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Automotive Electronics: Key System Components

Automotive electronic systems are the collection of electronic components and software systems that are used in modern vehicles to provide safety, comfort, entertainment, and other features. These systems have become increasingly complex over the years as technology has advanced, and they play a critical role in the overall operation of the vehicle.

Some examples of automotive electronic systems include the following [1]:

1) engine control unit (ECU)
2) antilock braking system (ABS)
3) advanced driver assistance systems (ADASs)
4) infotainment systems
5) climate control systems
6) powertrain control module (PCM)
7) lighting systems.

Overall, automotive electronic systems are crucial components of modern vehicles, and they play an important role in providing comfort, safety, and convenience to drivers and passengers. However, connecting automotive electronic subsystems requires careful planning and design to ensure that the different subsystems can communicate effectively and function as intended. Currently, there are some common methods for connecting automotive electronic subsystems, such as wiring harnesses (designed to carry power, ground, and signal wires for different subsystems, such as the ECU, lighting systems, and infotainment systems); bus systems [used in modern cars, including the controller area network (CAN), local interconnect network (LIN), and FlexRay]; gateway modules (to translate messages between different bus protocols); Ethernet (for high-bandwidth applications, such as infotainment systems and ADASs); and wireless communication (Bluetooth for infotainment systems and tire pressure monitoring systems) [2]. In Figure 1, some current vehicular networks are presented. The CAN bus, which is a computer network that enables ECUs to communicate using digital protocols, is currently the most widely used standard, particularly for the powertrain. However, in modern vehicles that operate as computer systems on wheels, other networks operate alongside the CAN and may eventually supersede it. As depicted in Figure 1, contenders, such as FlexRay, the LIN, and Ethernet, are emerging as potential replacements for the CAN [2].

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ECU

An ECU is an electronic control module that is responsible for managing various functions of an internal combustion engine (ICE). It receives input from various sensors located throughout the engine and other parts of the vehicle and uses these data to control a variety of engine parameters, such as fuel injection, ignition timing, and emissions control. Instances of ECUs from Bosch are depicted in Figure 2.

ECUs use sophisticated algorithms and programming to ensure that the engine is operating at optimal efficiency and performance while also minimizing emissions and maximizing fuel economy. The ECU can also detect and diagnose faults or malfunctions in the engine and can generate warning signals to alert the driver or technician of any issues that need to be addressed.

In modern vehicles, the ECU is often integrated with other control modules, such as the transmission control module, to ensure that all of the different systems of the vehicle are working together seamlessly. The ECU has become a critical component in modern vehicles, playing a key role in ensuring that they operate safely and efficiently.

There are several new trends in ECUs that are emerging in the automotive industry [3].

First, with the rise of connected and autonomous vehicles, ECUs are increasingly being integrated with other vehicle systems, such as ADASs, infotainment systems, and telematics. This integration enables the ECU to share data with other systems in real time, which can enhance overall vehicle performance, safety, and driver experience.

