INTERNATIONAL

Welcome to your Digital Edition of
Automotive Engineering February 2023


DEWESoft®
DESIGNING TEST EQUIPMENT THAT SIMPLIFIES THE ADVANCEMENT OF HUMANITY.
7
DEWESoft®
YEAR WARRANTY
www.dewesoft.com | sales.us@dewesoft.com | +1-855-339-3669

SAE INTERNATIONAL®

AUTOMOTIVE ENGINEERING®



Time for Hydrogen

EV limitations open the door for fuel-cell and other alternatives

y 2023 mobilityengineeringtech.com


Cooling that Satisfies the World's Most Demanding Applications.
Cooling Performance and Low-GWP Sustainability
Today automotive refrigerants need to be sustainable *and* get the job done. Plain and simple. Trust the refrigerant that's the preferred R-1234yf of eleven global car manufacturers. Trust Opteon™ YF.
Opteon™ YF
R-1234yf Refrigerant
MADE IN USA

SAE INTERNATIONAL®

AUTOMOTIVE ENGINEERING®

Time for Hydrogen

EV limitations open the door for fuel-cell and other alternatives

ALSO:

BMW's new H_2-powered iX5

Rethinking the pathways for reducing transportation's climate impact

February 2023 mobilityengineeringtech.com

DISCOVER

NITREX'S SMART SOLUTION FOR BRAKE ROTORS

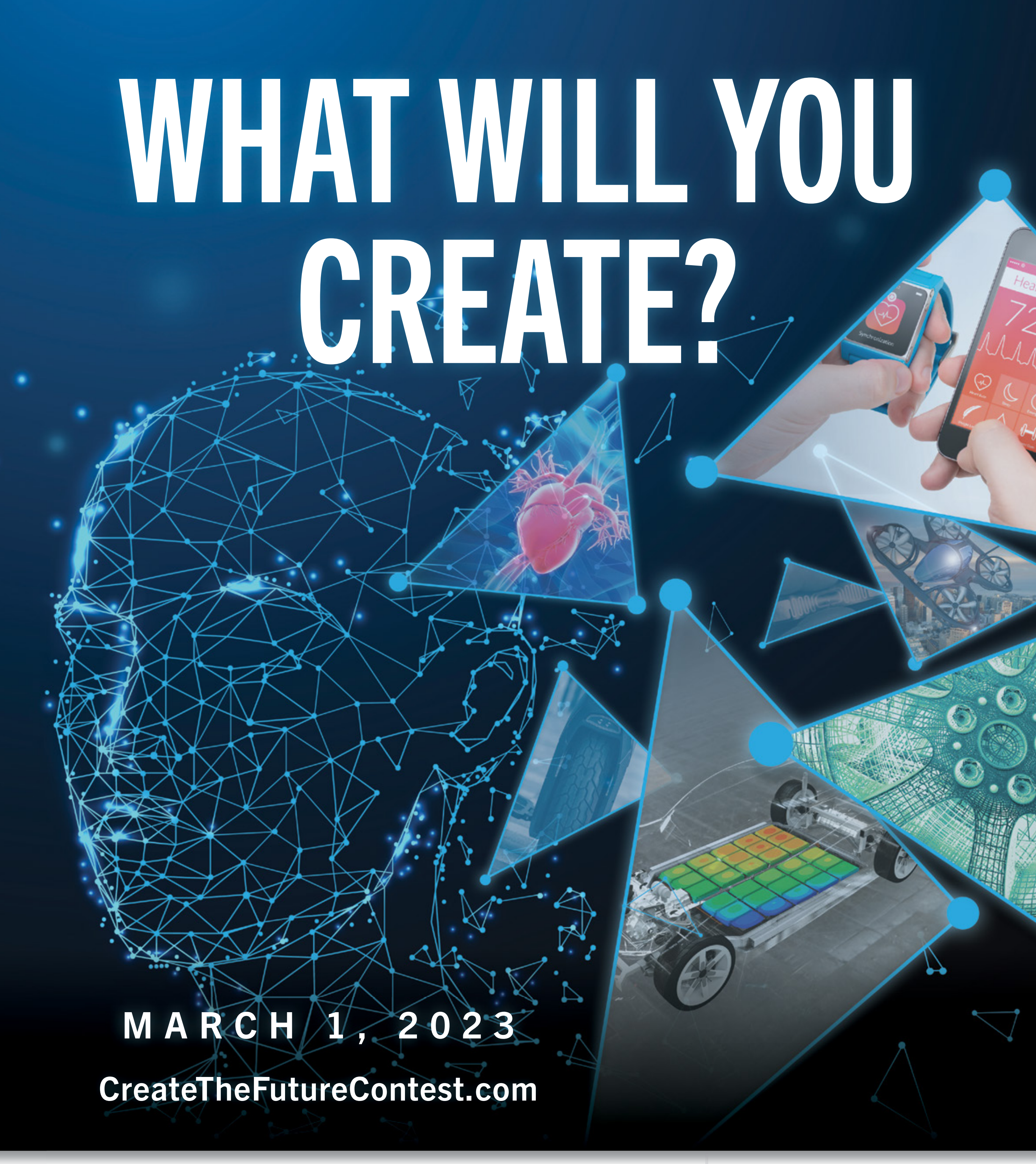
Smart
ONC®

UNPARALLELED CORROSION & WEAR PROTECTION FOR BRAKE ROTORS

- Meeting new emission standards
- Reducing brake dust and particle emissions
- Consistent and repeatable results
- Low operating costs
- Adaptable to big or small productions
- No cleaning or post-finishing
- Green technology, no waste pollution

NITREX

TALK TO AN EXPERT:
nitrex@nitrex.com / **nitrex.com**



PRINCIPAL SPONSORS

COMSOL

MOUSER ELECTRONICS

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

intel

CATEGORY SPONSOR

ZEUS

CONTENTS

ON THE COVER

As the conversation intensifies regarding the applicability of battery electrification for all ground vehicles, hydrogen gains momentum as a low- or no-carbon EV alternative in fuel-cell and IC-engine propulsion. (Cover image: Sandvik)

Follow us on social media

@SAEAutoMag @saeaei SAE Magazines

Automotive Engineering®, February 2023, Volume 10, Number 1. *Automotive Engineering* (USPS 474-100) is published 9 times a year in February, March, April, June, August, September, October and December (except digitally in May) by SAE Media Group, 261 Fifth Avenue, Suite 1901, New York, NY 10016 and printed in Mechanicsburg, PA. Copyright © 2023 SAE International. Annual print subscription for SAE members: first subscription, $15 included in dues; additional single copies, $30 each North America, $35 each overseas. Prices for nonmember subscriptions are $115.00 North America, $175.00 overseas, $30.00 digital subscription, $30.00 single copies. Periodicals postage paid at New York, and additional mailing offices. POSTMASTER: Please send address changes to *Automotive Engineering*, P. O. Box 3525, Northbrook, IL 60062. SAE International is not responsible for the accuracy of information in the editorial, articles, and advertising sections of this publication. Readers should independently evaluate the accuracy of any statement in the editorial, articles, and advertising sections of this publication that are important to him/her and rely on his/her independent evaluation. For permission to reproduce or use content in other media, contact copyright@sae.org. To purchase reprints, contact advertising@sae.org. Claims for missing issues of the magazine must be submitted within a six-month time frame of the claimed issue's publication date. The *Automotive Engineering* title is registered in the U.S. Patent and Trademark Office. Full issues and feature articles are included in SAE Mobilus®. For additional information, free demos are available at https://saemobilus.sae.org/.
(ISSN 2331-7639 print)
(ISSN 2331-7647 digital)

Audited by

EDITORIAL

Engineering 'electron guzzlers'

"We don't want a gas guzzler," my father asserted as we walked across the local Chrysler-Plymouth dealer's lot. It was early 1968; I was a car-nut school kid and he was a Mopar man on the hunt for a new station wagon. The average U.S. retail price of regular gasoline then was about $.30 per gallon. V8s reigned supreme. My ever-frugal dad wanted a big car for our family and so bought a 1968 Plymouth Fury III wagon — an 18-ft-long (5.5-m) land yacht.

As an arch penny-pincher, however, Dad eschewed the four V8s offered in the Fury in favor of the base inline 6-cylinder. Its 145 hp (108 kW) and the car's 4000-lb (1815-kg) curb weight conspired for an anemic power-to-weight ratio. No matter. There would be no gas guzzlers in our family's garage. The 225-six Fury got 18 mpg on the highway, while a 440-V8 powered model might eke out 13 mpg. Dad also deleted air conditioning: "Another *waste of gas!*" he lectured.

Most EVs are over-battered, overweight and overpriced.

Those memories returned when I saw 'gas guzzler' used in a recent news article about EVs. In this case, the writer wasn't referring to big V8s. Rather, the objects of her scolding were all IC engines, including the 1.8-L gasoline four-banger in her VW Golf.

Apparently, 'gas guzzler' now encompasses any vehicle that burns hydrocarbon fuels, no matter how efficient. Anything with an exhaust pipe! So, allow me to introduce a term to describe many of the current-generation EVs.

Let's call them *electron guzzlers*.

It's time to acknowledge that many incumbent EVs are as "electron-inefficient" as the thundering muscle cars were fuel-inefficient back in the day. EV engineers know how to configure electric-propulsion systems to deliver optimum miles per kilowatt-hour, or MPGe. Unfortunately, however, OEM product planners and marketers rule that max buzz is essential for making mass electrification attractive. They mistakenly chose 0-to-60 mph (0-to-97 km/h) acceleration as a key selling point. "We had to dispel the notion that electric cars perform like golf carts," one marketing boss told me.

But range and other energy-gobbling features also are important. As a result, most current EVs are over-batteried, overweight and overpriced for the majority of customer use cases.

Electron guzzlers are by design lithium-intensive hogs. GMC's Hummer EV, a notorious example, packs a 400-volt, 200-kWh, 617-amp-hour Ultium battery that weighs just shy of 3000 lb. (1360 kg), pushing the vehicle's curb weight to more than 9000 lb. (4082 kg). The Hummer's specs were driven in part by a silly 0-to-60 bogey: three seconds. Sure, it's quicker than a golf cart. But wouldn't a 6- or 7-second truck be just as marketable?

Further up the GVWR scale, Tesla's Class-8 semitractor is the ultimate guzzler. Its battery is estimated to weigh 10,000-lb. (4536-kg). With the transportation sector already concerned about future battery-materials supply and cost, the prospect of millions of pounds of lithium-battery demand serving comparatively few heavy trucks is lopsided. And heavier vehicles mean more tire wear, already an issue in the airborne-particulates battle.

The escalating cost of both lithium batteries and EVs is finally bringing some rationality to product development. New approaches to electrical architectures and component design are helping to reduce battery size. Hydrogen fuel-cell developments are a real alternative for larger vehicles. And the 0-60 obsession may be fading.

The rising EV market doesn't need electron guzzlers. Cost/price reduction and practicality now are the keys to capturing potential EV buyers. My late dad would be one of them – if he could option-delete the A/C.

Lindsay Brooke, Editor-in-Chief

EDITORIAL

Bill Visnic
Editorial Director
Bill.Visnic@sae.org

Lindsay Brooke
Editor-in-Chief
Lindsay.Brooke@sae.org

Chris Clonts
Senior Editor
chris.clonts@saemediagroup.com

Ryan Gehm
Associate Editor
Ryan.Gehm@sae.org

Matthew Wolfe
Assistant Editor
matthew.wolfe@saemediagroup.com

Amanda Hosey
Editor, Custom Content
amanda.hosey@saemediagroup.com

Contributors

Kami Buchholz
Detroit Editor

John Kendall
Europe Editor

Bradley Berman
U.S. West Coast Editor

Sebastian Blanco, Don Sherman, Paul Weissler

DESIGN

Lois Erlacher
Creative Director

Ray Carlson
Associate Art Director

SALES & MARKETING

Joe Pramberger
Publisher
joe.pramberger@saemediagroup.com

Kaitlyn Sommer
Marketing Director
kaitlyn.sommer@saemediagroup.com

Martha Tress
Recruitment Sales Manager
+1.724.772.7155
Martha.Tress@sae.org

REGIONAL SALES

North America

New England/Eastern Canada:
ME, VT, NH, MA, RI, QC
Brian Hines
+1.647.296.5014
brian.hines@saemediagroup.com

CT:
Stan Greenfield
+1.203.938.2418
greenco@optonline.net

Mid-Atlantic/Southeast/TX:
TX, OK, LA, AR, MS, AL, TN, FL, SC, NC, GA, DC, WV, VA
Ray Tompkins
+1.281.313.1004
ray.tompkins@saemediagroup.com

NY, NJ, OH:
Ryan Beckman
+1.973.409.4687
ryan.beckman@saemediagroup.com

PA/DE:
Desiree Stygar
+1.908.300.2539
desiree.stygar@saemediagroup.com

Midwest/Great Lakes:
IN, MI, WI, IA, IL, MN
Chris Kennedy
+1.847.498.4520, x3008
chris@didierandbroderick.com

Midwest/Central Canada:
KS, KY, MO, NE, ND, SD, ON, MB
Bob Casey
+1.847.223.5225
bobc@caseyreps.com

CA, WA, OR, AZ, NM, Rocky Mountain States:
Tim Powers
+1.908.892.2838
timothy.powers@saemediagroup.com

International

Europe:
Sven Anacker
+49.202.373294.11
sa@intermediapro.de
Sabine Schoett
+49.202.373294.13
ss@intermediapro.de

China:
Alan Ao
+86.21.6140.8920
alan.ao@sae.org

Japan:
Shigenori Nagatomo
+81.3.3661.6138
Nagatomo-pbi@gol.com

South Korea:
Eun-Tae Kim
+82-2-564-3971/2
ksae1@ksae.org

Integrated Media Consultants

Daniel Barrett
+1.973.409.4762
daniel.barrett@saemediagroup.com

Patrick Harvey
+1.973.409.4686
patrick.harvey@saemediagroup.com

Todd Holtz
+1.973.545.2566
todd.holtz@saemediagroup.com

Rick Rosenberg
+1.973.545.2565
rick.rosenberg@saemediagroup.com

Erik Schenck
+1.973.841.6040
erik.schenck@saemediagroup.com

Jason Setti
+1.973.874.0271
jason.setti@saemediagroup.com

SUBSCRIPTIONS

+1.866.354.1125
AUE@OMEDA.COM

CASE struggles to fulfil expectations

The saying ‘Two steps forward, one step back’ describes the overall progress of CASE — Connected, Autonomous, Shared and Electrified vehicles and infrastructures. While electrification and connected technologies arguably have each taken a step forward, funding four industry-changing secular shifts in unison was always a lot to ask. The resulting investment headwinds are not surprising, given the added impacts of COVID, microchip and labor shortages, the Russia-Ukraine war, and inflation/higher interest rates dampening vehicle sales.

Viewed from 30,000 feet, CASE’s uneven takeoff trajectory has been governed by often unproven technologies being deployed within unrealistic timelines. OEMs and suppliers have devoted billions to the development and implementation of electrified propulsion in the major developed markets. Regulations have made the ‘E’ in CASE the highest priority. This includes battery-electric vehicle development and assembly, battery chemistry R&D, cell plants, strategic materials sourcing, downstream materials recycling and the required charging infrastructure buildout. The scale of investment and risk acceptance has been staggering.

