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Trends in Automotive Electronics

Automative Computers

Automotive computers have been standard devices on cars since the late 1960s. From the management of engine emissions and fuel economy under increasingly stringent standards to the control of the entire driving process, automotive computers are used more and more. The first use of a small computer in a car was for an electronic fuel-injection system developed by Bosch (Gerlingen, Germany) for a 1968 Volkswagen (VW) model. Because the computer was devoted to engine control, it came to be known as an *electronic control unit* (*ECU*). Today, ECUs and, more recently, networked powertrain controllers (xCUs) perform millions of calculations per second to solve long equations and decide the best output reference values to maintain optimum vehicle performance.

After VW, Ford (Dearborn, Michigan) introduced its first computer-controlled antiskid system in 1969, and General Motors (GM) (Detroit) announced a computer-controlled transmission in 1971. The demand for such systems increased, and GM, in partnership with Motorola (Chicago), started to develop a custom microcomputer for its vehicles in 1976. Two years later, GM introduced a trip computer powered by a Motorola microprocessor in a Cadillac model. In 1981, all GM vehicles began using a Motorola 6802-based ECU for emissions control. Intel's 8061 custom-designed automotive microcontroller chips started to be used in Ford vehicles in 1983. Carnegie Mellon University (Pittsburgh) presented the first self-driving, autonomous car, Navlab 1, in 1986. The same year, Chrysler (Auburn Hills, Michigan) introduced multiplexing wire-communication modules with chips supplied by Harris Semiconductor (Melbourne, Florida), and, in 1987, the first automotive microcontroller chips, produced by Intel (Santa Clara, California) and Philips Semiconductors (Eindhoven, The Netherlands), for controller area network (CAN) vehicle-bus standards began to be used.

During the early 1990s, Ford and Motorola formed a partnership to design and produce an xCU and transmission microcontrollers. In 2000, Intel acquired Ford Microelectronics. The first commercially available self-driving vehicle, the Navya shuttle, was introduced in late 2014. One year later, Daimler (Stuttgart, Germany) presented its first road-ready self-driving truck, the Freightliner Inspiration. Now, practically all carmakers offer different levels of autonomous-driving products, a development that spurred Intel to buy Mobileye, a developer of vision-based advanced driver-assistance systems, in 2017.

Automotive computers have come a long way from the modest ECU in the 1968 VW, and their next generation will face complex requirements for fully self-driving vehicles. Numerous carmakers are working intensively on their autonomous cars, which will only add to the number of microprocessors that they use. Up-to-date cars include more than 100 microprocessors, and that kind of demand leads tech companies to undertake huge efforts in computer systems and sensor development to push autonomous cars onto our roads.

Autonomous Cars in Florida

Many of the obstacles that stood in the way of companies hoping to test autonomous vehicles in Florida have been removed by governor Ron DeSantis [1]. The legal framework for self-driving cars to operate in Florida, including prototypes and standards for self-navigation without a human operator, has been established. Carmakers and tech companies will be allowed to test autonomous cars on Florida's roads without anyone behind the wheel or inside the cabin. Prototypes will need to fulfill basic safety and insurance regulations. For instance, when a human operator is behind the wheel, the autonomous prototype must be able to produce visual and audible alerts if it detects a fault in the central system. If a problem occurs when the car is in full autonomous mode, the vehicle must be able to safely bring itself to a complete and secured stop, meaning that the system should slowly pull over and activate the hazard lights without

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slamming on the brakes in the middle of a busy intersection.

The law considers the autonomous driving system to be the car operator when it is engaged, even if there are passengers inside the cabin, meaning that the company in charge of the prototype is responsible in the event of an accident, which forces engineers to ensure that the technology they develop is safe and reliable. For autonomous-vehicle companies operating in Florida, there is no excuse if a driver—human or computer—is not paying attention. However, the law authorizes people behind the wheel of autonomous vehicles in self-driving mode to use wireless communication devices and infotainment (a portmanteau of *information* and *entertainment*). So, for those drivers, there is no more prohibition against watching television shows, movies, and any other broadcasts on the state's highways.

The law's framework will help carmakers and tech companies release new and better autonomous models to the public. The major players in that high-stakes race pledge a new category of drivers who consent to be passengers, with the objective of giving people more time to work, read, and catch up on their favorite television series during their daily commutes. Therefore, the legislation makes Florida one of the friendlier states for autonomous-vehicle testing and development. Figure 1 provides an example of two autonomous vehicles that people may soon encounter on Florida's roads.

FIGURE 1 A prototype Waymo self-driving truck and Chrysler Pacifica hybrid autonomous minivan. (Source: Waymo; used with permission.)

Electronic Components, Sensors, and Actuators

Waymo (Mountain View, California) launched its Laser Bear Honeycomb perimeter sensor (Figure 2) [2]. Its three main characteristics are

- a wide field of view (FOV)
- multiple returns per laser-beam pulse
- a minimum range of zero.