Next, as the automotive industry shifts toward electrification, there

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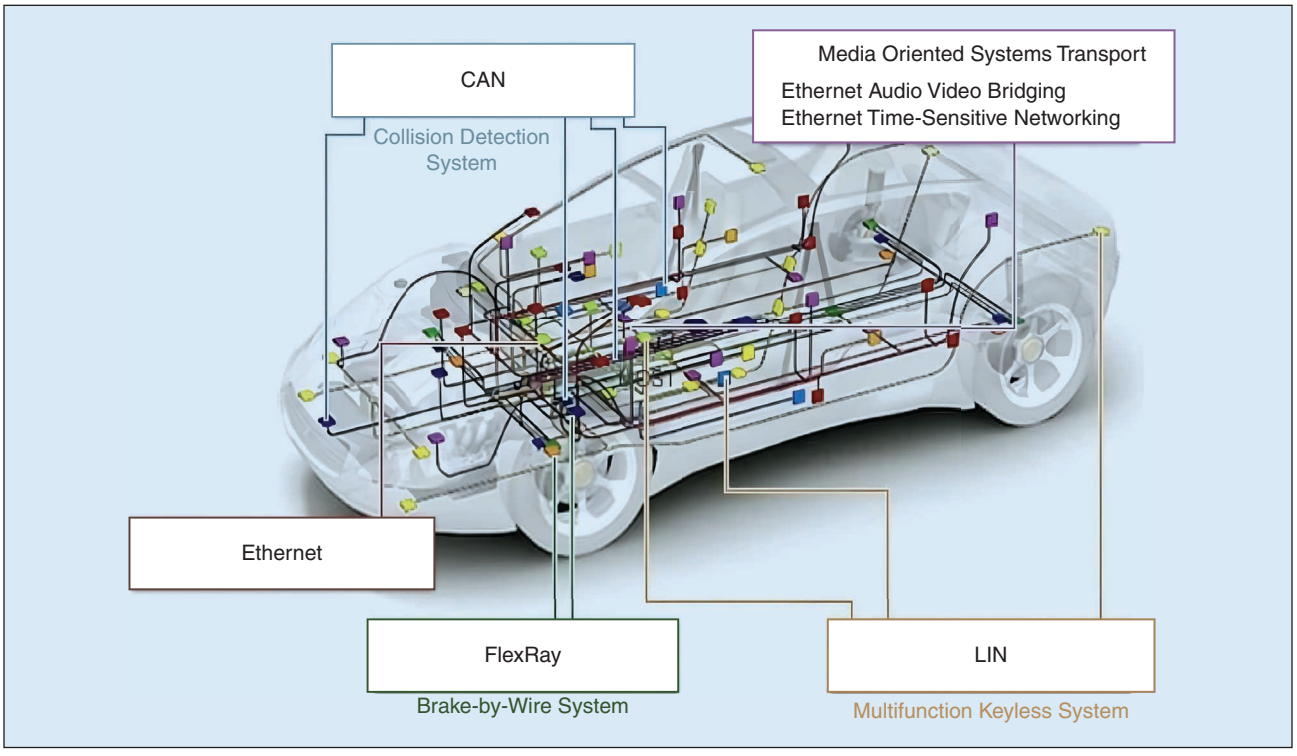

FIGURE 1 Modern vehicle trends in communication. (Source: https://www.renesas.com/; used with permission.)

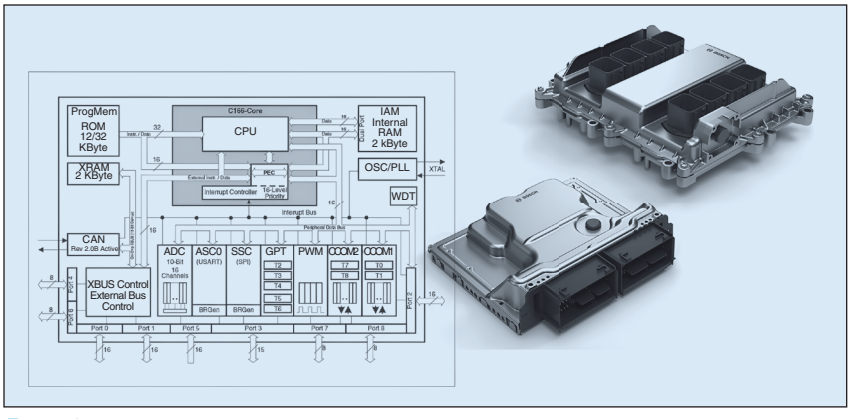

FIGURE 2 A Bosch ECU. IRAM: intelligent random-access memory; OSC: oscillator; PLL: phase-locked loop; XTAL: external oscillator; ADC: analog-to-digital converter; USART: universal synchronous asynchronous receiver/transmitter; GPT: Generative Pretrained Transformer; PEC: Protocol Execution Controller; WDT: watchlog timer. (Source: https://www.bosch-motorsport.com/; used with permission.)

is a growing need for ECUs that can control electric motors, battery management systems, and other components of electric powertrains. These ECUs need to be able to manage high voltages and currents and also handle complex power management tasks.

ECUs are also beginning to incorporate artificial intelligence (AI) and machine learning (ML) algorithms to improve performance and efficiency. For example, AI and ML algorithms can be used to optimize engine parameters in real time based on driving conditions and driver behavior [4].

With the increasing connectivity of vehicles, cybersecurity is now becoming a critical concern for ECUs. Manufacturers are now incorporating advanced cybersecurity features into ECUs to prevent hacking, data breaches, and other security threats.

Finally, many modern ECUs now support over-the-air (OTA) updates, which allow manufacturers to remotely update ECU software and firmware without requiring a physical visit to a service center. This can save time and money for both manufacturers and vehicle owners and can help ensure that vehicles are always running the latest software.