The new vehicle platforms in ‘E’ are a key enabler, along with the ability to vastly increase (beyond Tesla’s track record) meaningful over-the-air (OTA) software updates. That’s the ‘C’ in CASE — making real-time improvements to software and modifying/opening vehicle functionality. The potential for ‘C’ to bolster customer satisfaction/convenience aligns well with emerging electric-vehicle development.

By comparison, the initial trajectories of the ‘S’ and the ‘A’ for CASE have been problematic. Vehicle sharing (the ‘S’) is highly dependent upon improved autonomous (‘A’) capabilities and, to a lesser degree, connected tech. The promise of Mobility as a Service (MaaS) as a sustainable business model depends on having driverless automation at SAE levels 4 and 5. Scores of OEMs and suppliers have reviewed the timelines and ROI for L4 and L5 MaaS and concluded that

Michael Robinet
Executive Director, Consulting, S&P Global Mobility

SAE Foundation Trustee

michael.robinet @spglobal.com

An uneven takeoff governed by unproven technologies and unrealistic timelines.

the ongoing investment, delays, and priority realignments are not worth their time. The recent dissolution of Argo AI is one example.

Some OEMs and suppliers continue to march forward on CASE’s elusive elements. But from an Autonomous perspective, the industry’s focus increasingly is on near-term deployment of Level 2 and Level 2+ (enhanced ADAS) capabilities. Driving the strategy shift are higher and more rapid investment returns, lower development costs and reduced deployment risks.

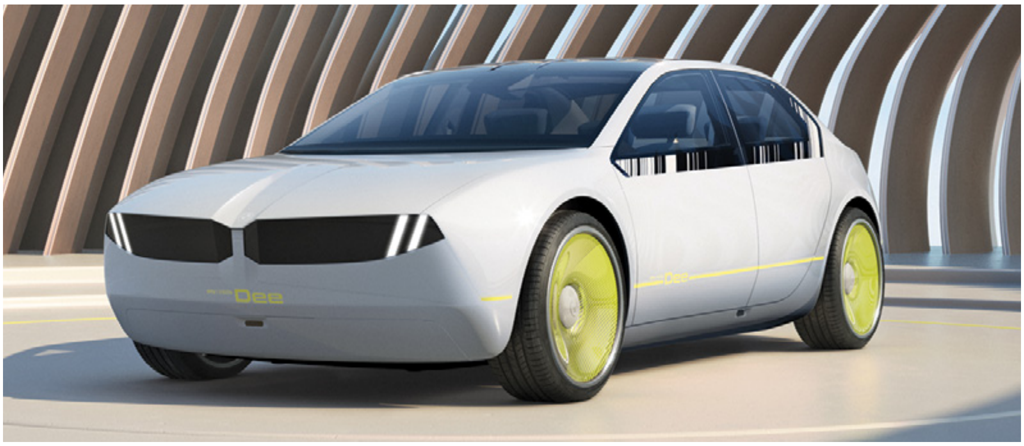
Regular updates to the S&P Global Mobility Autonomy Forecasts over the last 12-plus months underscore the movement in raising the safety and convenience levels of new vehicles using SAE Level 2 capabilities. But the latest enhancements to the Autonomy Forecasts introduce the Level 2+ breakout as the differences in functionality, strategy and vehicle content remain meaningful for both consumers and OEMs. Level 2+ includes Driver Facial Monitoring that enables some form of eyes-on-the-road, hands-off-the-wheel capability.

The incremental “hands-off” element of driver assistance may seem trivial, but competitive differentiation in this space is fierce. OEMs reckon they can increase brand and vehicle values with the driver convenience features, improved occupant safety, faster speed to market (with upgrades coming via OTA) and cost management. In 2022, it was estimated that vehicles equipped with Level 2 and Level 2+ total 43% of North American light vehicle production. That’s forecast to grow to at least 55% by 2030. Within this Level 2/2+ grouping, Level 2+ share will more than triple from an estimated 8% in 2022 to more than 30% by 2030.

In the end, CASE investments are both expensive and fraught with risk. Within the ‘A,’ OEMs are placing less risky, near-term bets on Level 2+ capabilities as they devote hefty investments toward the ‘E’, and reap the value of ‘A’ technology, with ‘C’ enhancements via OTA. Meanwhile, they wait for the ‘S’ business model to truly emerge. ■

BATTERIES

BMW readies move to structural batteries, '46120' cells



Behind the BMW i Vision Dee's razzle-dazzle, the concept is a serious tech showcase for next-gen batteries and propulsion, UX/HMI and BMW's' critical Neue Klasse architecture.

BMW

The technology below the smooth skin of **BMW**'s i Vision Dee concept car, unveiled at CES 2023, marks a major step forward in the company's electric-vehicle competitiveness. Models based on the automaker's Neue Klasse EV architecture will ditch today's rectangular prismatic batteries for the type of large, cylindrical-form-factor cells that **Tesla** is pioneering with its "4680" cells, so named for their 46 mm x 80 mm dimensions. For its sixth-generation EV batteries, BMW and its battery partners — including China's **CATL** and **EVE Energy** — will adopt even-larger cells of "4595" and "46120" sizes.

At a pre-CES media backgrounder held in Munich in December 2022, Martin Schuster, BMW Group VP for high-voltage batteries, said the new cells pack at least 10% more active battery material relative to their metal cases and are 20% more energy-dense.

For BMW's Neue Klasse platform, space and weight are saved by using the battery pack as a structural, crash-resistant chassis member: the entire floorpan yawns open until the pack fills the gap. That "pack-to-open-body" design will allow BMW tailor battery sizes to a wide range of vehicles and applications: Pack sizes can range from 75 kWh to a beefy 150 kWh, with motor output ranging from an estimated 268 hp (200 kW) to a dizzying 1341 hp (1000 kW). The design also saves more than 10 mm (0.39 in.) in vehicle height, reducing costs and lowering the center of gravity while improving aerodynamics. BMW executives, including CTO Frank Weber, said the goal is to squeeze more miles from every cell, not to cram ever-larger batteries aboard.

"Going big on cell power and extreme range is not the solution, because the size and weight penalty is counterproductive," Weber said. "Instead, we must get the best out of every watt-hour by further reducing rolling resistance, improving aerodynamics and increasing onboard energy efficiency."

Favoring the cylindrical form factor

Compared with more-volatile prismatic cells, whose myriad circuit connections make it harder to protect against runaway heat and potential fires, each heat-shielded cylindrical cell can be individually monitored and isolated to avoid thermal runaway, the engineers noted. The new layout also eliminates a modular structure that required removing the pack to access electronic controls — currently the chief source of BMW EV maintenance issues.

Next, an improved nickel-cobalt-manganese (NCM) chemistry reduces by 50% the cathodes' content of cobalt (pricey and often ethically sketchy in its sourcing), with 20% less graphite in the anode. Like other automakers, BMW will continue to beef up silicon content in anodes to boost efficiency and performance (BMW also repeated a bold claim to have a 100% solid-state battery in a BMW Group model by 2030).

Executives confirmed the Neue Klasse design also will support lithium-iron phosphate (LFP) cell chemistry for lower-end BMW Group models. LFP, rapidly gaining industry popularity, is less energy dense than the most advanced nickel-rich cells, but makes up for reduced range with lower cost, excellent safety and durability – and no cobalt or nickel whatsoever.

Add it up and BMW said its nickel-rich cells will boost driving range by 30%. With the company's highest-stamina EVs currently delivering more than 300 miles (483 km) of EPA-rated range, a 30% jump would let these high-performance machines cover roughly 400 miles (644 km), addressing both range and recharging anxieties. And with batteries responsible for a jaw-dropping 40% of the cost of every BMW EV, according to the engineers, the new cells and other efficiencies will cut BMW's battery costs by 50% at the pack level, they claimed. That raises renewed hopes for the "price parity" between EVs and conventional ICE models that's been promised but has proven elusive in showrooms.

BMW

With its next-generation EV architecture, BMW will transition away from the prismatic battery-cell format (rear) to more energy-dense cylindrical cells.

There's more in it for consumers. The Neue Klasse will match Tesla, **Hyundai** and **Kia** with a robust 800-volt architecture, for 30% faster DC fast charging at rates well beyond 200 kW, versus a maximum of 150 kW in current models such as the i4.

For a company that projects having 10 million EVs on the world's roads by 2030, the efforts can't come too soon. While Tesla has struggled to bring its large-format cells to mass production, BMW is confident it can scale up from laboratory to showroom, beginning with a pilot battery plant in Parsdorf, Germany. On the environmental front, the company claims the cells can deliver a 60% cut in CO_2 emissions over their full lifecycle.

Schuster said that effort extends into the very ground, via partnerships with lithium, nickel or graphite suppliers, and by developing robust supply chains (including in North America's free-trade zones) that barely exist today. Those supply chains suddenly have every automaker scrambling to set up shop here: President Biden's bipartisan infrastructure

Assembly of incumbent-tech high-voltage battery packs at the BMW plant in Dingolfing, Germany.

law makes EV consumer tax breaks conditional on final assembly taking place in the U.S., with critical battery minerals sourced from America or its free-trade partners.

"For now, North America is the most difficult place to obtain materials," Schuster acknowledged. "But we have to have localized materials."

BMW's global plans envision six cylindrical-cell gigafactories around the world – two each in the North American zone, Europe and China – each with at least 20 gigawatt-hours of capacity, for a total 120 GWh. In October, BMW and Japan's **Envision AESC** announced plans for an $810-million, 30 gigawatt-hour battery factory in South Carolina – powered by 100% net carbon-free energy – to supply cells to BMW's massive Spartanburg, S.C. factory. BMW plans to have Spartanburg cranking out a half-dozen EV models by 2030, ideally with enough affordable batteries and consumer tax sweeteners to keep business humming.

Lawrence Ulrich

PROPULSION

ZF introduces complete e-drive system for passenger, commercial vehicles

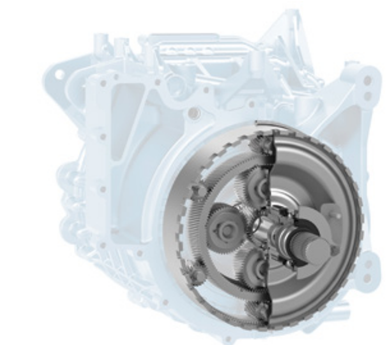
The **ZF Group** said its new e-drive system architecture that is more compact, offers greater energy density and is easily adaptable will appeal to manufacturers introducing new battery electric vehicles when it is ready for production in 2025. In late 2022, the company showed key details of the new modular-concept system that can be configured to run at 400V or 800V. Executives speaking to global media in a virtual workshop said the customization-friendly system that includes matched motor, inverter, gearbox and software would offer shorter development times for OEMs.

"ZF is positioned very well to meet both current and future challenges," said Markus Schwabe, product line manager of electric systems. ZF, traditionally a transmission powerhouse, has been making increasing investments in electrification and in 2019 began supplying the entire electric propulsion system for the Mercedes EQS SUV. For the new system, engineers focused on improvements in four metrics: cost, EV range, torque and power density.

The system is designed to be as plug-and-play as possible. ZF predicts that 80% of customer uses can be met directly off-the-shelf, with the remainder being easily customized to fit any application. One key to the new technology is that the different needs of, say, 400V and 800V systems, is handled on the controller chip and via inverters with individual power switches. The company asserted that this architecture results in fewer components than today's power modules. "We can serve different market requirements faster and more precisely," said Otmar Scharrer, head of electric drive technology development.

The system starts at 100 kW (134 hp) per axle and can go up to 300 kW (402 hp).

On its new motors, ZF engineers said that a new braided wiring design was a large contributor to increasing the power density of its systems. "Hairpin wiring, the state of the art today, was introduced five to seven years ago, [and]



ZF has improved on previous offset gearboxes by using two planetary gearsets to achieve a 50/50 power split.

requires hundreds of laser welding points," said Roland Hintringer, head of e-motor product lines. He said ZF's braided wiring is formed and braided in one step, saving time and requiring less space. "It only requires 24 welding spots," he said. The braiding also reduces the raw material used by 10%.

ZF engineers focused heavily on cooling as another path to increased power density. In addition to the water-cooled motor housing, cooling oil is pumped not only around the metal of the stator, but through slots in the braided windings themselves. Hintringer said the result is an 85% increase in peak performance and a 50% increase in power.

Getting power to the wheels is a new coaxial reduction gearbox that draws on the company's planetary-gearbox expertise to use two planetary gears to generate the desired axle ratio and a 50/50 power split. The bonus is that it also includes a fully integrated differential function, said Robert Peter, head of engineering product line for axle drives. Peter said that compared to two-stage offset helical gear solutions that have been in use since 2011, the new gearbox requires 25% less installation space, has higher power density and offers a 10% reduction in weight with 20% lower transmission losses. NVH is on par with offset-type gearboxes or better, he claimed.

Chris Clonts

BMW

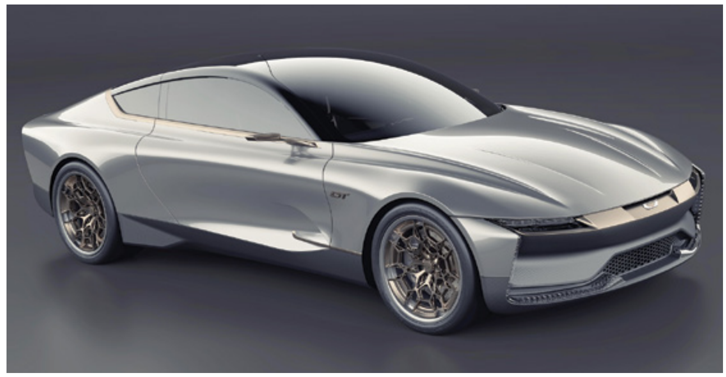
MANUFACTURING

A Divergent approach to vehicle development and production

Among the most intriguing vehicles on display at the 2022 Pebble Beach Concours D' Elegance was a pair developed by an obscure brand, **Czinger Vehicles**, and its parent company, **Divergent Technologies**.

The 21C V Max and Hyper GT that impressed the concours audience showcase Divergent Technologies' breadth of capabilities in design, engineering and production – a systems approach that is predicated on no specific designed tooling for components or assembly.

This has led to the Waterloo, Ontario, Canada-based company doing everything from developing its own topology-optimization software, called "Bi-directional Evolutionary Structural Optimization," to working with 3D-printer company SLM Solutions to develop a high-throughput additive manufacturing system, to developing many of the metal powders that are used to build parts. It also has created a robot-based automated assembly system and formulates the adhesives that are used for bonding.



The Czinger Hyper GT is a four-place vehicle that will be structurally based on AM and showcases the flexibility of Divergent's production system.

Full development

"We spent a number of years engineering the joint architecture," of the two show vehicles, said Mike Kenworthy, Divergent's CTO, in an interview with SAE Media. He said about 350 parts per vehicle were created using additive manufacturing (AM, or 3D printing). The system being used is the SLM NXG XII 60. It employs 12 1,000-kW lasers to produce parts at a rate that is 10 to 20 times faster than most service bureaus using the latest four-laser systems, Kenworthy said.