As specified by Waymo, the sensor has a 360° horizontal FOV (the maximum possible), combined with a 95° vertical FOV, which is unique since most 3D lidar sensors have a more limited 30° vertical FOV. Waymo's product has a single Laser Bear 3D unit that replaces three more limited sensors stacked vertically. Fewer pieces mean less to go wrong and easier calibration. All of these characteristics make the Waymo laser unique.

FIGURE 2 The Laser Bear Honeycomb. (Source: Waymo; used with permission.)

The Waymo unit detects up to four objects in its sight path. The extra data from multiple returns per pulse create a more highly detailed image and can help in discovering otherwise hidden objects. That degree of accuracy can improve the detection of people and animals moving behind shrubs and help systems anticipate decisions. The feature is not just about handsomer pictures. It has potential in multidomain-environment driving, where its minimum range of zero improves close vision and increases near-object detection.

The sensor's potential justifies Waymo's ambition to expand into other applications, including robotics, security, and agriculture. The company is looking for partners outside the automotive sector to spread the use of the sensor and help it build applications beyond self-driving. The partnerships could develop new technologies and increase the demand for larger FOV sensors having greater accuracy. That demand could make sensors more affordable through economies of scale and thereby help self-driving technology to develop faster.

The quality of Waymo's lidar equipment has been instrumental in making the company the first to put fully self-driving cars on public roads (see Figure 1). The company's origin dates to Google's self-driving car project. Google was immersed in developing an autonomous vehicle when it decided that none of the lidar solutions on the market were good enough or affordable enough, and so it started developing its own sensor. Even as the automotive lidar market exploded, Google kept developing its own sensors. Today, with the name Waymo, the company has three sensors to market for long-, medium-, and short-range measurements.

Separately, Velodyne (San Jose, California) announced a midrange lidar sensor that provides high resolution from a small package. The latest addition to the company's range of lidar sensors, the Puck 32MR, is pictured in Figure 3 [3]. It delivers high resolution in real time for mobile robots, shuttles, and autonomous-vehicle systems. Weighing 925 g and featuring a small form factor, the Puck 32MR provides precise, real-time localization and object detection for low-speed autonomous-vehicle markets. Moreover, it was designed to extend vehicle operating time within broad temperature and environment ranges without active cooling and for scalability and price.

The sensor detects objects within a 120-m range, with an accuracy of up to roughly 3 cm; features a 40° vertical and 360° horizontal FOV; and scans up to 1.2 million points per second at a 5–20-Hz refresh rate. The sensor uses 905-nm class 1 eye-safe technology. According to Velodyne, the Puck 32MR can precisely detect crosswalks, curbs, and obstacles in challenging environments, such as streets and warehouse aisles, due to its combination of high-resolution 3D perception and a broad vertical FOV. It was designed to provide safe, efficient navigation in roadway, commercial, and industrial settings.

FIGURE 3 The Puck 32MR sensor from Velodyne. (Source: Velodyne Lidar; used with permission.)

Innovusion (Los Altos, California) released Cheetah, an image-grade, high-resolution lidar sensor system [4] that features a dual rotating-polygon optical architecture and combines the company's detection electronics, optics, and algorithms. With a resolution of 300 × 300 dpi (across the entire 100° × 40° FOV) [4], the system can accurately identify a variety of objects without missing any important ones, as presented in Figure 4. Innovus ion says the sensor can detect small low-reflectivity objects as far away as 200 m and other obstacles at up to 280 m while receiving multiple points back. That capability provides perception systems with more time to correctly identify and react to potential road hazards.

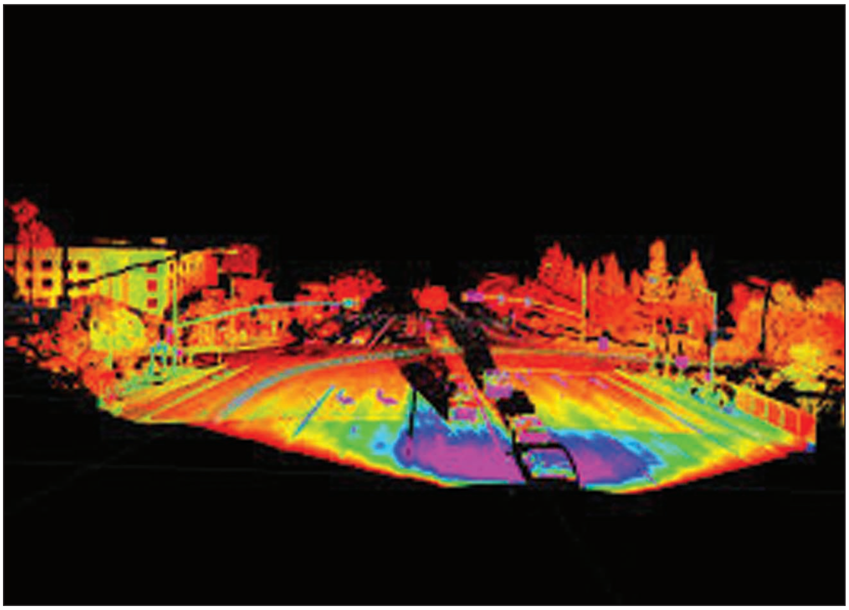
FIGURE 4 Cheetah, the image-grade, high-resolution lidar sensor. (Source: Innovusion; used with permission.)