There are several equipment manufacturers in the area of ECUs. The main ones are the following:

- *Bosch:* Bosch is a leading supplier of automotive ECUs and related equipment. It offers a range of ECUs for gasoline, diesel, and hybrid vehicles (https://www.bosch-mobility-solutions.com/).
- *Continental:* Continental is another major player in the ECU market, offering a range of ECUs for various vehicle systems

(https://www.continental-automotive.com/en-gl/).

- *Delphi:* Delphi is a global supplier of automotive technology, including ECUs for gasoline, diesel, and hybrid vehicles. It also offers a range of diagnostic and testing equipment for ECUs and other vehicle systems (https://www.delphiautoparts.com/).
- *Denso:* Denso is a leading manufacturer of automotive components, including ECUs and related equipment. It offers a range of ECUs for gasoline, diesel, and hybrid vehicles (https://www.denso.com/).
- *Infineon:* Infineon is a semiconductor manufacturer that provides components and solutions for ECUs and related systems (https://www.infineon.com/).
- *Vector:* Vector is a leading supplier of automotive electronics and software, including testing and development tools for ECUs and related systems (https://www.vector.com/).

The outlook for the global automotive ECU market appears favorable, with a range of opportunities in the passenger car, light commercial vehicle, and heavy commercial vehicle segments. Projections indicate that the market is poised to reach a value of approximately US$62.4 billion by 2027, with a compound annual growth rate of 8.2% anticipated from 2021 to 2027. Key factors driving this growth include an increase in electronic content per vehicle, rising vehicle production, and more stringent government regulations related to passenger safety. In addition to these drivers, there are several emerging trends that are expected to shape the future of the automotive ECU market. These include the integration of multiple ECUs to reduce costs as well as the development of ECUs specifically designed for autonomous driving (AD). These trends are likely to have a significant impact on the industry as a whole and should be closely monitored by stakeholders in the automotive sector [6] after reenumeration.

ABS

An ABS is a safety system that is designed to prevent wheels from locking up during braking. It is an electrohydraulic system that uses sensors and hydraulic valves to modulate the brake pressure in individual wheels controlled by an ECU, preventing them from locking up and allowing the driver to maintain steering control [6].

When a driver applies the brakes, the ABS monitors the speed of each wheel using wheel-speed sensors. If one or more wheels are about to lock up, the ABS modulates the brake pressure to that wheel, reducing the braking force momentarily and allowing the wheel to continue rotating. This process is repeated multiple times per second, as the ABS constantly adjusts the brake pressure to each wheel. The ABS is particularly useful in situations where the road surface is slippery, such as when driving on wet or icy roads. By preventing the wheels from locking up, the ABS allows the driver to maintain steering control and avoid a potential accident [6].

Many modern vehicles are equipped with an ABS as a standard safety feature. In addition, some vehicles also have more advanced ABSs, such as an electronic stability control (ESC) system or a traction control system (TCS). These systems use similar technology to further enhance safety and stability while driving. Figure 3 presents a comparison of cars with and without ABS. In 1978, when Mercedes-Benz introduced the first production car with an electronic four-wheel multichannel ABS, it sparked a revolution in safety and performance [6] after reenumeration.

The main manufacturers of ABS components are as follows:

- *Bosch:* Bosch is a leading supplier of automotive ABS components, including sensors, control units, and hydraulic units. It offers a range of ABS solutions for passenger cars, commercial vehicles, and motorcycles (https://www.bosch-mobility-solutions.com/).
- *Continental:* Continental is another major player in the ABS market, offering a range of ABS components and systems, including wheel-speed sensors, control units, and hydraulic units. It also offers advanced ABS solutions, such as ESC and the TCS (https://www.continental-automotive.com/en-gl/).
- *ZF Friedrichshafen AG:* ZF is a global supplier of automotive components, including ABS components and systems. It offers a range of ABS solutions for passenger cars, commercial vehicles,

FIGURE 3 An ABS demonstration. (Source: https://www.roadandtrack.com/; used with permission.)

and off-road vehicles as well as advanced ABS solutions, such as ESC and TCS (https://www.zf.com/mobile/en/homepage/homepage.html).

- *WABCO Holdings:* WABCO is a leading supplier of commercial vehicle technologies, including ABS components and systems for trucks, buses, and trailers. It offers a range of ABS solutions designed for various applications and environments (https://www.wabco-customercentre.com/catalog/en).