Kevin Czinger, founder and CEO of the company bearing his name as well as of Divergent Technologies, worked with SLM personnel to develop the machine. "On average, depending on build density and packing, we are printing around a kilogram to a kilogram-and-a-half [of components] per hour," he noted. The whole process is called the Divergent Adaptive Production System (DAPS). Although production of the first Czinger vehicle, the 21C planned for launch in 2023, is limited to a total build of 80 units, Kenworthy said that the DAPS is predicated on higher volumes.

The chassis of Divergent's 21C, produced using aluminum alloy components that are 3D-printed then adhesive-bonded.

BOTH IMAGES: DIVERGENT TECHNOLOGIES

This thinking led to the development of the adhesives that are used as the primary joining method. (The vehicle uses a limited number of mechanical fasteners.) Two types of adhesive are employed: UV-cured and heat-cured. The UV-cured adhesive is particularly important: during assembly it acts as a tack weld that holds the primarily aluminum parts (made from AL alloys that Divergent developed to have specific characteristics, e.g., crash-energy management) together during build in the robotic cell.

Kenworthy said the company tested "literally hundreds of adhesives on the market" and determined that none of them would meet the requirement that would provide what he calls "automotive-relevant cycle times and rates." The best UV-curing adhesive they found had a curing time of approximately 40 sec. The adhesive Divergent developed cures in about 3 sec. and, Kenworthy explained, can deal with the temperatures used when the primary structural adhesive is cured.

While most automotive OEMs currently are using AM for trim pieces, assembly jigs or small numbers of production parts, Kenworthy says Divergent is working toward hundreds of thousands of vehicle structure programs. In addition to Czinger, Divergent operates as a Tier One supplier. It currently has "around 20 active programs" with major OEMs, Kenworthy explained.

Electric vehicles? "There is a massive opportunity for additive manufacturing," he answered. "We can leverage it to reduce weight and improve the performance of those structures."

Steven Macaulay

ALTERNATIVE FUELS

'Electrofuels' that reduce Amazon's fleet emissions

Beyond the 100,000 new Rivian electric delivery vehicles it is acquiring through 2030, Amazon's current fleet of diesel vans will start using Infinium's electrofuel next year.

Amazon has a goal of having 50% of its shipments being made net-zero carbon by 2030. In 2021, more than 100 million packages were delivered to customers with zero-emissions vehicles and the company said that number will scale.

One of the retail and logistics giant's well-known initiatives is its pledge to purchase 100,000 **Rivian** electric delivery vehicles by 2030. Initial vehicles were delivered and put into operation in July 2022. In September, Amazon announced another initiative that by next year will replace diesel fuel in its internal-combustion delivery vehicles with ultra-low carbon 'electrofuels.' The supplier of that fuel to Amazon is Sacramento, Calif.-based **Infinium**.

As is the case with Rivian, Amazon has invested in Infinium through its $2-billion Climate Pledge Fund, which was established to help Amazon meet its goal of being net-zero carbon by 2040. Amazon will initially use electrofuel in its "middle-mile fleet," trucks that operate from vendors and its fulfillment centers to its sortation and delivery stations.

Proprietary process

The Infinium fuel is said to reduce greenhouse gases by some 95% compared with fossil fuels. The company is building an electrofuels-production operation in Texas that will use 'green' hydrogen — produced with renewable power — and 18,000 tons of recycled carbon waste to produce the fuels.

According to Infinium CEO Robert Schuetzle, the fuel is a combination of CO_2 and "green" hydrogen. He said to make the blend, "Infinium uses its proprietary-technology production process to combine industrial carbon-dioxide waste that would otherwise be emitted into the atmosphere with green hydrogen produced from renewable power. This is done through a two-step catalytic reaction, using proprietary catalysts to transform the CO_2 and H_2 into diesel, jet fuel and other drop-in fuels and chemicals."

Schuetzle said his company has spent more than a decade developing its fuel-production technology, which is unique because "it provides an end-to-end production process on-site, requiring no post-processing or refining in the base design." He described the electrofuels as "ultra-low-carbon liquid transportation fuels" that do not require a different kind of fuel tank in the vehicles. The fuels are "drop-in replacements" for traditional fossil-based fuels and can use today's incumbent storage, tankage and transportation infrastructure.

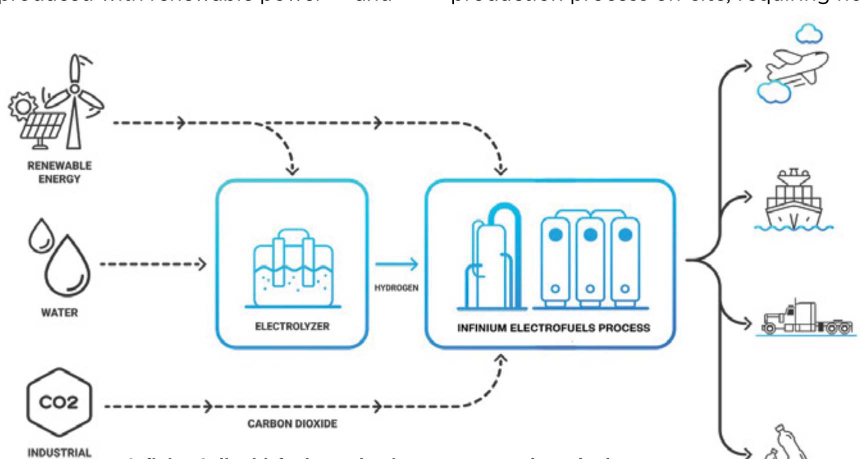
Multiple engine applications

Energy content of the Infinium fuel is similar to its fossil-based alternatives. The company currently produces diesel products that can be used in today's diesel engines and replacing gasoline is not a focus, Schuetzle explained. Diesel engines do not need to be modified (injectors, seals, etc.), he asserted. The fuel also can be used in marine and aircraft engines without modifications.

Regarding emissions, Schuetzle said the Infinium electrofuels reduce $CO2_2$ emissions by upwards of 100% over petroleum fuels and contain no sulfur. Their particulate (PM) constituent also is lower, he claimed. Oxides of nitrogen (NOx) and sulfur oxides (SOx) also are "lowered" when combusted compared to a traditional fossil-based fuel, the company said.

The Infinium fuel's production costs are based on multiple site-specific input factors, he said. The company expects that as electrofuels begin to scale and key production costs are reduced, their cost will become more competitive with other options in the marketplace.

Steve Macaulay



Infinium's liquid-fuels production process catalyzes hydrogen made from renewable energy and carbon dioxide to produce diesel, jet fuel and a naptha used for plastics production.

FROM TOP: AMAZON; INFINIUM

Toyota punches up the Prius

The 2023 Toyota Prius is fully redesigned with low and sleek bodywork that substantially departs from previous generations.

An undeniable technical achievement since its U.S. launch for the 2001 model year, **Toyota**'s Prius never has been able to shake its weenie-mobile reputation. It's an image formed largely by the combination off oddball, aerodynamics-first styling and the pursuit of ultimate fuel efficiency via low-power propulsion.

With EVs looming as the propulsion endgame and attention to the 20th-century concept of "fuel-efficiency" waning, Toyota's said "enough!" The 2023 Prius bodywork now is smooth, low and sleek, so different that there's virtually no visual connection to its trippy forerunners. Under the hood is a larger, powered-up 4-cyl. engine and similarly boosted drive motor that, combined, take the Prius to 194 hp (196 hp for AWD models) — a 60% jump over the wheezy 121 combined hp of its predecessor. Almost paradoxically, though, the 2023 Prius still sips gasoline at pretty much the same pace — up to a 57 mpg (4.1L/100 km) combined rating for the most-efficient LE trim in front-wheel drive. The low is the 49 mpg (4.8L/100 km) combined rating for the top-trim XLE in AWD layout.

Chief engineer Satoki Oya told SAE Media that the new Prius' revised Dynamic Force 2.0L Atkinson-cycle 4-cyl. (M20A-FXS) enjoys the same exemplary 41% brake thermal efficiency (BTE) as the previous, fourth generation of the engine. But Lisa Materazzo, group vice president of marketing, said the new car's design, rather than its efficiency, may be the attribute to lure the younger buyers Toyota hopes to attract.

TNGA revised

The 2023 Prius' slippery new profile displays its most striking dimensional change, a 2-inch (51-mm) lower roofline. The new car also is 1 inch (25.4 mm) wider and slightly longer, with wheelbase increased by 2 in. The windshield rake would be considered fast for nearly any vehicle but is particularly so for a Prius. Oya said the new shape's drag coefficient – 0.27 Cd – is on paper worse than the previous Prius' 0.24, but the sharper front end and grille create less frontal area, reducing CdA and effectively negating the detrimental overall aerodynamic effect of the new bodywork.

The new car rides on what Toyota said is the second generation of the Toyota New Global Architecture (TNGA) platform for C-segment vehicles, or TNGA-C. Oya said for the Prius, the architecture has a revised front MacPherson strut suspension, crossmembers are different and the rear portion of the floorpan is significantly altered to accommodate the new fuel tank and lithium-ion battery pack (the Prius no longer will use nickel-metal hydride batteries).

Oya said the target was to reduce weight of the underbody to help offset the 2023 Prius' larger engine and the use of bigger wheels and tires (17-inch for the base LE trim and 19-inch for XLE and Limited models). Curb weight nonetheless is up slightly for the fifth-generation Prius, ranging from 3097 lb. (1404 kg) for the front-drive LE to 3340 lb. (1515 kg) for an AWD Limited.

More engine, more motor

Nobody will carp that the new Prius doesn't perform better – much better. The 2L direct- and indirect-injected 4-cyl. develops 150 hp; the previous 1.8L engine managed just 96 horses. The new 2L engine's hike to a 14:1 compression ratio led to concern about required fuel octane, but Toyota assured journalists at the media introduction that maximum performance is achieved on 87-octane regular unleaded gasoline.

The central electrified component of the hybrid system, the permanent-magnet AC electric motor Toyota refers to as motor-generator 2, also is vastly upgraded. Thanks largely to a doubling of magnets to six per pole, power output increases to 111 hp, a 40-hp boost compared to the outgoing Prius' MG2. Torque also is enhanced by some 20%, to 152 lb-ft (206 Nm) versus the previous 120 lb-ft (163 Nm), yet the new design means the motor is smaller and lighter. The company said the 222-volt/4.06 amp-hour lithium-ion battery pack is 14% lighter yet 14% more powerful.

The Prius cabin is completely redesigned to include an instrument cluster directly in front of the driver and the gear selector in a more conventional location.

BOTH IMAGES: TOYOTA

The power quotient is even better for AWD models ($1400 extra for all trim levels). The rear axle now is driven, when needed, by a permanent-magnet motor that generates 40 hp and 62 lb-ft (84 Nm) — big increases over the meager 7 hp and 40 lb-ft (54 Nm) delivered by the previous AWD Prius' induction motor acting on the rear axle.

It all translates to "real-car" acceleration, with Toyota's figures indicating a 0-to-60 mph (0-to-97 km/h) time of 7.2 sec. for FWD models and a properly brisk 7 sec. for AWD. The only letdown is from the Prius' electronically controlled continuously variable transmission. The eCVT is reasonably quiet and cooperative in responding to most accelerator-pedal inputs, but full-throttle acceleration generates the signature CVT wail that it seems engineers could do little to dull.

All-new cockpit

The fifth-generation Prius' cabin is completely revised, with the most obvious change being a switch to a "conventional" instrument cluster in front of the driver and a large central touchscreen handling most ancillary display requirements. The digital instrument panel is located at what for some drivers might be an odd focal distance, however, and its comparatively small size — combined with the plethora of possible icons and other information it's tasked to display — can require too much concentration from the driver. And the odd height- and rake-adjustable nacelle in which the steering wheel sits seems to require placing the wheel distractingly low if the instrument cluster is to be seen.

In the center, standard screen size is 8 in. (203 mm), with a 12.3-in. (312-mm) display standard for Limited and optional for XLE. The substantially lower roofline means headroom might be at a premium for some occupants, with the rear seat seeming particularly trim. The new one-piece window for the hatch doesn't provide the most expansive rearward view (perhaps one reason why a digital rearview mirror is available), and the lower roofline's effect on cargo space also seems palpable — the up-trim XLE and Limited offer just 20.3 cubic feet (0.57 cubic meter) of seats-up cargo space versus 27.4 cubic feet (0.78 cubic meter) for the outgoing Prius.

Pricing runs from $28,545 for the LE front-drive to $36,960 for an AWD Prius in the top Limited trim. Materazzo said the plug-in Prius Prime will be available sometime in the spring of 2023. The 2023 Prius is built in Tsutsumi, Japan.

Bill Visnic

High-performance hybrid headlines Lexus's re-engineered RX lineup

Electrification is a pillar of Lexus's "next chapter." The fifth-generation Lexus RX progresses this objective, offering four new powertrains including a high-performance hybrid and the company's first-ever plug-in hybrid (PHEV) – though the latter is not available in the U.S. at launch.

Other "foundational elements" include bold design, intuitive technology and Lexus driving signature. Experienced first-hand by SAE Media on the hilly, twisty terrain north and west of Santa Barbara, the 2023 RX, which rides on the lighter, stiffer GA-K platform that also underpins the smaller Lexus NX, hits on all marks.

A new vertical-standing trapezoidal grille sets a bold design statement for the 2023 RX. For F Sport models, front vents regulate airflow around the tires, aiding straight-line stability.

Overall, the new RX is just 4.9 kg (11 lb) lighter than the previous generation, but the GA-K platform is 90 kg (198 lb) lighter than its predecessor. Its center of gravity is 0.6 inches (15 mm) lower. Panel thickness has been reduced on the side members and front and rear door assemblies thanks to the use of higher-strength steels such as 1180-MPa grade on side rockers, 1470-MPa for the roof and 2-GPa hot-stamp steel for B-pillars.

Additional bracing at the radiator support, center floor, rear suspension towers and back door opening improves overall rigidity. Although the 2023 RX retains its overall length at 192.5 inches (4890 mm), its 112.2-inch (2850-mm) wheelbase is 2.36 inches (59.9 mm) longer and its track is widened by 0.59 inches (15 mm) to 65 inches (1651 mm) in front, and by 1.77 inches (45 mm) to 66 inches (1676 mm) at the rear. The new RX overall is 1-inch (25-mm) wider and 0.4-inch (10-mm) lower than before, giving it a more muscular stance.

Lexus says its engineers thoroughly revised the suspension to better absorb high-frequency vibrations and shocks. Up front are MacPherson struts. An all-new five-arm multi-link rear setup reportedly is more compact, which for hybrid models aids battery-pack placement beneath the rear seat while yielding more legroom (37.36 inches/948.9 mm) for rear passengers and additional cargo volume (29.6 cu. ft./0.84 cu. m. with all seats up).

First-ever RX 500h

While the RX 350h hybrid model was designed with efficiency in mind, developers envisioned drivers having a more visceral connection with the all-new RX 500h F Sport Performance AWD. A 271-hp (202-kW) 2.4-L turbocharged inline-four is matched to a six-speed automatic gearbox and integrated power control unit and electric motor. An 80-kW rear eAxle consisting of an inverter and motor provides power to the rear wheels.