Innovusion plans to develop versions of Cheetah with increased resolution and flexibility. The company is wagering on its products finding applications in the nonautomotive space, including autonomous trucking, construction, and mining equipment; high-speed rail; and everything-to-vehicle traffic-monitoring systems for cities. Those applications require picture-like, long-distance, high-reliability lidar systems. Innovusion believes Cheetah has the capacity to contribute to the increase in vehicle automation, especially after level 3, where safety is paramount.

To support automotive designers, Texas Instruments (Dallas) unveiled an automotive system basis chip that mixes a controller and transceiver for a CAN with a flexible data rate (CAN FD). The TCAN4550-Q1 chip was designed to meet the high bandwidth and data-rate flexibility necessary for improved vehicle networks. It uses the serial peripheral interface bus of almost any microcontroller to implement, with minimal hardware changes, a CAN FD interface or increase the number of CAN FD bus ports in a system.

To overcome the challenge of amalgamating multiple discrete components and changing microcontroller setups when upgrading to or expanding CAN FD functionality (often, a time-consuming and expensive process), Texas Instruments enables designers to keep their existing microcontroller-based architectures and streamline the CAN FD upgrade or expansion in electronics and several automotive fields, including lighting, advanced driver-assistance systems, and gateway designs. That is a significant improvement, considering the fast changes that are systematically required for automotive upgrades.

In the field of driver-assistance systems, Renesas Electronics (Tokyo) launched Perception Quick Start software for its R-Car V3H system-on-chip hardware [5], which blends computer vision and artificial intelligence

(a) (b) (c)

Figure 5 The (a) COD reference software, (b) LOD reference software, and (c) RFD reference software. (Source: Renesas Electronics; used with permission.)

at low power levels for the front cameras in level 2+ autonomous vehicles. The software-hardware combination offers camera obstacle detection (COD), lidar obstacle detection (LOD), and road-feature detection (RFD). The R-Car V3H was adopted for the Nissan Skyline's ProPILOT 2.0 driver-assistance system, which combines navigated highway driving and hands-off, single-lane driving capabilities. The R-Car V3H system on chip was added to the RH850 automotive control microcontroller to implement the core xCU functionality required to handle driving judgment and control targets.

To achieve state-of-the-art recognition technology, all Renesas systems on chip have dedicated hardware accelerators for key algorithms, including convolutional neural networks (CNNs), dense optical flow, stereo disparity, and object classification. Perception Quick Start provides an end-to-end pipeline reference that covers input from sensor and recorded data, at every processing stage and displays outputs on screens. That approach enables customers to kickstart their application design, whether they are experts at using accelerators or have limited experience. Renesas sells three software packages:

- *COD*: This reference software uses a CNN, a computer-vision engine (CV-E), and image rendering (IMR) to detect 2D objects, such as cars, trucks, buses, and pedestrians. It achieves approximately 30 frames/s. An example is presented in Figure 5(a).
- *LOD*: This software uses a CNN and CV-E to detect 3D objects, including cars and trucks, achieving roughly 15 frames/s, with 3D bounding boxes at 50 m, as presented in Figure 5(b).
- *RFD*: This reference software uses a CNN, CV-E, IMR, and a versatile pipeline engine to identify drivable free space, lanes (crossable and uncrossable), road boundaries, distances to lanes, and nearest objects to support the New Car Assessment Program 2020. It achieves approximately 30 frames/s. An example is proposed in Figure (5c).

Recognition features are under development for car interiors. Vayyar Imaging (Yehud, Israel) claims to have produced the first sensor capable of meeting the industry's dual-band needs, specifically to increase safety and passenger monitoring, as shown in Figure 6 [6]. In-cabin safety operations include seatbelt reminders, optimized airbag deployment, gesture control, driver drowsiness alerts, and child occupancy and detection alarms. Vayyar's radio-frequency sensor on chip has 48 transceivers at the 60- and 79-GHz wide bands, enabling thousands of virtual channels. The chip also consists of an internal digital signal processor for real-time signal processing, eliminating the need for an external ECU. It is easily integrated into existing automotive frameworks and offers multifunction capabilities to reduce the overall cost and number of sensors needed for a vehicle.