ABSs for electric vehicles (EVs) are like those used in traditional ICE vehicles, but there are some differences due to the unique characteristics of electric propulsion.

One important consideration is regenerative braking, is a feature of many EVs that allows the motor to act as a generator and convert the vehicle kinetic energy into electrical energy that can be stored in the battery. Regenerative braking can reduce wear and tear on the physical brakes, but it also requires special programming for the ABS to operate effectively.

Another consideration for ABSs in EVs is the need to manage the power delivery from the electric motor during emergency braking. This requires precise control of the regenerative braking system as well as the hydraulic brake system to prevent the wheels from locking up and the vehicle from skidding.

Overall, ABSs for EVs must be designed to work seamlessly with the unique features of electric propulsion while still providing the same level of safety and performance as ABSs in ICE vehicles. As the market for EVs continues to grow, manufacturers are likely to focus on further refining and improving ABS technology to meet the specific needs of these vehicles.

ADASs

ADASs are a set of technologies designed to assist drivers in various ways, including improving safety, convenience, and comfort. An ADAS uses a combination of sensors, cameras, radar, and other technologies to gather data about the vehicle and its surroundings and then use these data to provide information to the driver or take action on behalf of the driver [7]. An example of a highly automated vehicle is presented in Figure 4.

Some common ADAS features are described next.

Adaptive cruise control (ACC) is a driver-assistance feature that automatically adjusts the speed of a vehicle to maintain a safe distance from the vehicle in front. ACC uses sensors, typically radar or cameras, to detect the distance between the vehicle and the vehicle in front and then automatically adjusts the speed of the vehicle to maintain a safe following distance. ACC can be particularly useful in heavy traffic or on long highway drives, where the driver may need to maintain a constant speed for an extended period. By automatically adjusting the speed of the vehicle to maintain a safe distance from the vehicle in front, ACC can reduce driver fatigue and improve safety. ACC can come in various forms, including