Lexus opted for nickel-metal hydride batteries in both the 500h (288 V, 240 battery cells) and 350h (259 V, 216 cells), claiming their overall performance is comparable to that of lithium-ion batteries. Engineers will continue to evolve both battery types and use them accordingly, a spokesperson said.

In total, the system produces 366 hp (273 kW) and 406 lb-ft (550 Nm) – figures worthy of the vehicle's F Sport Performance nomenclature. Lexus's more-traditional hybrid, the RX 350h, couples the fourth-generation hybrid system with a 2.5-L four-cylinder Atkinson-cycle gasoline engine and CVT, resulting in a total system output of 246 hp (183 kW) and max. 233 lb-ft (316 Nm).

The RX 500h features a new Direct4 AWD system that utilizes the rear eAxle to provide nearly double the max output of the MGR (motor at rear axle) in the eFour AWD system employed on the RX 350h and the RX 450h+ plug-in hybrid model. Relying on sensors for wheel speed, acceleration and steering angle, the "performance-oriented" Direct4 adjusts the driving force to the front and rear wheels between 70:30 and 20:80.

Engineers explained that during departure and straight-line acceleration, the system controls the front-to-rear ratio between 60:40 to 40:60 "to suppress

RX 500h Sport Performance cabin.

BOTH IMAGES: LEXUS

vehicle pitching and provide a direct acceleration sensation." When cornering, the system distributes torque closer to the front (70:30 to 50:50) at the start of steering and closer to the rear (50:50 to 20:80) when exiting a corner. The result of this seamless transitioning: minimal body movement and extremely smooth turns that reminds this is still primarily a luxury vehicle but with a healthy dose of dynamism.

Aiding maneuverability is an exclusive-to-RX 500h Dynamic Rear Steering (DRS) system that enables the rear wheels to turn up to 4 degrees, in phase or counter-phase to the front wheels depending on speed. F Sport models offer an Adaptive Variable Suspension (AVS) system that uses linear solenoid-type actuators to modify shock absorbers' damping force based on driving operation and road conditions.

While the RX 450h+ PHEV won't be available in the U.S. until later (production-year timing was not announced), other markets will launch with the PHEV, a spokesperson said. RX's first plug-in powertrain combines the 2.5-L four-cylinder engine with an 18.1-kWh lithium-ion battery and rear eFour AWD motor.

In the RX 350 (FWD/AWD), the 2.4-L inline four turbo realizes higher torque and output – 317 lb-ft (430 Nm) and 275 hp (205 kW) – thanks to technologies such as a center injection system for more stable combustion, spherical lipless pistons for high-speed combustion, and a continuously variable capacity oil pump. The eight-speed Direct Shift-8AT offers improved shift control, and the on-demand eFour AWD varies front-to-rear driving force from 75:25 to 50:50.

Safety and convenience

As expected for a luxury SUV starting at $48,550 for the RX 350 FWD – $62,750 for the 500h F Sport Performance AWD – there are driver-assist and safety technologies aplenty. Lexus was quick to differentiate between the RX's "convenience" versus safety features, for legal purposes. For example, Traffic Jam Assist is categorized as a convenience feature since it's optional and not part of the Lexus Safety System+ 3.0 that is standard on all RX vehicles.

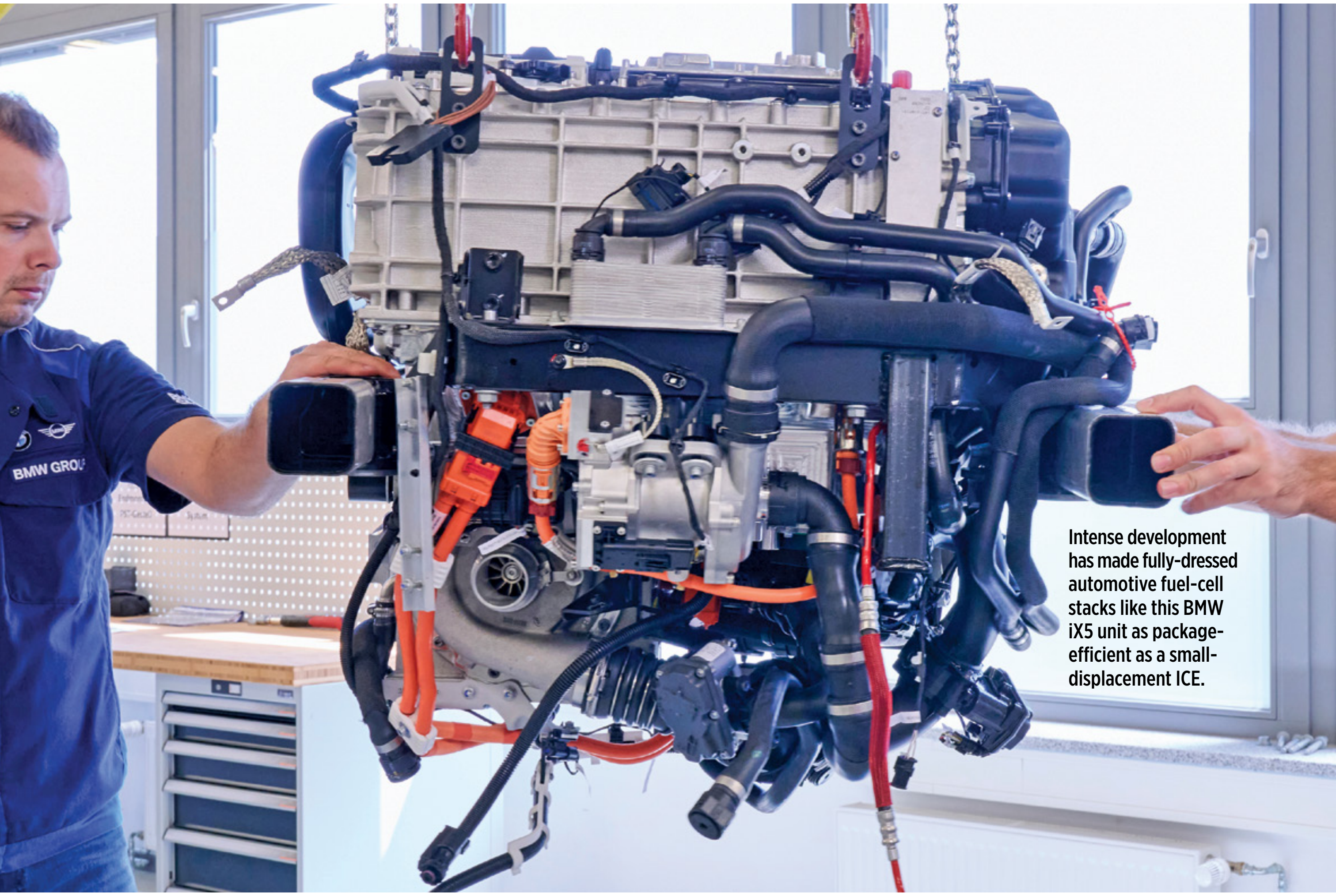
Lexus Safety System+ 3.0 provides additional features and an available driver monitor system. Pre-Collision System (PCS) can detect a potential frontal collision and prepare Brake Assist for increased brake force, in some cases automatically braking the vehicle to a stop. Enhanced radar and camera capabilities make it possible to detect a motorcycle or bicyclist in daytime and pedestrians in daytime and low-light conditions. PCS has left-turn intersection detection capability for a pedestrian and vehicle.

DRCC with Curve Speed Management works in conjunction with LTA to help drivers stay centered in their lanes. Lane-recognition performance reportedly has been enhanced to realize smoother and less-disruptive steering support. Curve-speed reduction is unable to be turned off, Lexus said, but sensitivity can be adjusted via the touchscreen.

The 2023 RX is built at Toyota Motor Manufacturing Canada and Toyota Motor Kyushu. It went on sale in late 2022.

Ryan Gehm

TIME FOR HYDROGEN



Intense development has made fully-dressed automotive fuel-cell stacks like this BMW iX5 unit as package-efficient as a small-displacement ICE.

BMW

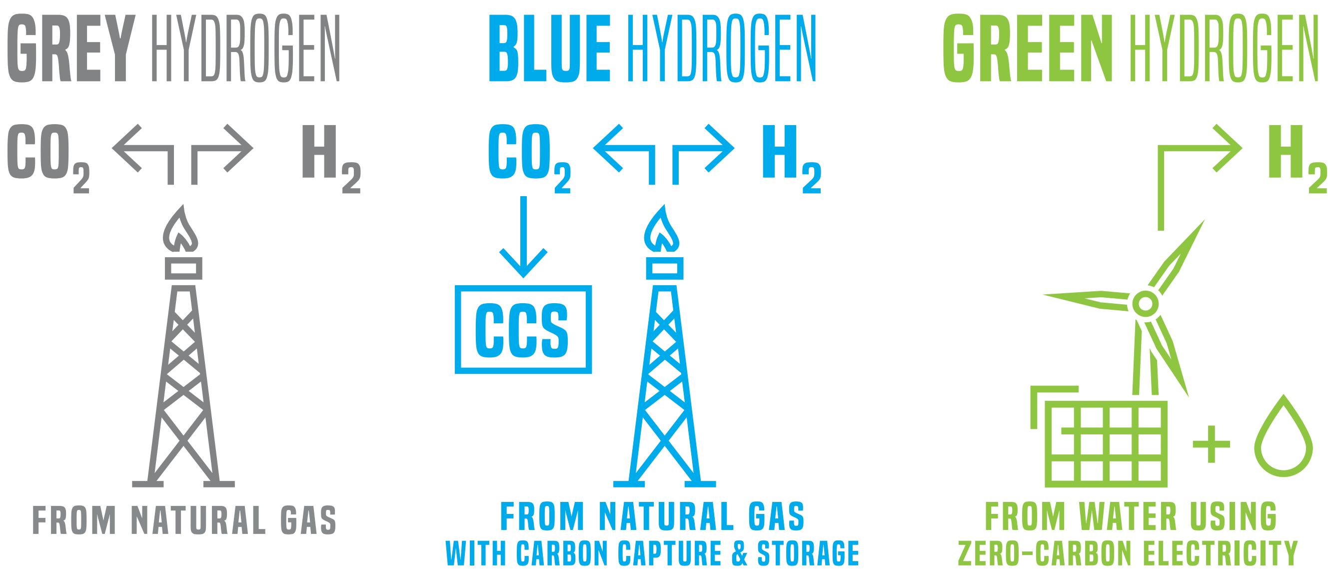
No longer '20 years in the future,' hydrogen and fuel cells are a vital, high-growth solution for carbon reduction across the transportation and other industry sectors.

by Lindsay Brooke

After decades of R&D, some false starts and a smattering of low-volume production vehicles, hydrogen has emerged as a vital enabler for carbon reduction across the transportation sector. In gaseous form, the lightest and most abundant chemical element is an efficient energy carrier and battery-like storage medium. When produced from decarbonized sources and used in fuel-cell systems, hydrogen can be a genuinely low- or zero-emission source of electricity.

Energy-grid experts increasingly see hydrogen as a valuable "knob to turn," broadening renewables' effectiveness by serving as a load-balancer for wind and solar. For vehicle engineers and customers, hydrogen fuel cells — with an energy-to-weight ratio 10X greater than lithium batteries — offers some key practical advantages over battery-electric propulsion. Time required to fill a 350- or 700-bar (5,000- or 10,000 psi) high-pressure storage tank is as quick as topping up with gasoline or diesel. And compared with the ponderous mass of large-EV battery packs — 3,000 lb. (1360 kg) in GM's Hummer EV and an estimated 10,000 lb (4536 kg) in Tesla's Class-8 Semi — a fuel-cell propulsion system with similar performance is a veritable lightweight.

Fuel cells' performance and efficiency are indeed a logical fit in commercial vehicles, according to a dozen industry experts interviewed for this article. The aim is to replace the reliable and durable heavy-duty diesel engine — admittedly a tough bogey. **Daimler**, **Hyundai**, **Kenworth** (using a **Toyota** fuel-cell stack), **Nikola** and **Volvo** have pilot fleets of hydrogen fuel-



The three most common hydrogen types by source, denoted in colors.

cell Class-8 semitractors in haulage operations. Fuel-cell power is beginning to appear in medium-duty truck chassis, buses (where China leads) and on up the GVW scale to huge mining machines, railway locomotives and ships. In the light-duty pickup segment, battery-electric has thus far been the clean-propulsion choice. However, engineers working on those programs at **Ford**, **GM**, and **Rivian** have told SAE Media that their trucks' all-season range as a function of payload and towing has fallen frustratingly short of IC-engine expectations.

Ford CEO Jim Farley spoke pragmatically about EV limitations — and hydrogen's benefits — during last fall's media intro of the 2023 F-250 Super Duty trucks. "If you're pulling 10,000-plus pounds, an electric truck is not the right solution," he asserted. "And 95 percent of our [Super Duty] customers tow more than 10,000 pounds. This is a really important segment for our country and it will probably go hydrogen fuel cell before it goes pure electric," Farley said.

Perhaps not coincidentally, at January's CES 2023, Patrick Koller, CEO of hydrogen storage tank supplier **Forvia**, told *Reuters* that he expects a fuel-cell pickup to be launched in the U.S. by 2025. It's worth noting that a 10,000-lb. (4536-kg) max towing rating also is available in the light-duty F-150 Lightning equipped with the 131-kWh extended-range battery — a $20,000 option.

Highlighting the challenge of electrifying the largest vehicles, propulsion systems and power generators, Dr. Gill Pratt, CEO of the Toyota Research Institute, noted that a typical battery-electric Class-8 truck will need an average of 1 megawatt of power to charge the 1-megawatt battery that powers the truck. "It's also going to take an hour to charge," Pratt explained. "At a typical truck stop, for example, for every existing diesel fuel pump that can fill a truck's tanks in six minutes, you would need 10 chargers operating at the same time. So, that's 10 megawatts of power you need to replace one diesel pump. It's just not going to happen. That's why hydrogen is such a big focus of our attention."