Vayyar's sensors provide a method for manufacturers to maximize in-cabin safety and prevent hot-car deaths. They can detect children, even those in car seats or covered by a blanket, who have been left in a vehicle, regardless of environmental conditions, including darkness, and send a notification to a driver's

Figure 6 An example of 360° in-car and out-of-car sensing. (Source: Vayyar; used with permission.)

phone. That ability would help manufacturers meet regulatory requirements, such as the Hot Cars Act of 2019, in the United States, and the New Car Assessment Program, in the European Union.

Recent infotainment developments include the use of vehicle windows to display information and advertisements, turning standard automotive glass into single- and full-color dynamic displays. The two primary applications powering this trend are vehicle-to-pedestrian communication and advertising, illustrated in Figure 7 [7]. The window displays must support two states: fully transparent and dynamic and colorful. When they are not displaying information, they are transparent and, ideally, look identical to the other windows in the car. When they are communicating information or playing a video, they display bright, colorful graphics that pedestrians and passengers can easily see.

A projector-based transparent window display consists of a small projector mounted to the interior roof surface (or another location) and a transparent film typically sandwiched or laminated in a vehicle's side or rear windows or the windshield. The film has several types:

- *405-nm emissive phosphor*: Light from a 405-nm-compatible projector excites the phosphor, which diffuses the energy at a different wavelength, such as blue or green. Since the light is emitted in all directions, the image is visible from any viewing angle. It is possible to create multicolor displays by using multiple films excited by different wavelengths.
- *Smart glass*: This film has two states, transparent and frosted, that are controlled by voltage to the glass, much like the films used in e-tinting applications. An image is projected onto the inside of the glass during the frosted state, similar to the working of a rear-projection TV. The frosting provides a good contrast, improving image quality. A red-green-blue (RGB) LED projector illuminates the film.
- *Microlens array diffuser*: This is an engineered diffuser film that can provide some amount of screen gain, which results from diffusing or concentrating light directionally. Instead of transmitting the light in all directions, the film is engineered to define a viewing angle where the image is visible. Outside of the viewing angle, there is no visible image. An RGB LED projector can illuminate the film.
- *Holographic film*: This film has unique features, such as the ability to create an image viewable from inside a car but not from the outside. An RGB projector illuminates it. Achieving maximum efficiency and brightness requires a careful selection of the LED wavelengths to match the holographic film and the use of a true-green LED at the appropriate wavelength.

FIGURE 7 Two examples of advertising and ride-hailing transparent displays. (Source: Texas Instruments; used with permission.)

All of the films have their strengths and weakness. Depending on the application, one type of film may be better suited than the others. For instance, digital light processing, from Texas Instruments, is light-source agnostic and can illuminate all four of the film types [7].

In other developments, Porsche (Stuttgart) unveiled its fully electronic Taycan model cabin interior that includes numerous screens and voice controls, all of which aim to limit the use of physical buttons and switches. Taycan was inspired by the Porsche 911's cabin layout but with a modern twist. It blends traditional and digital elements, and the controls are mostly accessible from a series of displays, as presented in Figure 8 [8]. The instrument cluster consists of a curved, rounded 16.8-in screen with touch-enabled buttons on the side. It will have four modes:

- *classic*: displays the car's power meters
- *map*: replaces the center power meter with a map layout
- *full map*: replaces all of the gauges with a navigation map across the instrument cluster
- *pure*: displays only essential information, such as speed, traffic signs, and navigation directions.

Apart from the touch display on the instrument cluster, a central 10.9-in display acts as the main infotainment control and includes Apple Music integration. An optional, identical display serves the front passenger. There is an 8.4-in touch panel with haptic feedback located directly below the center touchscreen and within the driver's reach, while a 5.9-in display is available for rear-seat passengers to adjust the climate and other comfort settings. Taycan enables drivers to access apps through a customizable home screen.

Regarding actuators, Kongsberg Automotive (KA) (Norway) developed an automated manual transmission (AMT) that combines the fuel economy and performance of a manual transmission with the driving simplicity of an automated one. The AMT changes gears quickly and smoothly with minimal power interruptions, which is valuable for large trucks, especially in dense traffic and when climbing hills where a lot of shifting is required. The AMT's actuation technology can fit any medium- and heavy-duty transmission application and be used in combination with hybrid traction systems.

To design the AMT, KA focused on smart system integration, reducing the number of components and the weight, and ensuring durability.

FIGURE 8 Porsche's fully electronic Taycan model cabin. (Source: Porsche; used with permission.)

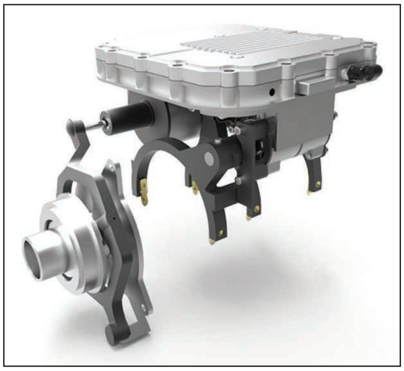

FIGURE 9 KA's AMT. (Source: Kongsberg Automotive; used with permission.)