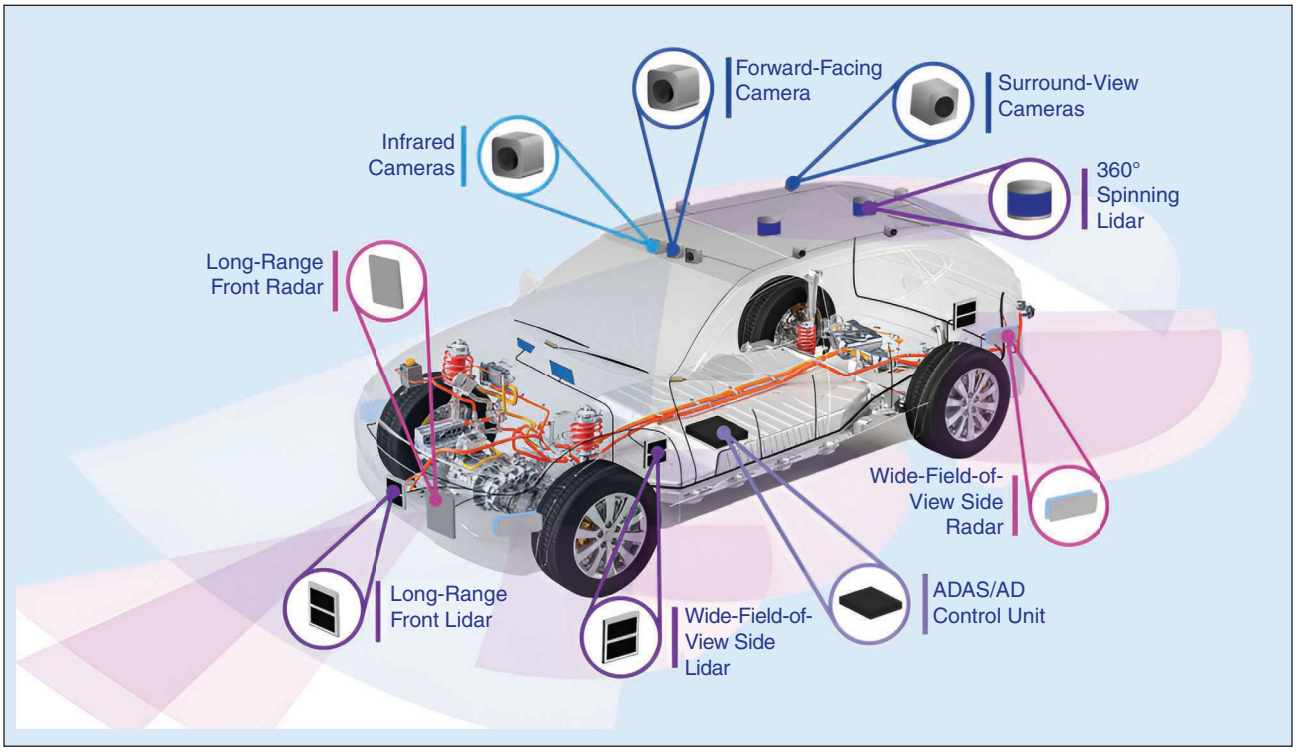

FIGURE 4 An example of a highly automated vehicles. (Source: https://www.idetechex.com/; used with permission.)

- *Full-range ACC:* This type of ACC can detect vehicles at any distance and speed and can bring the vehicle to a complete stop if necessary.
- *High-speed ACC:* This type of ACC is designed for highway driving and can detect vehicles at high speeds, typically up to 120 km/h.
- *Low-speed ACC:* This type of ACC is designed for city driving and can detect vehicles at low speeds, typically up to 50 km/h.

Lane departure warning (LDW) is a driver-assistance feature that alerts the driver when the vehicle begins to drift out of its lane. LDW uses cameras or sensors to monitor the vehicle position in the lane, and if the vehicle begins to drift out of its lane, the system provides an audible, visual, or tactile warning to the driver. LDW can help prevent accidents caused by distracted driving, drowsiness, or other factors that can cause a driver to unintentionally drift out of his/her lane. Some LDW systems are also equipped with lane-keeping assist, which can automatically steer the vehicle back into its lane if the driver does not respond to the warning.

Automatic emergency braking (AEB) is a driver-assistance feature that uses sensors, typically radar or cameras, to detect an imminent collision and automatically applies the vehicle brakes to avoid or mitigate the impact. AEB is designed to help prevent accidents caused by distracted driving, slow reaction times, or other factors that can cause a driver to miss a potential collision. AEB can be particularly effective at reducing the severity of rear-end collisions, which are among the most common types of accidents on the road. Some AEB systems are also equipped with pedestrian detection, which can detect pedestrians in the vehicle path and apply the brakes if necessary.

Blind spot monitoring (BSM) is a driver-assistance feature that uses sensors, typically radar or cameras, to detect vehicles in the driver's blind spots, which are areas around the vehicle that cannot be seen using the mirrors or the driver's peripheral vision. BSM provides an audible, visual, or tactile warning to the driver when a vehicle is detected in the blind spot, alerting the driver to the potential danger and allowing him to take appropriate action.

BSM can be particularly useful on highways and in heavy traffic, where lane changes are common and drivers may not always be aware of vehicles in their blind spots. Some BSM systems are also equipped with rear cross-traffic alert (RCTA), discussed next, which can detect vehicles approaching from the side when reversing out of a parking space, for example.

RCTA is a driver-assistance feature that uses sensors, typically radar or cameras, to detect vehicles approaching from the side when reversing out of a parking space or driveway. RCTA provides an audible, visual, or tactile warning to the driver when a vehicle is detected, alerting the driver to the potential danger and allowing her to take appropriate action. RCTA can be particularly useful in parking lots and other situations where the driver's visibility is limited and there is a risk of collisions with vehicles or pedestrians. Some RCTA systems are also equipped with BSM, which can detect vehicles in the driver's blind spots and provide warnings when changing lanes.

Some of the major manufacturers of ADAS components and systems include

- *Bosch:* Bosch is a leading supplier of ADAS components and systems, including sensors, cameras, and software (https://www.bosch-mobility-solutions.com/).
- *Continental:* Continental is a major player in the ADAS market, offering a range of components and systems, including radar, cameras, and software (https://www.continental-automotive.com/en-gl/).
- *Valeo:* Valeo is a global supplier of automotive technology, including ADAS components and systems, such as cameras, sensors, and software (https://www.valeo.com/en/).
- *Aptiv:* Aptiv is a technology company that provides ADAS components and systems, such as radar, cameras, and software, for a range of vehicle types (https://www.aptiv.com/en/)
- *Mobileye:* Mobileye is a subsidiary of Intel that provides advanced vision-based driver-assistance technology, including cameras, software, and mapping data (https://www.mobileye.com/).