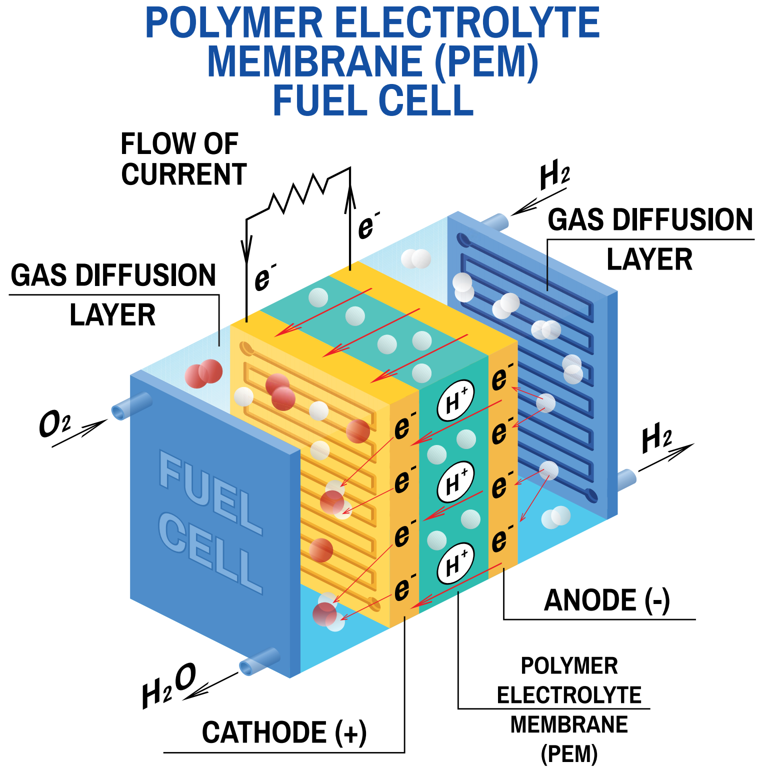
Last year, Toyota and partner Kenworth, using a fleet of Kenworth T680 semitractors powered by Toyota hydrogen fuel cells, demonstrated vehicle range, payload and fueling times that equaled those of comparable diesel-engined rigs in normal haulage operations. The project was supported by Toyota, **PACCAR** and **Shell**, and funded with a $41 million grant awarded by the **California Air Resources Board**.

Demand, development, investment

Google any combination of "hydrogen, fuel cells, vehicles, automakers, suppliers, and markets" and it yields screens full of news on investments, partnerships and joint ventures, mergers and acquisitions, vehicles, technologies, hydrogen generation, facility expansions and research. "Momentum in terms of investment and development is super strong, and it's increasing," observed Dr. Byron McCormick, former executive director of GM's global fuel-cell program. McCormick is revered at **Los Alamos National Laboratory**, where as a scientist in the early 1970s he launched the lab's fuel-cell R&D for vehicles. His seminal work at LANL and GM led to breakthroughs in cathode performance, specific power, cold-weather operability and overall stack durability that benefit industry engineers today.

A recent report by Boston-based **BCC Research** forecasts the global market for hydrogen fuel cells for all applications to grow from $7.5 billion in 2022 to $19.5 billion by 2027, at a compound annual growth rate (CAGR) of 21% during the period. While development activities are at a higher pace among commercial-vehicle

Charlie Freese, head of GM's global fuel cell business, sees common intermodal solutions driving hydrogen's growth.



Inside a typical PEM fuel cell, the most common type used in vehicles.

OEMs, a growing number of passenger-vehicle makers (and some who manufacture both) have launched or ramped up their hydrogen work in parallel with their electric-vehicle developments. Some analysts view these strategies as a hedge if EV sales, battery-chemistry advancements and strategic materials sourcing fall short of 2035 electrification goals.

Honda, for example, is collaborating with GM (which has built prodigious intellectual property in the field over 50 years) on fuel-cell development. Honda will launch U.S. production of hydrogen fuel-cell vehicles in 2024; the first model is a plug-in hybrid based on the new CR-V. **BMW**, which like Honda is following a multi-modal propulsion strategy, is building a pilot fleet of 100 iX5 Hydrogen SUVs. Fuel-cell technology and vehicle development continues with aggressive programs at Toyota and Hyundai, both among the industry leaders. GM itself has created a separate business unit, **Hydrotec**, that is moving to productionize a range of modular PEM (polymer-electrolyte membrane)-type fuel cells designed for use across multiple industry sectors, including the largest transportation and power-generation uses.

"Electrification and hydrogen fuel cells are very complementary to each other," observed Charlie Freese, executive director of GM's Global Fuel Cell organization. "The physics and technologies that go into making a very good battery are actually made better by what I hybridize in a fuel-cell application. A good fuel cell makes a battery stronger and vice-versa. We can optimize each one around the way they work best. What goes behind making them good for a very big truck also makes them good for the other applications."

While batteries serve as both energy storage and energy-recovery tools, Freese asserted that "for working vehicles, there is a very real issue: Bigger batteries take longer to charge or demand much higher-powered fast chargers." And battery mass frequently must be offset by payload reductions. "This is where hydrogen comes in," he said.

The OEMs' rekindled interest in hydrogen fuel cells has spurred significant investments (and profound business-model pivots) by suppliers including **Bosch**, **Schaeffler Group**, **Faurecia**/Forvia, **Mahle** and **Magna**, and supplier collaborations (recently **ZF** with **Freudenberg**, Forvia with **Symbio**).

Industry stakeholders aim to leverage federal incentives in Europe and North America. In the U.S., the Inflation Reduction Act of 2022 gives hydrogen production, storage and utilization multiple tax benefits. The law introduces a 10-year production tax credit (PTC) for "clean hydrogen defined by the lifecycle greenhouse-gas emissions rate achieved at a qualifying hydrogen production facility on which construction starts before 2033." It extends and creates Investment Tax Credits (ITCs) for clean-energy generation. Producers can opt for either credit type. The IRA defines "clean energy" by a maximum emissions rate of 4 kg of CO2e (carbon dioxide equivalent) per kilogram of hydrogen. It provides a substantial credit for clean commercial vehicles and expands the alternative-fuel station credit to help grow the number of hydrogen fueling stations. Under the IRA, the hydrogen must be produced in the U.S.

"Government can help kick-start this, but then investors must see a viable return," McCormick observed. "Clearly that is occurring."

"If you're pulling 10,000+ pounds, an electric truck is not the right solution."

H_2 in IC engines

While enormous progress in developing fuel cells, vehicle systems, and hydrogen storage and generation solutions has been made and continues, challenges remain — but engineers are confident they can be addressed this decade. Hydrogen as IC-engine fuel, substituting (with modifications) for diesel fuel in commercial-vehicle, stationary and marine diesels, is controversial. The concept appeals both to diesel-engine manufacturers and some fleet/equipment operators as a near-term step while electrification issues are sorted out. Hydrogen ICEs have been a focus of various OEMs, notably Daimler (which offered a limited run of H_2-fueled passenger cars), Toyota and **Cummins Engine**, which is developing its own fuel cells but also sees great promise for hydrogen with its diesel engine platforms.

Fuel-cell pioneer McCormick quickly disregards burning hydrogen in a combustion engine: "They tend to make less specific power and are thus less efficient than diesel," he told SAE Media. "One reason fuel cells match so well with H_2 is that they're at least 2X more efficient than combustion engines. So they make up in efficiency what they lose in more-challenging [fuel] storage."

Veteran combustion-engineering researcher Dr. David Foster at the University of Wisconsin-Madison, notes "aspects of hydrogen as a fuel that are really great. No carbon. Flame speeds are high. You can go very, very lean with hydrogen, which is good. NOx is reduced and you may be able to meet NOx emissions without aftertreatment. Going very lean, with lots of boost, you can start to recover some, but not all, of your max load limit.

"Viewing it as a system, there are challenges," Foster admitted. "The really high energy density that comes with each injection of liquid fuel into a cylinder is very difficult to replicate with hydrogen because you're injecting a gas." He noted ongoing work by Mahle, with its jet igniter, that's trying to overcome the limitations. Hydrogen also causes metal embrittlement "so there are some materials issues to deal with. Not trying to belittle the hurdles, but I classify these as engineering challenges. In the end, there is nothing that's a stopper for using hydrogen in an IC engine."

Cost-reduction crusade

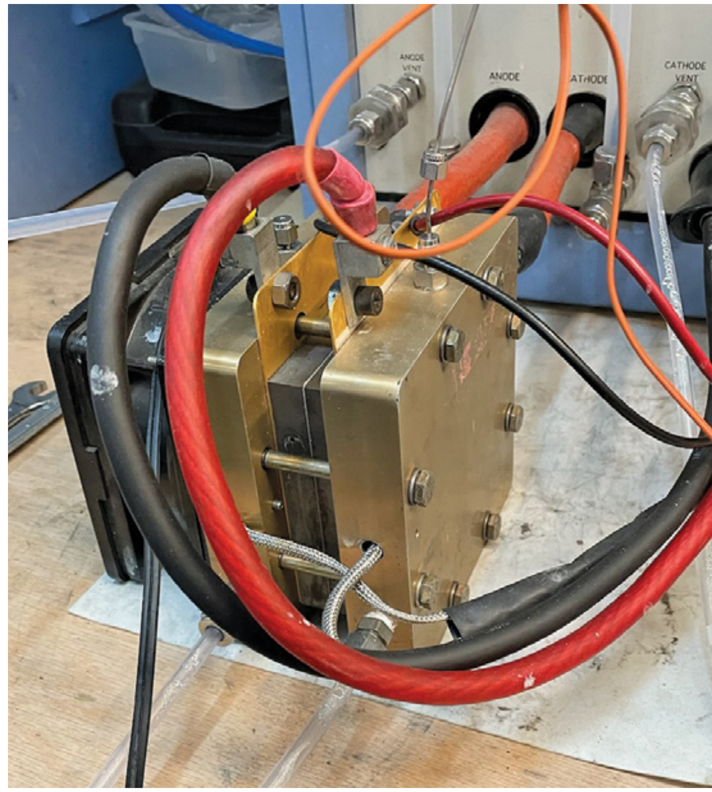
Engineers working in fuel-cell development who spoke with SAE Media believe most of the technological hurdles of the stack and its chemistries and ancillaries have been overcome. Continuing to prove durability and cost reduction are near-term focuses, as are robust and durable sealing solutions from source to end use: the tiny hydrogen molecules are notorious escapees. The major cost reductions that everyone is working on are a function of industrialization of internal components and hardware. "For a long time, a big concern was the cost of platinum [catalyst for the hydrogen and oxygen reactions, determined by the U.S. Dept. of Energy to represent 40 percent of overall cost at 500,000-unit/year volumes]," noted Pratt at Toyota. "We've managed to lower that amount in our latest version and we will keep on doing that with future versions."

GM HYDROTEC

Fuel cell architecture lends itself to modular designs that are easily scaled for various applications. GM Hydrotec 'power cubes' (shown) contain more than 300 fuel cells with integrated thermal and power management. Each is capable of generating +80 kW. They're designed to be arrayed in multiple units per vehicle depending on power requirements. A Class-8 semitractor requires 2-3 modules, a railway locomotive up to 25, to generate 3.3 MW. Aircraft and stationary power are also in the works.

In working toward platinum-free catalysts, innovators are looking to reduce the platinum loading per fuel cell. One of them is **Pajarito Powder**, a manufacturer of fuel cell catalysts and electrolyzers. During a visit to the company's Albuquerque, New Mexico, facility, company CEO and co-founder Tom Stephenson explained to SAE Media that Pajarito's quest is to make the diminishing quantities of platinum in each fuel cell more efficient. The black catalyst powder Pajarito developed in a collaboration with LANL and the **University of New Mexico** (which licenses the technology to Pajarito Powder) is under evaluation within the fuel-cell industry. Stephenson believes his company's patented technology will reduce fuel-cell catalyst costs by half. One

Gill Pratt of the Toyota Research Institute is bullish on continued tech improvements to lower stack costs.



At Parjarito Powder's prototype lab, a fuel cell assembly containing the company's unique catalyst chemistry undergoes a bench test.

Pajarito investor, Hyundai, is helping to fund a catalyst manufacturing facility that will use the company's VariPore process.

Costs also can be mitigated by design-engineering the system for its specific application. "Every electrochemical cell has some resistance to it, so the higher the power draw or current, the greater the resistive losses that occur within the cell," Pratt explained. "The stack's efficiency peaks under light power draw and decreases as the power draw further increases. You can use a stack that is bigger, to give higher efficiency. Or you can use a smaller stack, which is lower cost, lower mass, and fits better in the vehicle, but its efficiency will be lower unless the platinum loading is increased. Finally, we can vary durability with different aspects of the design, which affects cost ," he noted.

Fuel cells offer many "dials to turn" to optimize the system, the experts state. It comes down to the amount you want to spend on initial system purchase, versus its operating cost. To optimize total cost of ownership, "you weigh them against each other," Pratt said.

Electrolyzers' role

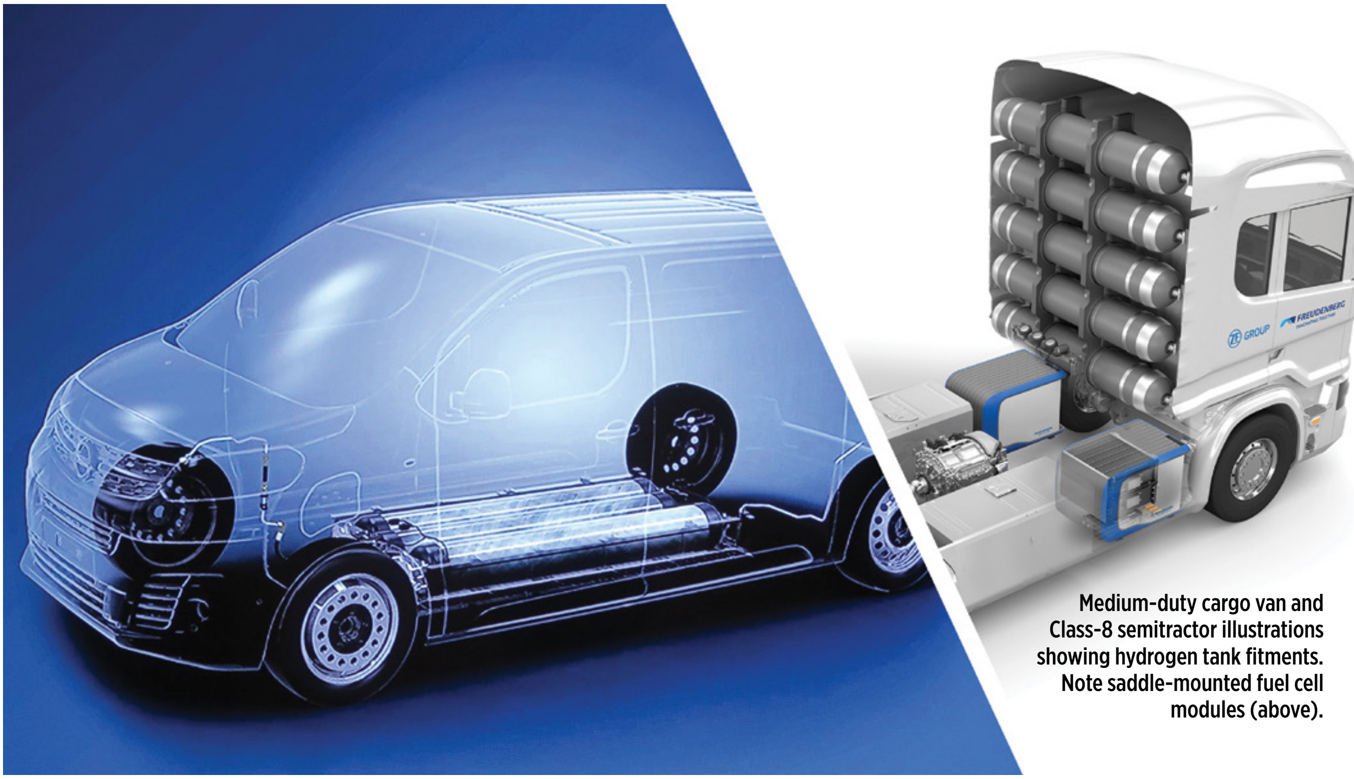
Hydrogen is primarily produced by the reforming of conventional hydrocarbons, typically natural gas (the so-called 'grey' hydrogen in the accompanying graphic). Electrolysis, a process in which an electric current is run through water to produce streams of hydrogen and oxygen gases, is gaining share in the hydrogen-production market due to its ability to generate the gas carbon-free if renewably-sourced electricity is employed. McCormick calls the electrolyzers "the way forward" in making fuel cells a truly zero-emission source of electricity, when the hydrogen is produced from decarbonized sources.