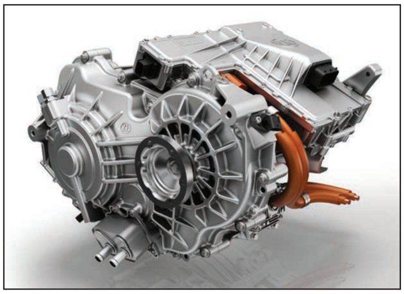

FIGURE 10 The ZF two-speed transmission. (Source: ZF Friedrichshafen; used with permission.)

The transmission requires minimal service, which is important as manufacturers increasingly adopt AMTs for heavy-duty trucks. The KA ATM is presented in Figure 9 [9], and its features include

- a computer-operated clutch that does not require a pedal
- higher fuel efficiency than manual transmissions
- increased driver comfort
- improved driveline durability and lower maintenance costs.

ZF Friedrichshafen (Germany) developed a two-speed gearbox for electric vehicles (EVs). At 70 km/h, the taller second gear can be engaged to lower the EV's speed and increase efficiency. A side effect is that the gear also increases the vehicle's top speed. The two-gear design enables a vehicle's torque to be optimized, making it easier for a truck to pull a trailer.

Today's EVs do not have shifted gearboxes but use a single gear stage that reduces their high speed to a rotational speed that the wheels can handle. That forces EV makers to choose between a high initial torque and a fast top speed. Two-speed gearboxes are considered too expensive and heavy while doing nothing to improve efficiency and range. That is why ZF's is considered to be a novelty (see Figure 10). Unlike traditional ones, ZF suggests that its two-speed drive increases efficiency enough to make a difference, in part because it can be connected to digital maps and GPS [10]. For example, a vehicle could compute the distance to the next charging station and, if necessary, switch to an economy mode. It could shift gears more effectively by knowing and accounting for the topography of an Interstate and by using routing and traffic information during intercity journeys. EV manufacturers are likely to be interested in the product, which could enable them to reduce battery sizes without shortening their vehicles' range.

Looking at machines, Magnax (Kortrijk, Belgium) says its yokeless axial flux motor has 98% efficiency [11]. The motor's design provides more power density and less weight than radial motors. Its wiring has a rectangular section rather than a round one, which saves space, makes filling more effective, and reduces copper losses. There are two permanent magnet rotors, and the stator is yokeless to shorten the flux paths as much as possible. The coils rely on a cooling system to maintain the rated temperature for normal operation, but, most significantly, it is the axial flux that gives the motor an interesting power-to-weight ratio. While the radial electric motors normally used in EVs offer roughly 120 kW of power and 250 Nm of torque and weigh 50 kg, a Magnax axial flux motor with the same torque level can provide power up to 200 kW at only 16 kg and is, therefore, very compact, as shown in Figure 11. Since mass is one of the three pillars of efficient vehicles and EVs already have to deal with heavy battery packs, any weight advantage is always welcome.

Its lightness makes the Magnax motor less demanding of natural resources, which is an important issue for EV mass development. It requires less neodymium, a rare material, for its permanent magnets, than traditional electric motors do. Magnax claims that the motor is ideal for cars, motorcycles, and airplanes, with a peak power ratio of roughly 15 kW/kg and a nominal one of 7.5 kW/kg [11]. The company is prepared to begin its first prototype motors by the end of 2019, with the goal of unveiling them next October, as presented in Figure 11. Two prototypes are under development. The first will be a 275-mm-diameter motor weighing 22.5 kg and capable of 300–408 kW. The second will be a smaller version weighing 7 kg with a diameter of 185 mm and a peak power output of up to 84 kW.

Semiconductor Technologies

Several changes in the automotive industry are expected during the coming years, including developments in the semiconductors used in vehicles and related products. Infineon Technologies announced a partnership with VW's Future Automotive Supply Tracks (FAST) strategic supplier network [12], which builds cooperation in key future fields. As a semiconductor supplier for electromobility, Infineon plans to contribute to electric drivetrains, in partnership with VW (Wolfsburg, Germany), the world's second-largest carmaker. Infineon power modules will control the electric drive in VW's modular electric drive matrix (MEB), displayed in Figure 12, which the automaker intends to be the industry's largest common electrification platform. As part of FAST, Infineon and VW will discuss future semiconductor requirements to create products that increase EVs' range and reduce charging times. Infineon produces its electromobility semiconductors from bare dies, discrete components, chips embedded in printed circuit boards, and power modules. Its portfolio includes products based on silicon as well as silicon carbide (SiC).