ADASs are a rapidly developing and hotly contested area of automotive technology. The development of ADAS technologies is being driven by a few factors, including an increasing demand for safer and more convenient vehicles as well as the rapid development of AD technologies. Figure 5 illustrates the R&D activities by Valeo for autonomous cars. Many automotive manufacturers are investing heavily in ADAS R&D, and there is significant competition among suppliers to develop the most advanced and effective ADAS solutions.

Overall, the ADAS market is expected to continue growing rapidly in the coming years, driven by increasing consumer demand and government regulations around vehicle safety.

Infotainment Systems

Infotainment systems are in-car entertainment and information systems that integrate various features, such as audio, video, navigation, and communication functions, into a single user interface. These systems provide drivers and passengers with access to a wide range of information and entertainment options, including music, news, weather, traffic updates, and more.

Infotainment systems can be controlled through a variety of input methods, including touchscreens, voice commands, physical buttons, and steering wheel controls. Some systems also allow for integration with smartphones and other mobile devices, allowing users to access their favorite apps and content while on the go [8].

In addition to entertainment and information features, many infotainment systems also include safety and driver-assistance functions, such as collision warnings, LDWs, and rear-view cameras.

Currently, the most popular infotainment systems are Apple CarPlay (a system that allows users to access their iPhone features and apps through a car infotainment system; https://www.apple.com/ios/carplay/) and Android Auto (a system that allows users to access their Android smartphone features and apps through a car infotainment system; https://www.android.com/auto/). As an example, the Hyundai IONIQ 5-based Android Auto media source is presented in Figure 6.

FIGURE 5 Driving assistance R&D. (Source: https://www.valeo.com/; used with permission.)

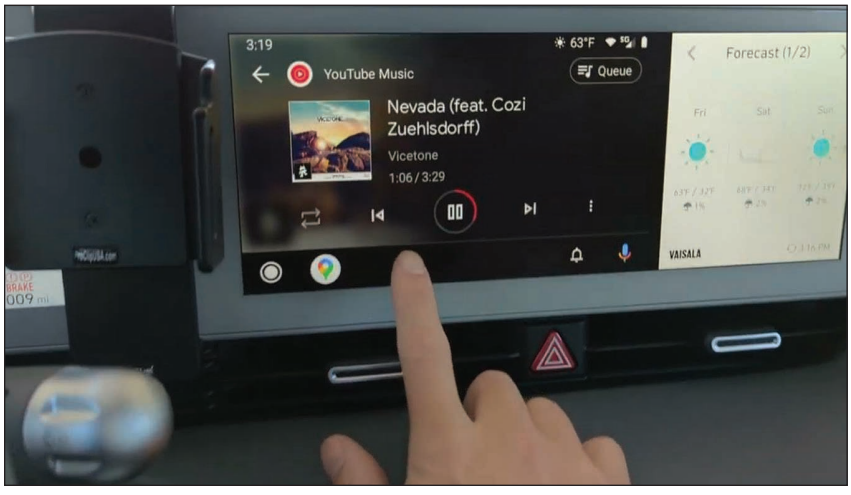

FIGURE 6 The Hyundai IONIQ 5-based android auto media source. (Source: https://www.hyundai.com/; used with permission.)

Infotainment systems have become increasingly advanced and sophisticated in recent years, with many manufacturers incorporating features such as gesture control, augmented reality (AR), and more.

Voice assistants, like Siri, Alexa, and Google Assistant, are becoming more common in infotainment systems, allowing drivers to control various functions of the vehicle without taking their hands off the wheel. This can improve safety and convenience for drivers.

AR technology is being integrated into infotainment systems to provide drivers with real-time information about their surroundings, such as navigation directions or nearby points of interest. AR can also be used for entertainment, such as displaying virtual images or videos for passengers.

Automakers are offering more customization options for infotainment systems, allowing drivers to personalize their experience and create profiles for different drivers. This can include settings for preferred music, climate control, and other features.

Climate Control Systems

Climate control systems are in-car systems that provide heating, ventilation, and air-conditioning (HVAC) to maintain a comfortable interior temperature for the driver and passengers. These systems are designed to regulate the temperature, humidity, and air quality inside the car, providing a comfortable and healthy driving environment [9].