"Electrolyzers are inevitable," said GM's Freese, a 30-year veteran of propulsion-systems technology development. "All the 'green' energy like wind and solar on the grid introduces cyclical behavior and irregularities in supply-and-demand that end up causing complexity to the grid that makes it difficult to manage. The only way to manage it may be to overcapacitize the grid for everything, then underutilize the assets you put on the grid. But that's not economical. You can do that on a transition, but it can't be sustained long-term to operate an efficient grid."

What's needed to balance the grid and run it at optimum levels, Freese asserted, is the ability to store energy for long periods of time — take it off the grid when there isn't natural demand for it. "Hydrogen is an excellent way to provide that energy storage, if you have electrolyzers to take the energy off the grid on demand."

Freese noted that the optimum type of electrolyzer for this uses the same PEM-based technology that GM and most others use in their fuel cells, but with the chemical process running in reverse. In 2022 GM and **Nel Hydrogen U.S.**, a subsidiary of Norwegian company **Nel ASA**, began collaborating on more efficient, lower-cost and scalable electrolyzers that then can be used as a way to do distributed off-take power agreements with the grid. "It will also enable hydrogen to be produced closer to the point of use for fleet refueling and

FROM LEFT: TOYOTA; LINDSAY BROOKE



Medium-duty cargo van and Class-8 semitractor illustrations showing hydrogen tank fitments. Note saddle-mounted fuel cell modules (above).

dispensing to retail outlets," Freese said, noting that transportation is a significant chunk of hydrogen's cost. Lowering the cost of electrolyzers "is lowering the cost of making the fuel from renewable electrical sources," emphasized Pratt.

Infrastructure

For hydrogen and the myriad of fuel-cell applications to be successful, a robust infrastructure for hydrogen generation and distribution is necessary. It's the same scenario with EVs (including billions in government support), except they are entering the market with a basic electrical grid already in place. By comparison, hydrogen is starting from scratch.

The infrastructure build-out "cannot be done only by the government," McCormick said. "It must be able to produce an acceptable and timely return on investment."

Freese and Pratt agree that the key to a ubiquitous and accessible hydrogen-supply network are the synergies being developed from adjacent markets — intermodal rail, marine terminals, truck terminals, airports.

"There is already an economic model for forklift fleets that favors fuel cells, as GM now uses in some of our 3-shift plants," Freese explained, "with the same types of behaviors related to a big commercial vehicle: fast refueling, uptime requirements, low maintenance and the ability to generate power to do work. Once you have the hydrogen in place, what else comes into a plant or warehouse? Trucks. It's an intramodal-freight node that can share infrastructure. Then the trucks go to the railyard, whose infrastructure can refuel both the trucks and the locomotives. They also go to ports and airports, where the same intramodal fuel sharing can be done. It creates a tailwind for fuel-cell adoption once you get to the critical mass out there."

The nodal strategy to building out the hydrogen infrastructure creates high-volume usage, which in turn leads to investment worthiness," McCormick maintains. He points to investors already creating funds and structuring a hydrogen-supply rollout on major freight corridors. Personal fuel-cell-powered vehicles would come last in this evolution because until sufficient numbers of vehicles are on the road, "the investment doesn't pay out in a timely manner."

But the boom in hydrogen investment also is driving other concepts for hydrogen distribution. A new California-based company, **Universal Hydrogen**, proposes shipping hydrogen like dry freight, using dedicated road trailers, as company CEO and co-founder Paul Eremenko detailed during a recent presentation. "Unless you have a need for it, there is no reason to build pipelines," added Toyota's Pratt.

Going forward toward 2030, hydrogen and fuel-cell technologies will be an increasingly critical piece of global de-carbonization solutions. "We always worried about whether hydrogen could be coming down to where it's actually competitive with offsetting the petroleum-based fuels," commented GM's Freese. "There are pathways to do that now." ■

FORVIA AND ZF-FREUDENBERG

Quicker pathways to reduce transportation's CLIMATE IMPACT

Reducing U.S. vehicle emissions will require policies that support a variety of alternatives to fossil-fuel-burning, non-hybrid vehicles. 'Perfect' should not be the enemy of 'good.'

by Dave Foster, John Koszewnik, Wallace Wade and Ward Winer

Current U.S. energy policies are laser-focused on addressing climate change — as they should be. Meanwhile, 2022's soaring gasoline prices showed that U.S. dependence on foreign oil continues to be a significant vulnerability for the economy and national security. Policy options that tackle both issues — reducing climate-warming carbon emissions as well as oil dependence — currently center on encouraging the manufacture and purchase of battery electric vehicles (BEV).

Fully deployed, BEVs could reduce transportation-related emissions to the lowest possible level. But this strategy alone does not recognize some of the limitations of BEVs, nor the advantages of other climate-friendly technologies. Expanding current policies beyond their focus on BEVs would engage more of the U.S. in the transition to lower emissions on a quicker timetable.

As engineers who have worked in academia and the auto industry, we see policy opportunities that could make transportation cleaner and cheaper more quickly. These opportunities can and should be taken during the transition to a fully sustainable zero-carbon energy system.

Government policies directed at lowering carbon emissions balance multiple tradeoffs involving fuels, infrastructure and vehicles. Sorting through these tradeoffs involves considering not only the carbon emitted by a transportation technology, but also emissions involved in the vehicle's manufacture and disposal, as well as the production of the fuel or electricity it uses. Such lifecycle analyses (LCA) provide a more accurate picture of the environmental impact of alternative technologies. They can play a crucial role in helping choose transition technologies that minimize total carbon emissions during the nation's transition to a sustainable future.

The LCA prepared by the **International Council on Clean Transportation** (ICCT), an independent nonprofit environmental advocacy group, offers useful insights. The ICCT's data compare today's baseline level of carbon emissions from vehicles solely powered by gasoline-fueled IC engines, which constitute 90% of new-vehicle sales in the U.S., to other combinations of power systems and fuels. BEVs using renewable energy clearly are the most environmentally friendly alternative, even though they are not truly zero-emission when all factors are considered.

The current approach to addressing climate change focuses primarily on the endgame: taking steps to maximize the number of BEVs on the road as quickly as possible. However, an alternative approach is to focus on more rapidly replacing fossil-fuel-burning, non-hybrid vehicles on the road with multiple vehicle and fuel alternatives that reduce emissions. We believe that such policy options are worth exploring as they could reduce CO_2 emissions on a quicker timetable.

The power of "second-best"

Although BEVs work extremely well for some vehicle owners and applications, they don't work for everyone. For a homeowner with solar panels on the roof, a 240-volt Level 2 charger in the garage, a backup battery system for sunless days and a second family vehicle that can be used for vacation trips, BEV ownership is ideal, saving time and money through home recharging.

But for people who live in apartments, who have only one vehicle, or who live in a cold climate — which can reduce driving range by as much as 40% in the winter — BEVs are not an easy substitution for an IC-engine-powered vehicle. The fact that BEVs cost more than IC-engine vehicles further raises the barrier to adoption. In fact, a recent study of EV owners in

SHUTTERSTOCK.COM

For those who live in apartments, who have only one vehicle, or who live in a cold climate, BEVs are not an easy substitution for IC-engine-powered vehicles.

California found that 97% of them live in single-family homes or townhouses and 95% own a second, gasoline-powered vehicle.

Plug-in hybrids (PHEVs) offer the benefits of electrification to a broader set of consumers while providing a more climate-friendly alternative to vehicles that are solely powered by IC engines. As shown in the above chart, PHEVs offer roughly two-thirds of the lifecycle CO_2 reduction per mile that a BEV offers. For those with a daily commute of less than 40 miles (64 km), the CO_2 produced during their drive is the same as that of a BEV. PHEVs also enable owners to drive long distances whenever they want to without incuring lengthy recharging delays.

In the drive to quickly bring electric transportation to more people, a unique advantage of PHEVs, ironically, is their smaller batteries. According to **Toyota**, approximately eight PHEV batteries can be produced using the same amount of lithium, cobalt, nickel and other natural resources as one BEV of equivalent size and content. This results in fewer CO_2 emissions associated with raw material extraction and battery manufacturing. It also may avoid some of the significant price increases that are likely when demand for battery materials outstrips supply, as demonstrated by the steep increases in lithium prices over the last year. Plus, it mitigates possible risks of a single country — China — controlling nearly three-quarters of the raw materials required to produce lithium-ion batteries.

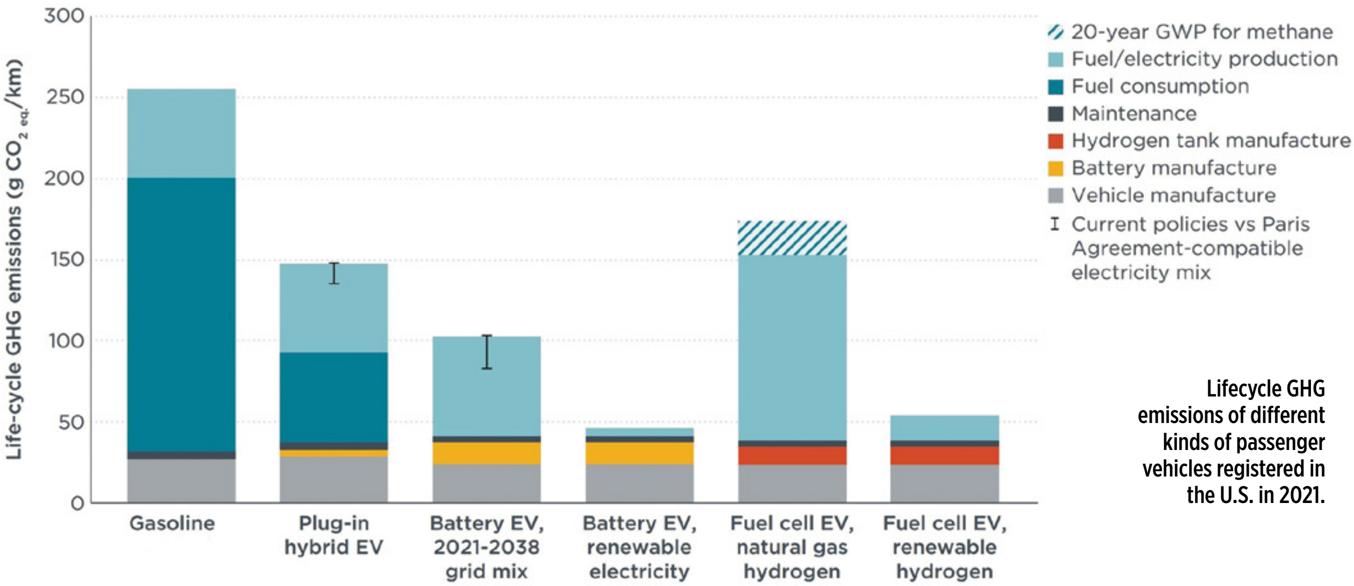
Government policies have an enormous impact on the acceptance of EVs. Although the incentives included in the Inflation Reduction Act of 2022 undoubtedly will make BEVs and PHEVs more affordable for many households, the IRA's stipulations are very complex. The incentives include vehicle purchase-price limits, purchaser income limits and vehicle qualification requirements based on sourcing an increasing percentage of critical battery materials and battery manufacturing within the U.S. or with free trade partners. Given the uncertainty these restrictions may have on total EV sales, the **U.S. EPA** should closely monitor the impact of this legislation through the first half of 2023, making recommendations to Congress on any needed changes.

"Expanding current policies beyond their focus on BEVs would engage more of the U.S in the transition to lower emissions on a faster timetable."

New incentives needed

While the current policy push towards BEVs and PHEVs is important, not all BEVs are equally environmentally friendly. For example, the Tesla Model 3 expends half as much energy per mile driven as the Porsche Taycan Turbo S (a BEV, despite its name). General Motors' Hummer EV has a battery more than five times the size of the battery used in the Nissan Leaf, releasing significantly more CO_2 during its manufacture. Even though some BEVs are much better for the environment than others, incentives for all of them currently are the same — and consumers have few ways to distinguish among them.

Today, the EPA requires that dealers place labels on the windows of IC-engine vehicles detailing their fuel efficiency in miles per gallon. Changing the labeling requirements for EVs would enable consumers to make knowledgeable choices about the true environmental impact



Lifecycle GHG emissions of different kinds of passenger vehicles registered in the U.S. in 2021.

"The costs associated with increasing the hydrogen infrastructure are large. But so are the capital costs associated with upgrading the grid to support EVs."

of the vehicle they are considering – and the charging time it really would require. Such a change also would create incentives for the auto industry to produce EVs that deliver the environmental impacts and charging times that consumers want.

To accomplish this, the EPA should mandate a new-vehicle window label that ranks the vehicle's kilowatt-hour/mile and CO_2 emissions against others in its size classification, as well as against the average BEV — just as it does for the fuel economy of gasoline and diesel vehicles. And future federal tax credits should be revised by Congress to reward and encourage more efficient BEV vehicles.

Window labels also could address currently misleading statements about the time it takes to charge a vehicle. Charging times in press releases and advertising materials are based on the highest power rating the vehicle can accept and assume availability of a DC fast charger with the same or higher power rating. This can lead to unrealistic customer expectations.

For example, in 2020, **Cadillac** announced that its new battery-electric SUV, the Lyriq, would feature GM's new 800-volt technology, allowing a 90% charge in just 10 minutes (OEMs don't share 100% charge time information because the last 10% charge rate is much slower). Cadillac's actual marketing materials for the 2023 Lyriq, however, provide less-impressive numbers. They claim 76 miles (122 km) of range can be obtained within 10 minutes with "DC fast-charging rates." However, this calculation assumes the charger has a rated power of 190 kW, the highest level the Lyriq can accept. Chargers with this power rating are rare: roughly two-thirds of U.S. public DC fast chargers available today are rated at 50 kW, which decreases the actual range provided within 10 minutes from 76 miles to 20 miles (32 km).

On such a typical DC fast-charger, it would take more than two-and-a-half hours to obtain the Lyriq's 312-mile (515-km) range. Even less impressive is the six-and-a-half hours of charging time for the Lyriq on a 240-volt Level 2 charger shown in the EPA's 2023 Fuel Economy Guide.

To provide consumers with accurate charging-time information, the EPA's window sticker should include the vehicle's battery capacity in kilowatt-hours and a comparison of its maximum charging rate (miles/minute) and the average charging rate with a 50-kW charger, at least until such time that higher-power chargers become predominant.