To cater to the automotive industry's growing demand for power electronics, Infineon is expanding its production capacities. The sector needs innovative power semiconductors to reduce energy losses when electricity is converted between a charging station, battery, and motor. The use of SiC accelerates the transition to EVs through efficiencies that give cars longer ranges and faster charging times, while reducing cost and weight and saving space. But the SiC technology has been pushed practically to its limits, and replacements are under development, such as the gallium nitride (GaN) high-electron-mobility transistor.

VW is also collaborating with Cree (Research Triangle Park, North Carolina) to engineer SiC-based components for future vehicles. Cree is expanding its SiC capacity by developing an automated 200-mm SiC fabrication facility and a materials factory in Durham, North Carolina. The company has largely bet on its Wolfspeed SiC and, more recently, GaN business. [13]. Upon completion in 2024, the facilities will substantially increase its SiC-materials capability and wafer-fabrication capacity for wide-bandgap semiconductors for the automotive market's shifting technology.

Vehicles and Energy-Storage Systems

EVs are on the road to dominating the global sales of passenger cars and buses by 2040 and significantly encroach on the market for vans and short-distance trucks, according to the latest forecast from research firm Bloomberg New Energy Finance (New York) [14]. Based on an analysis of the evolving economics in different

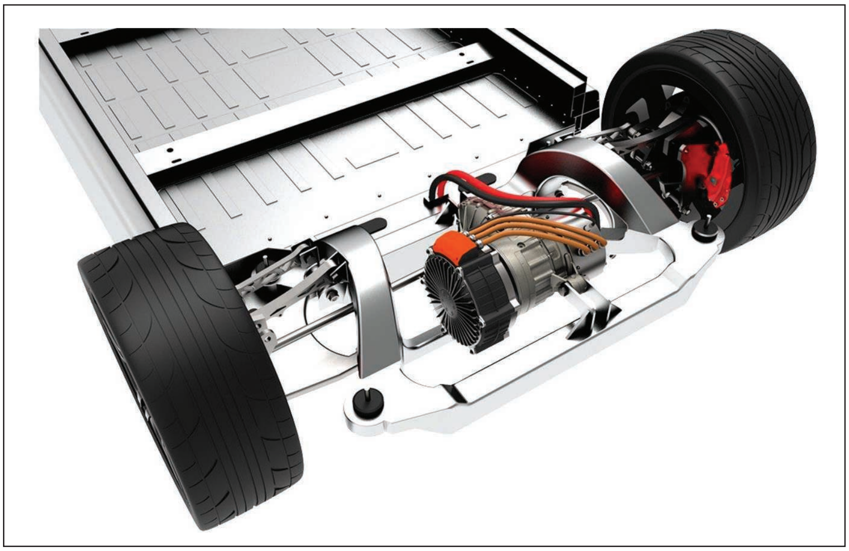

FIGURE 11 Magnax's yokeless axial flux motor concept. (Source: Magnax; used with permission.)

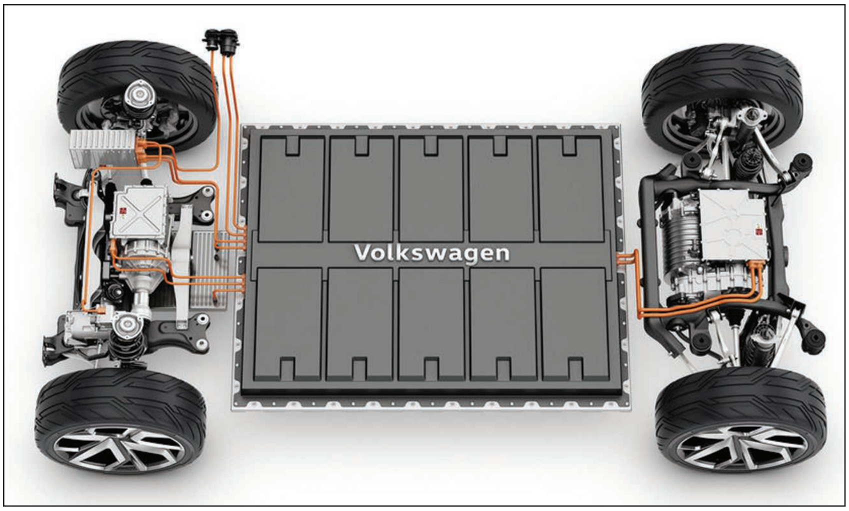

FIGURE 12 VW's MEB. (Source: VW; used with permission.)

vehicle segments and geographical markets, the report shows electrics taking up to 57% of global passenger-car sales by 2040, slightly higher than it estimated a year ago. Electric buses are expected to hold 81% of municipal bus sales by the same decade [14].

Equipment manufacturers and researchers have worked hard to overcome EV technical hurdles. The driving range and battery price have long been the hot points of EV development, and energy-storage advancements seem promising. During the transition to lower-carbon energy, the demand for lithium-ion batteries will grow significantly. Driven by EVs and energy-storage demands, the worldwide battery market is expected to reach roughly 600 GWh/year by 2025, compared to fewer than 200 GWh in 2018 [15]. There is still a lot of important work to do in this field, and it will require innovation and modern, efficient facilities to answer the demand.

A year ago, Saft Batteries (Levallois-Perret, France) set out to develop a new generation of lithium-ion batteries that use solid-state technology; this involved a partnership with the European Battery Alliance, through which the company works with four European industrial heavyweights. Two are Brussels, Belgium-based producers of chemicals and materials, Solvay and Umicore. The others are Manz (Reutlingen, Germany), a provider of battery cell and module assembly equipment, and Siemens (Munich, Germany), which offers products, among others, for Industry 4.0 facilities.

The consortium strives to improve batteries for multiple markets, from e-mobility to energy-storage systems and specialty industries, through a two-path strategy. First, it wants to improve existing lithium-ion technologies by increasing their energy density—in other words, to manufacture batteries that are more compact, lighter, and also cheaper but able to deliver more power. Battery-cell electrochemistry, design, and manufacturing processes are the main areas of focus (see Figure 13). This part of the plan is slated to last three to five years.

Afterward, the alliance's focus will be on solid-state batteries, which represent a paradigm shift in battery technology. In solid-state batteries, the liquid electrolyte is replaced by a solid compound into which lithium ions are able to migrate. The solid-state design offers a huge advantage for safety at the cell and battery levels. Inorganic solid electrolytes are nonflammable when heated, unlike their liquid counterparts. Lithium-ion batteries are subject to many constraints to ensure their stability and safety. Solid-state technology would remove those obstacles and produce nonflammable batteries that would be denser, have a longer life, and cost less to manufacture. The development of new, better-performing, and safer batteries will be the consortium's goal for the next decade.

Ultracapacitors, also known as *supercapacitors* (*SCs*) and *electric double-layer capacitors*, have been used for their high power density, exceedingly long lifetimes, slow degradation, and wide operational temperatures. The automotive sector is a key market for capacitors and SCs due to the wide number of applications that can take advantage of their capabilities. Start-stop functions and power steering make use of capacitors, whereas hybrid electric drives require the increased power capability of an SC. As EVs continue to develop and start entering the mainstream market, SCs will be used more extensively. Future advances could result in storage systems that combine SCs and lithium-ion batteries. New storage systems are appearing, at a small scale, with the denomination lithium-ion capacitor, which is targeted to deliver high power and energy capabilities.

The announcement that Tesla (Palo Alto, California) acquired Maxwell Technologies, a San Diego developer and producer of SCs, provided a clue to the technology's potential. The deal extended Tesla's capabilities in electrification at the mobile and stand-alone levels. Maxwell's products are used in the start-stop applications in some GM and Groupe PSA models. While a battery is appropriate for powering a car during the long run, an SC provides a more transient push. One way that SCs can be recharged in a vehicle is through regenerative braking, which captures kinetic energy to reuse for traction. SC banks are very suitable for the fast dynamics of those operations, and Maxwell is working with Lamborghini (Sant'Agata Bolognese, Italy) in that area. SCs could be used in EVs to manage peak transient load requirements and thus increase battery life; research is ongoing.

Several carmakers are studying SC high-power storage systems as a potential candidate for their products. The railway industry has begun to realize the potential of SCs, too. Some trams use an SC bank (see Figure 14) situated in the upper part of the carriages to recover braking energy, leading to electricity savings of 35%. The SCs can charge at stops and run between certain stops without the need for overhead cables [16]; this constitutes an interesting approach to light-rail operations in city centers (see Figure 14).

Electric Buses for Public Transportation

More and more electric buses are on the road, especially in large cities. Abellio (Utrecht, The Netherlands) confirmed an order for 34 Caetano electric buses to join its fleet in

FIGURE 13 Saft's medium prismatic MP series and small, cylindrical VL series rechargeable cells. (Source: Saft Batteries; used with permission.)

London [17]. The buses will enter service during first quarter of 2020 and be the first Caetano electric models in the United Kingdom. Abellio selected the e.City Gold model, at 10.7 m long, which holds 60 passengers and has a low floor from front to back (see Figure 15). It is a 100% electric urban bus that includes zero-emission heating and is developed by Caetano (Vila Nova de Gaia, Portugal) to comply with Transport for London's latest specifications. The buses will provide a number of features, including camera monitoring systems, intelligent speed assistance, an acoustic vehicle-alert system, and a revised front design to improve pedestrian safety. The battery capacity is modular, with energy between 85 and 250 kWh, providing a range of up to 200 km per charge. The buses are powered by one synchronous motor rated at 160 kW at its nominal speed of 1,500 r/min. The electric motor has a maximum torque of 2,500 Nm and a maximum speed of 2,500 r/min [17].