The recently enacted Infrastructure Investment and Jobs Act includes $7.5 billion to build out a nationwide network of 500,000 public EV chargers. Although far short of the 2.4 million chargers recommended by the ICCT to support the U.S. vehicle fleet forecast for 2030, it certainly is a step in the right direction. In administering the legislation, the Departments of Energy and Transportation should restrict funding to chargers with a power rating of at least 200 kW, thereby decreasing charging times on today's public chargers by a factor of four.

Furthermore, the EPA also should mandate that the actual power level be clearly specified on all public chargers, as well as on all websites providing charger locations.

A multi-fuel transition

The timelines that lawmakers are presenting for transitioning to BEVs are aggressive, both in the U.S. and in Europe. In August 2022, the **California Air Resources Board** signed off on a sweeping plan requiring all new

ICCT

The U.S. DoE is seeking an 80% reduction in the cost of green hydrogen by 2030, which would make hydrogen a much cheaper vehicle fuel than gasoline.

ROB CRANDALL/SHUTTERSTOCK.COM

passenger cars and light trucks sold in the state to be electric or otherwise emissions-free by 2035. In a similar action, members of the European Parliament in June, 2022 voted to ban the sale of new gasoline and diesel cars by 2035.

Despite these well-intentioned moves, turnover of the entire vehicle fleet will be slow. BEVs will continue to share the road with IC-engine vehicles for many decades. The average vehicle driven today is about 12 years old and new-vehicle sales each year represent between 6%-7% of the total number of vehicles in operation. This means that the aggressive 50% sales-mix target proposed by the Biden administration for EVs in 2030 will translate to an incremental shift of only 3%-4% of the total vehicles in operation each year.

To reduce transportation-related CO_2 emissions in the interim, we suggest reexamining low-carbon biofuels and synthetic fuels, which can be used in conventional IC-engine vehicles, simultaneously reducing petroleum dependence and CO_2 emissions. Most importantly, these benefits can be realized on the entire fleet of vehicles in operation as soon as these fuels become available, since compatible vehicles and the distribution infrastructure for such fuels already exist.

Significant gains could come from advancing next-generation "drop-in" biofuels — which do not require significant infrastructure investments to implement – with better carbon profiles that can entirely replace (or be mixed with) gasoline and diesel. These fuels use a variety of feedstocks, such as leftover cornstalks, genetically modified algae, halophytes (plants that thrive in salt water), and decomposed organic matter, which could create sustainable regional fuel sources as well as jobs.

Approaches that attempt to tackle two or more societal needs at once could be particularly helpful. For example, Red Rock Biofuels, which uses waste wood products including dead trees, tackles both the growing need for sustainable aviation and diesel fuel and the growing problem of catastrophic wildfires. The United States should continue to invest in the development of cost-competitive sustainable fuels, both bio-based and fully synthetic-based, looking in particular for solutions that reduce emissions, create jobs and help tackle other economic or environmental problems.

A final option that should get more attention is hydrogen. A fuel-cell vehicle (FCV) running on hydrogen produces only water as exhaust, and the tank can be refilled in 3 to 5 minutes — comparable to a conventional IC-engine vehicle. Most hydrogen available today comes from natural gas. However, there are other, cleaner paths to hydrogen production, with the most encouraging being "green" hydrogen produced from water through electrolysis using renewable electricity sources. The U.S. DoE is seeking an 80% reduction in the cost of green hydrogen by 2030, which would make hydrogen a much cheaper vehicle fuel than gasoline.

Hydrogen fueling is particularly attractive for long-haul heavy-duty trucks and heavy equipment that do not routinely return to a central depot, thereby reducing those vehicles' emissions while avoiding lengthy charging times that electric versions of these vehicles would require.

Today, California has 53 retail hydrogen refueling stations and another 68 in development. Admittedly, the costs associated with increasing the hydrogen infrastructure are large. But so are the capital

Quicker pathways to reduce transportation's

CLIMATE IMPACT

The authors advocate the U.S. DoE and DoT restrict funding to EV chargers with a power rating of at least 200 kW, thereby decreasing charging times on today's public chargers by a factor of four.

FORD

"Changing the labeling requirements for EVs would enable consumers to make knowledgeable choices about the true environmental impact of the vehicle they are considering and the time that it would really take to charge."

costs associated with upgrading the grid to provide sufficient electric power for BEVs and PHEVs. Both infrastructures will be needed to make quicker progress on emissions goals.

Hydrogen-fueled IC engines also may prove to be an attractive heavy-duty truck alternative because the engines are less expensive to build and can leverage the existing manufacturing infrastructure. And they are more tolerant to impurities in the hydrogen supply than are fuel cells.

To encourage hydrogen-fueled vehicles for both fuel cell and IC-engine versions, the EPA, as part of their implementation of Renewable Fuel Standards, should mandate that only "green" hydrogen be supplied for transportation use. Secondly, joint government and industry programs should be expanded for the installation of hydrogen fueling infrastructure.

'Perfect' vs. 'good'

Multiple vehicle options exist that are better than today's fossil fuel-powered vehicles. Net-zero operating CO_2, as will eventually be provided by fully electric BEVs powered by renewable energy, certainly is part of the long-term endgame. However, even with thoughtful policies, the path to that vision will be slow and haphazard. In the interim, transportation-related CO_2 emissions can be reduced more rapidly by pursuing CO_2 reductions across all vehicles, not just in new BEV vehicles sold to a subset of relatively affluent Americans.

Multiple types of relatively climate-friendly vehicles and accelerated development of sustainable substitute fuels should all be part of the picture. Pursuing all these policies will provide a more rapid reduction in CO_2 emissions in the near-term while ultimate zero-emission technologies are being improved and implemented — and ensure that in the transportation sector, perfect does not become the enemy of good. ■

Dave Foster is the Phil and Jean Myers Professor Emeritus of the Mechanical Engineering Department of the University of Wisconsin-Madison. **John Koszewnik** is the retired chief technology officer of Achates Power and retired chief engineer, V-engine engineering, Ford Motor Co. **Wallace Wade** is the retired technical fellow and chief engineer of Powertrain Systems Technology and Processes of Ford Motor Co. **Ward Winer** is the Eugene C. Gwaltney Jr. School Chair Emeritus of the Woodruff School of Mechanical Engineering at Georgia Institute of Technology.

This article originally appeared in Issues in Science and Technology, *November 17, 2022. It is republished here with permission. Article link:* **https://issues.org/reduce-vehicle-transportation-emissions-foster-koszewnik-wade-winer**

BMW REAPPROACHES HYDROGEN

BMW iX5 Hydrogen during winter testing to validate the fuel-cell system's performance in low ambient temperatures.

BMW

Top engineers in Munich talk about the vital role of H2 fuel cells in the climate crusade as iX5 pilot-fleet production begins.

by Lawrence Ulrich

Automakers have raised and dashed hopes for using hydrogen to power cars and trucks, including **General Motors**' notorious 2007 promise that it would sell 1 million fuel-cell vehicles annually (actual number: zero). With EVs now seizing the lead in showrooms and public infrastructure, hydrogen might still seem dubious. But the complexities of global electrification have many OEMs and policymakers willing to give our lightest atomic element another chance.

BMW is convinced that without hydrogen supplementing the energy mix — including for large trucks that are poor fits for battery propulsion — the transportation sector and nations have little chance of keeping global temperatures in check. BMW is the first German automaker to sign onto the United Nations' "Race to Zero" pledge, as the company aims to reach full carbon neutrality by 2050.

"Hydrogen is a versatile energy source that has a key role to play," said Frank Weber, member of the BMW board of management. "We are certain that hydrogen is set to gain significantly in importance for individual mobility."

iX5 system details

Recently in Germany, BMW took journalists behind the scenes of the new iX5 Hydrogen fuel-cell SUV as it kicked off pilot production, part of a test fleet that will begin operation this spring. Based on the South Carolina-built X5, the iX5 ditches a gasoline engine for a 125-kW (170-hp) fuel-cell stack and rear-axle electric motor. The system is fed by an enormous pair of underfloor tanks (pressurized at an industry-standard 700 bar/10,150 psi) that hold 6 kg (13.2 lb.) of hydrogen; conveniently, one hydrogen kilogram holds the energy equivalent of one gallon of gasoline. The traction motor and small 2.5-kWh battery fill in power gaps from the fuel cell with 150 kW (200 hp), and recapture energy via the vehicle's brakes.

The upshot is a total 275 kW (369 hp), a 500-km (311-mile) range and 190-km/h (118-mph) top speed. Easy, EV-crushing refills take less than five minutes. Easy, that is, if one can find an H_2 oasis. Pumps for hydrogen — currently priced around $7 to $10 per gallon in the U.S. — remain scarce worldwide, with about 320 public stations in the EU and U.S. combined. Where it's even available, hydrogen's per-mile costs are two to three times that of gasoline, in part because few companies manufacture or supply the gas for retail. And *that* hydrogen is almost exclusively manufactured using energy-intensive fossil fuels, mainly natural gas.

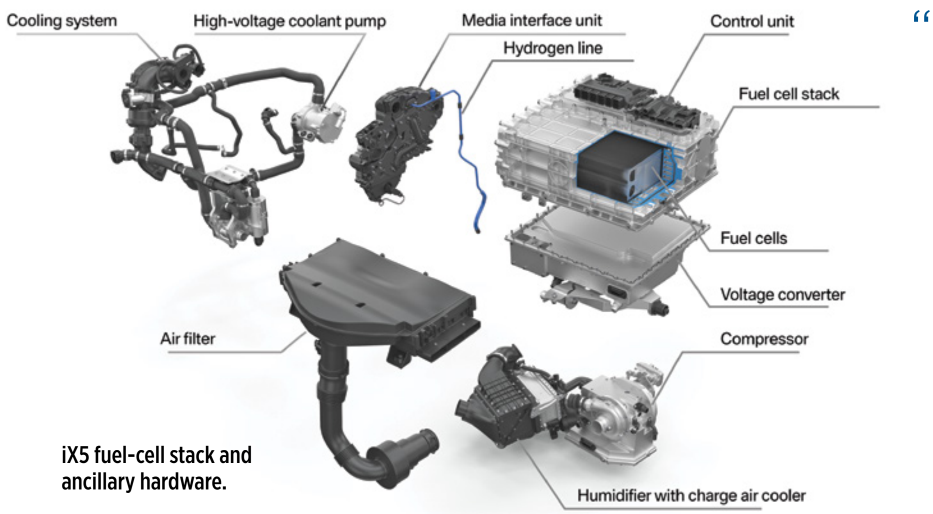
It's the chicken-and-egg scenario from the pre-**Tesla** EV era: What hydrogen passenger vehicles exist, including a Honda CR-V-based model coming in 2024, end up being a mirage in showrooms.

In the 2000s, BMW fiddled with burning cryogenically stored hydrogen in the IC engines of a short run of 7-Series sedans. Two decades later at the company's Hydrogen Competence Center near Munich, engineers showed their latest tech. BMW's fuel-cell system, developed in-house, starts with wafer-thin bipolar plates — about the size of a home A/C filter — sourced from partner **Toyota**; the plates are the same as those in the Japanese automaker's Mirai. A turbo-like electric compressor forces hydrogen into sandwiched plate membranes, whose catalyst separates hydrogen molecules into protons and electrons. Those particles take separate paths to a cathode, electrons create a flow of electricity and water vapor is the green byproduct.

The individual cells are inspected by vision machines to ensure no leakage of escape-prone H_2. An automated process precisely stacks and compresses hundreds of cells. The resulting stack is sealed in a housing and mounted in the rear carrier of the X5.

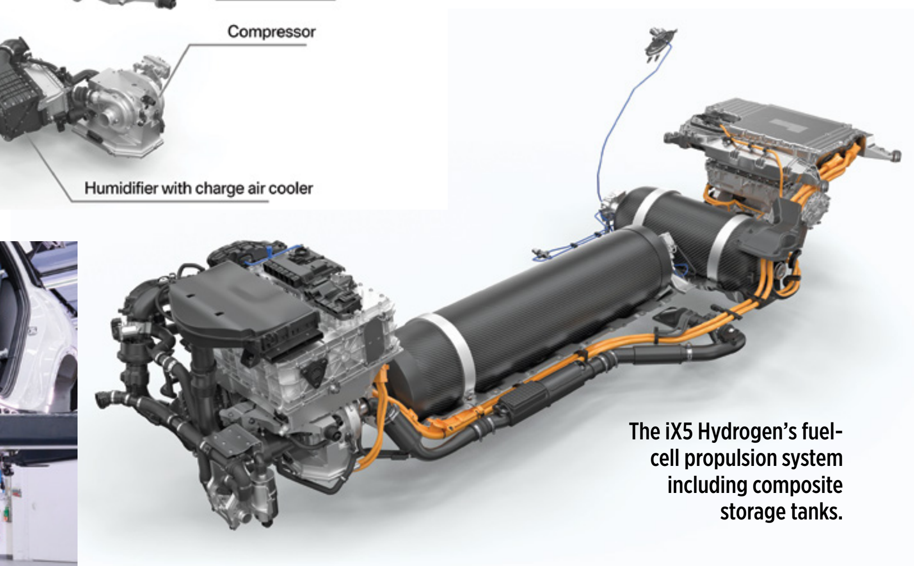
Infrastructure investments

As with previous fuel-cell bids, this might all seem quixotic. And proponents like Thomas Hofmann, BMW hydrogen project manager, acknowledge every hurdle. But

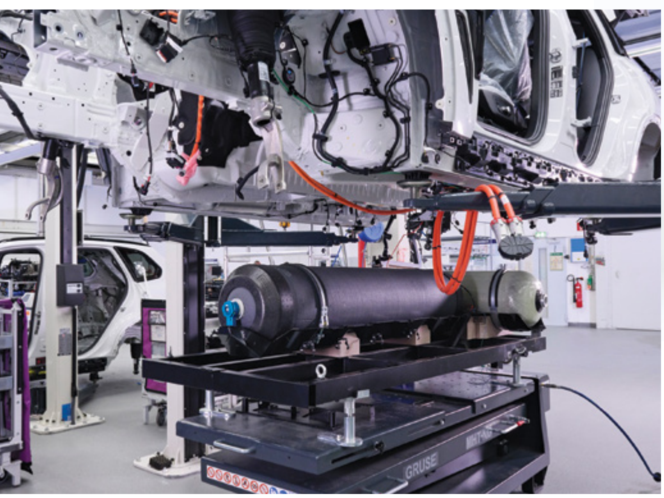


iX5 fuel-cell stack and ancillary hardware.

“The heavier and larger the vehicle, the more hydrogen makes sense.”



The iX5 Hydrogen’s fuel-cell propulsion system including composite storage tanks.



Assembly of an iX5 pilot-fleet vehicle shows the centerline location of its main hydrogen tank.

they insist that if fully renewable, carbon-free transportation is the ultimate goal, EVs and their infrastructure can’t possibly serve every vehicle or use case.

Electricity “is unlikely to work 100 percent of the time,” says Hofmann, who co-authored a major white paper on the hydrogen economy for **VDE Renewables**, a quality-assurance service provider. According to his paper: *Electricity generation from wind and solar is subject to strong daily and seasonal fluctuations. The potential to produce “green” electricity also varies greatly geographically. Hydrogen provides an optimal solution for bridging the gap between volatile generation and the need to supply green energy on-demand across all sectors.*

While BMW is focusing on passenger vehicles, the company still sees medium-to-large trucks as hydrogen’s optimum play. “The heavier and larger the vehicle, the more hydrogen makes sense,” Hofmann says, as EV batteries deliver ever-diminishing returns in range and cost.