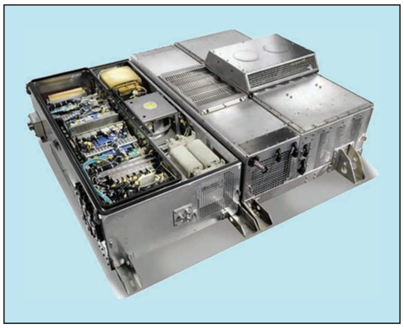

FIGURE 14 The Bombardier MITRAC Pulse for light-rail based on SCs. (Source: Bombardier Transportation; used with permission.)

Abellio operates bus services across London on behalf of Transport for London, plus rail replacement and event services throughout the United Kingdom. It is responsible for more than 8% of the London bus network, with 700 vehicles and 2,500 staff at six depots in central, south, and west London. The company advocates for public transportation as a vital part of community life [17].

FIGURE 15 The Caetano e.City Gold transit bus. (Source: Caetano; used with permission.)

(a) (b)

FIGURE 16 The (a) APM and (b) Toyota Concept-I for the 2020 Olympics in Tokyo [18]. (Source: Toyota; used with permission.)

The Massive Deployment of EVs

Toyota (Aichi, Japan), an Olympic and Paralympic Games partner, will provide EVs, including unique versions of certain models and specially developed vehicles, to the Tokyo games in 2020. With that lineup, Toyota, along with the Tokyo Organizing Committee of the Olympic and Paralympic Games, aims to achieve the lowest emissions of any official fleet used during the Olympics and help the games remedy their environmental issues.

Toyota will supply 3,700 mobility products and vehicles for Tokyo 2020. Nearly 90% of the official vehicle fleet will be electrified. The EVs include hybrid EVs (HEVs); fuel cell EVs (FCEVs), such as the hydrogen-powered Mirai; plug-in hybrid EVs (PHEVs), including the Prius PHEV; and battery EVs (BEVs), including an accessible people mover (APM), the e-Palette, and the Toyota Concept-I [18]. Two of the vehicles are presented in Figure 16 [18]. The unique fleet will include approximately 500 FCEVs and roughly 850 BEVs, the largest EV roster for an Olympics to date.

During the games, 2,700 vehicles will offer transportation between venues. They will be commercially available cars, such as the Mirai and Prius, and preliminary estimates suggest that their carbon-dioxide emission will average fewer than 80 g/km, a roughly 50% reduction compared to a similar group of conventional gasoline and diesel models [18]. Further reductions are anticipated from the other mobility products and EVs, some of which were designed specifically for the event.

To help avoid collisions and reduce/mitigate damage and injury, the commercially available vehicles for staff transportation will be equipped with Toyota safety technologies: Toyota Safety Sense and the Lexus Safety System+. Nearly all of those vehicles will have intelligent clearance sonar that applies the brakes in the event of an unintended application of the accelerator. Besides the official fleet, Toyota will support the Olympics with other vehicles. These include the mass-transit fuel-cell bus Sora, devices that help passengers into their seats and when obtaining wheelchair access, and fuel-cell forklifts.

FIGURE 17 The eMining eDumper. (Source: eMining; used with permission.)

The World's Largest Electric Truck

An interesting demonstration of how strong an EV can be concerns the eDumper truck. It claims the title of the world's largest EV (Figure 17). Developed by Swiss universities, eMining (Heimberg, Switzerland) and Kuhn Schweiz (Heimberg), the EV operates in a quarry in Péry, Switzerland. It is 9 m long, 4 m wide, and 4 m tall, according to eMining [19].

The eDumper began its life as a Komatsu HD 605-7 powered by a 23.1-L, straight-six turbodiesel. Kuhn Schweitz replaced the engine with electric motors supplied by a 4.5-ton, 600-kWh lithium-ion battery pack. To add context, the battery pack in the second-generation Nissan Leaf is 15 times smaller in capacity (40 kWh). The pack operates with regenerative braking to give the eDumper an infinite driving range. No breakthroughs in battery technology were involved: the development was accomplished through simple physics. The 45-ton eDumper climbs a 13% slope to pick up its 65-ton loads of lime and marl for delivery to a nearby cement plant. It is so heavy that, when it travels back down the hill, its regenerative braking system produces and stores enough energy for the next trip.

To guarantee longevity, the Interstate University of Applied Sciences (Buchs, Switzerland) studied the battery pack's thermal management and calculated the necessary strength of the battery holders as well as the design of the welding seams. The school was also responsible for monitoring the eDumper's battery during real-world use. To ensure fire safety in the event of a short circuit or mechanical damage, the Swiss Federal Laboratories for Materials Science and Technology examined the behavior of the lithium-ion cells. Never has a land vehicle been equipped with such a huge battery pack. The eDumper is now designed in such a way that a failing cell cannot affect adjacent cells.

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