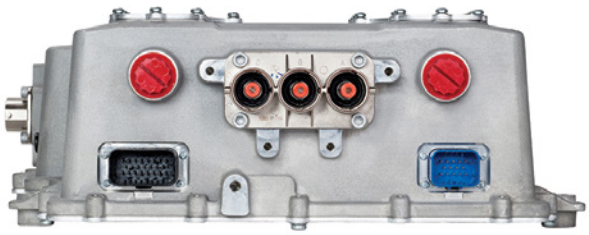
Unlike electricity, hydrogen can be cheaply stored and moved via pipeline, the BMW engineers noted. It can diversify the energy supply chain and buttress it against shortages: The iX5 requires no lithium, cobalt or nickel. Hydrogen could fill gaps in transportation that are more expensive or impractical for electricity. Pointing to a German infrastructure study, the BMW experts argue that building two complementary infrastructures — electricity and hydrogen — ultimately would cost less than electricity going it alone. As for a near-absence of renewable hydrogen, a Sept. 2022 analysis by **McKinsey & Co.** asserts green hydrogen’s price will quickly fall below that of fossil hydrogen as market penetration expands.

H_2 backers also cite major governmental and environmental momentum for hydrogen, including support under President Biden’s Bipartisan Infrastructure Law, and growing fealty to the Paris Accords. The EU is preparing rules calling for a minimum number of hydrogen stations. Hofmann’s study projects a roughly $240 billion global investment in hydrogen through 2030. Yet the paper cautions that current hydrogen investment remains largely tied to global subsidy programs, with major uncertainty over expected return on private investment.

That uncertainty extends to showrooms. BMW’s iX5 is strictly a technology testbed. BMW does intend to sell its first series-production fuel-cell model by the end of the decade, however — around the time it projects having 10 million EVs already on the road. ■

SPOTLIGHT: POWER ELECTRONICS

Traction inverters



Curtiss-Wright (Christchurch, United Kingdom) expanded its traction inverter lineup with its second-generation CWTI. The company claims their latest motor control software provides increased efficiency between the inverter and motor. Testing results from electric motors reportedly demonstrated improvements of up to 38% on peak torque and power as well as a 2% improvement in efficiency, resulting in an increased vehicle range of up to 14%. The units are compatible with multiple motor technologies, including AC induction, permanent-magnet synchronous and interior permanent-magnet and offer full fault protection as well as a current and temperature measured directly on the IGBTs. The temperature measurements ensure higher power output from the motor, while current measurements offer superior short-circuit protection to the system.

For more information, visit http://info.hotims.com/84491-400

Oscilloscopes

RIGOL Technologies (Portland, Oregon) introduced their HDO series of Oscilloscopes. The HDO series features 12-bit resolution and are available in 70MHz - 800MHz bandwidths and 2 or 4 channels. The HDO series also features RIGOL's new UltraVision III platform with a custom ASIC chipset. This reportedly provides dramatically lower front-end noise which will enable users to analyze much smaller signal artifacts with greater speed and accuracy. HDO4000 oscilloscopes are available in 200-800MHz with 4 channels and 4GSa/sec sampling with 100 µV/division range and 250 MPts of memory standard (500 MPts optional). HDO1000 scopes offer 70-200MHz bandwidth with 2 or 4 channels, 1GSa/sec sampling, 500 µV/division range, and 50 MPts of memory standard (100 MPts optional). Both series feature 12-bit resolution and a 10.1-in. intuitive touch screen display.

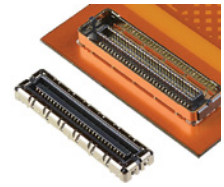
For more information, visit http://info.hotims.com/84491-401

Microcontrollers

MikroElektronika (Belgrade, Serbia) launched a new SiBRAIN add-on board, the SiBRAIN for GD32VF103VBT6, which enables designers to start prototyping with the GigaDevice RISC-V microcontroller. SiBRAIN is a standardized microcontroller add-on board, which allows very simple installation and replacement of the microcontroller unit (MCU) on a development board equipped with the SiBRAIN Card socket. By introducing the new SiBRAIN standard, MIKROE said it has ensured the absolute compatibility between the development board and any of the supported MCUs, regardless of their pin number and compatibility. SiBRAIN is equipped with two 168-pin mezzanine connectors, allowing it to support even MCUs with extremely high pin count.

For more information, visit http://info.hotims.com/84491-402

Board connectors



I-PEX (Austin, Texas) released their new NOVASTACK 35-HDH fully shielded, board-to-board connector at 1.5-mm (.05-in.) mating height and 0.35-mm (.013-in.) pitch. I-PEX claims this is the first connector of its size that combines mating workability with high electrical performance, while being fully shielded. The connector features 360-degree metal shielded ZenShield design, which reportedly reduces EMI emanating from the connector. This minimizes its impact on the antenna even if the connector is placed close to the antenna. P-PEX also states that the connector was designed with signal contacts suitable for high-speed transmission. The connector is capable of 40 Gbps/lane transmission and supports the latest transmission standards.

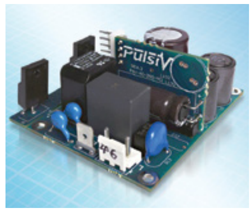
For more information, visit http://info.hotims.com/84491-403

Inverters

Magneti Marelli (Corbetta, Italy) developed a new platform of 800-volt silicon carbide (SiC) inverters. The company claims that its inverter offers improvements in terms of overall size, weight and efficiency compared to competitors. Marelli states that its inverter platform features an optimized thermal management system with structural and cooling channel designs that drastically reduce the thermal resistance between the SiC components and the cooling liquid. The company also claims that their inverter can extract more energy from a battery at a higher efficiency and provide a significant increase in the driving range of an electric vehicle.

For more information, visit http://info.hotims.com/84491-404

Storage capacitors for AC-to-DC



Pulsiv (Plymouth, United Kingdom) announced its OSMIUM storage capacitor for AC to DC conversion in charging/discharging applications without the need for a PFC inductor. Pulsiv states that their OSMIUM microcontroller family and supporting components can be combined with commodity flyback DC-DC converters. With a universal input, single switch 150W flyback power supply, the system can deliver 97.5% average (99.5% peak) front-end efficiency while maintaining 90% at just 2W. A 240W interleaved flyback also is currently being developed. Pulsiv's OSMIUM microcontrollers (PSV-AD-150 and PSV-AD-250 sampling now) do not directly determine output power and can be used as a platform for any application requiring 1W to 10kW.

For more information, visit http://info.hotims.com/84491-405

Potentiometers

Harold G. Schaevitz Industries (Bloomfield Hills, Michigan) expanded its sensor product range by offering the LPPS-36B linear potentiometer position sensor with rod ends. The LPPS-36B series can monitor and track the linear motion or position of a target from 350 mm up to 700 mm (14 to 28 inches) and is mounted in a housing with a diameter of 36mm (1.4 inches). The swivel rod ends allow for self-alignment and the swivel rod can be rotated up to 360 degrees. The LPPS-36B series sensor is made from industrial duty materials for resistance to dust, temperature, shock and vibration and are engineered for use in a wide range of gauging applications including automotive R&D, and motorsports.

For more information, visit http://info.hotims.com/84491-408

Electrolytic capacitors

Omni Pro Electronics (Addison, Texas) announced the release of the NSPE-HC series of AEC-Q200 automotive-grade surface mount aluminum electrolytic capacitors. Omni states that they feature high capacitance per case size and are offered in five case sizes ranging from 6.3 x 6.3 mm to 10 x 12.8mm (.24 to .5-in.). The series covers capacitance values from 56 uF to 560 uF in voltage ratings of 25VDC and 35VDC over operating temperatures of -55°C to 105° C (-67° to 221° F) with a load life rating of 5000 hours at 105 C. The company also states that the hybrid construction (polymer and liquid electrolyte) of the unit results in high ripple current ratings (up to 4Arms/100KHz), low ESR and high reliability.

For more information, visit http://info.hotims.com/84491-406

Smart charging

Energy Web (Zug, Switzerland) and **Volkswagen** (Wolfsburg, Germany) collaborated to develop a new smart-charging solution enabling EV owners to charge their vehicles with renewable electricity that is matched directly with the vehicle's real-time electricity consumption. The system utilizes a "24/7" matching algorithm which optimizes charging to maximize the use of clean, locally sourced electricity. Users can dictate the date and time of charging, the desired level of charge by the end of their session and the renewable energy facility from which electricity is drawn. Several VW ID4s reportedly were charged with local clean energy over the span of three months; most testing took place near Wolfsburg with energy sourced from local wind and solar farms.

For more information, visit http://info.hotims.com/84491-409

Voltage regulators

ITG Electronics (Elmsford, New York) introduced a new line of trans-inductor voltage regulators (TLVRs). The lineup includes the AHA series of TLVT coupling inductors, as well as L10142 Series and SLA2843B series compensation inductor. ITG states that their AHA series offers a broad range of options such as a ferrite-based TLVR inductor with low core loss and an inductance range of 70-150 nH. The AHA series also offers high current output chokes up to 125 amps with approximately 20% roll off. The maximum height of the unit is 10 mm (.39 in.). The narrow-body version TLVR inductors, such as AHA40475A and AHA47475A Series, are developed for future 4 x 6-mm (.15 x .23-in.) applications.

For more information, visit http://info.hotims.com/84491-407

Encoders

Elma Electronic (Freemont, California) offers the E18 family of mechanical incremental encoders. The company states they are a drop in rugged encoder designed for harsh environments with a footprint that matches their current PCB design. The E18 encoders are available in a variety of configurations, including with or without a push button, and with or without a threaded bushing. There is also an option to have the shaft already mounted in the encoder body or to have the shaft supplied separately for tape and reel packing and/or industry-standard reflow soldering processes. The entire line of E8 encoders includes Elma's Swiss Click indexing system that optimizes encoder life.

For more information, visit http://info.hotims.com/84491-410

The 'haters' go after Toyota

Your article is right on. Frankly, we at The Car Lab have felt that the industry, including SAE, has been running its own version of The Emperor's New Clothes for some time — enabling, via silence, the general media, the public and legislators to think we can soon be 100% EV and that Moore's Law applies to batteries. We're all complicit in getting to the current state. No one of knowledge in the industry believes any of the looming mandates are possible, but we've been silent so long. Everyone's afraid to speak up, lest we reveal the cowards we've been.

Between climate deniers on one side and purple-unicorn (EV) believers on the other, we've managed to waste 20 years with really very little progress against transportation GHGs. We'd all have been a lot better off to approach it incrementally — say, 1-2% reductions per year — via CAFE standards and hybrids of all sorts. If we'd adopted that rational strategy in 2000, we could be at 1994 GHG levels today.

From D-segment vehicles and up (+$65,000), BEVs will be doable as business cases for OEMs, for affluent end-user households. Below that, we'll have to use other solutions. Every month we pretend otherwise, and allow the naked parade to roll on, will cost our children dearly.

Eric Noble
eric@thecarlab.com

Your "The haters go after Toyota" Editorial in December's SAE *Automotive Engineering* was one of the best I ever read. You are spot on! I have never written before but felt compelled.

Dennis Mooney

Mr. Mooney is the former chairman and managing director at GM Holden.

Thank you for your December Editorial about 'the haters.' Regarding electric vehicles, I'd say the auto industry is way ahead of infrastructure. And way ahead of the haters. I've been looking at moving out of state, and many of the homes I've looked at have zero or one empty breaker position in the home's 100-amp breaker panel. Wait 'til the haters find out they can barely support a Level 1 charger at their home, or on the street outside their apartment.

Dave Steidinger

I thought your Editorial about haters vs.Toyota was a bit over the top. Toyota needs no defense from any of us, but all NGOs are not "haters." And climate change is going to do untold damage, not so much us, but to coming generations. I can't see much point in being nice to the footdraggers, who, as Bill Visnic's article (and much else that *AE* has been publishing) stated are not the automakers but mostly fossil-fuel interests and their acolytes, including more than a few political figures. The simple irrefutable fact is that the world is going to overshoot the 1.5° C Paris goal, probably by a lot, with a high likelihood of irreversible and potentially disastrous consequences — more so for poorer countries than the U.S. and other wealthy nations. The only way I can see of "managing" what's happening is through truly forceful action by governments. That's of course hard to envision, but it does no good at all to demonize those pushing for more meaningful responses, which are needed now.

John Alic

Your editorial in December issue was great. Maybe it will stir some brains. The coverage of Cadillac's Celestiq flagship was also very good.

Henry Sommerstorfer

I've been impressed with the posture on EVs that Toyota has taken for months (if not years) and frustrated that they don't seem to be getting any traction. In fact, as you say, they're being vilified for simply making sense. Keep up the good work and keep your fingers crossed that somehow, logic and reality will start to peek through the noise.

Bernard Robertson

READERS: Let us know what you think about *Automotive Engineering* magazine. Email the Editor at Lindsay.Brooke@sae.org. We appreciate your comments and reserve the right to edit for brevity and clarity.

UPCOMING WEBINARS

BETTER PRODUCTS IN LESS TIME: HOW AUTOMATION AND OPTIMIZATION TAKE CAE TO THE NEXT LEVEL

Thursday, February 2, 2023 at 11:00 am U.S. EST

Today's CAE engineers are faced with the increasing complexity of processes and delivering results in shorter time. Within the engineering process, multiple disciplines like NVH, thermal-mechanical-electrical analyses, safety evaluation, tolerance management and cost must be considered. Connecting multi-physics simulation and multidisciplinary optimization becomes essential for workflows to manage different disciplines and teams. This 30-minute Webinar will demonstrate how automation and optimization take CAE to the next level and reduces overall turnaround time.

Speaker:

David Schneider, Ph.D.
Lead Product Manager,
Ansys

Sponsored by: Ansys

Hosted by: SAE INTERNATIONAL

For additional details and to register visit: www.sae.org/webcasts

---

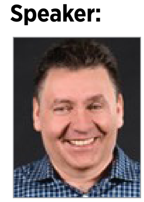
TOTAL APPEARANCE MEASUREMENT SYSTEM FOR AUTOMOTIVE APPLICATIONS

Available On Demand

For maximum impact, the surface quality of an automotive paint finish must instantly produce an appealing visual sensation for the customer. This 30-minute Webinar discusses a new way of quantifying appearance quality by using double-focus image technology to imitate the functions of the human eye and mimic the sensations that take place in the brain.

Topics will include how to define quality and harmony in appearance with a single value, and using contrast, image sharpness, waviness and dominant structure size to produce a comprehensive description of the visual sensation.

Speaker:



Mark Lombardi
Technical Support Manager,
Konica Minolta Sensing

Sponsored by: KONICA MINOLTA | SENSING AMERICAS

Hosted by: SAE INTERNATIONAL

For additional details and to register visit: www.sae.org/webcasts

COMPANIES MENTIONED

AD INDEX