Climate control systems can be manual or automatic. Manual systems require the driver or passengers to adjust the temperature and airflow manually, typically using physical knobs or buttons. Automatic systems use sensors and advanced algorithms to automatically adjust the temperature, airflow, and humidity based on the driver's and passengers' preferences and the current weather conditions.

Some examples of popular climate control systems include the following:

Dual-zone climate control: This system allows the driver and front passenger to independently adjust the temperature and airflow on their respective sides of the car.

Tri-zone climate control: This is a system that allows the driver and front passenger to independently adjust the temperature and airflow on their respective sides of the car while also providing a separate climate control zone for the rear passengers. An instance of dual-zone climate control from Continental is presented in Figure 7.

Rear-seat climate control: This system provides separate climate control for the rear passengers, typically through vents and controls located in the rear of the car.

Air purification: Some climate control systems also include air purification features, such as HEPA filters, to remove pollutants and allergens from the air inside the car.

Smart HVAC systems: Smart HVAC systems use sensors and AI to detect passenger preferences and adjust the temperature and airflow accordingly. This can improve comfort and energy efficiency while reducing the need for manual adjustments.

Automated temperature control: Many modern vehicles now offer automated temperature control, which allows passengers to set a desired temperature and let the HVAC system do the rest. Some systems even use GPS and weather data to adjust the temperature automatically based on the outside conditions.

As EVs and hybrid vehicles become more popular, automakers are developing devoted HVAC systems that are more energy efficient and can operate independently of the engine. This can improve the overall range of the vehicle and reduce emissions [10].

Overall, the trends in automotive HVAC systems are focused on improving energy efficiency, air quality, and passenger comfort using advanced technology and automation.

PCMs

A PCM is an electronic control unit that manages the engine and transmission systems in a vehicle. The PCM is responsible for regulating the fuel injection, ignition timing, emissions, and other critical systems that affect the performance and efficiency of the engine and transmission.

The PCM receives input from various sensors, such as the oxygen sensor, throttle position sensor, and crankshaft position sensor, to monitor the vehicle operating conditions and adjust the engine and transmission accordingly. By analyzing the sensor data, the PCM can determine the optimal fuel mixture, ignition timing, and other parameters to maximize performance and efficiency.

Some common functions of the PCM include:

Fuel management: The PCM controls the fuel injectors and fuel pump to regulate the amount of fuel that is delivered to the engine.

Ignition timing: The PCM controls the timing of the spark plugs to optimize combustion and maximize power and efficiency.

Transmission control: The PCM manages the transmission shift points, torque converter lockup, and other functions to optimize performance and fuel efficiency.

Emissions control: The PCM monitors the vehicle emissions and adjusts the engine and transmission to reduce pollution.

More recently, for EVs the PCM is responsible for managing the flow of electricity among the battery, motor, and other components. As an example, Figure 8 depicts the real-time power flow for the Toyota Prius. The PCM regulates the power output of the electric motor to ensure optimal performance and efficiency. It also controls the charging of the battery and manages the thermal management system to maintain safe operating temperatures for the battery and other components.

Since EVs have fewer moving parts than traditional ICE vehicles, the PCM plays an even more critical role in controlling the powertrain. Additionally, the development of EV technology is rapidly advancing, and as a result, PCM technology for EVs is also evolving. New PCM systems for EVs are being designed to optimize battery life and range, improve acceleration and braking, and

FIGURE 7 HVAC control. (Source: https://conti-engineering.com/; used with permission.)

integrate with other vehicle systems, such as regenerative braking and vehicle-to-grid communication.

Some examples of popular PCM brands manufacturers include

- *Bosch:* A global supplier of automotive components and systems, including PCM systems and components, as well as battery management systems for EVs (https://www.bosch-mobility-solutions.com/)
- *Continental:* A German company that produces automotive technology, including PCM systems and components (https://www.continental-automotive.com/en-gl/).
- *Denso Corporation:* A global supplier of automotive components and systems, including PCM systems and components (https://www.denso.com/)
- *Magneti Marelli:* An Italian company that specializes in automotive electronics, including PCM systems and components (https://www.marelli.com/).

Some of the developments and advancements in PCM for automotive applications are as follows:

Integration with other vehicle systems: PCM systems are becoming more integrated with other vehicle systems, such as ADASs and infotainment systems, to provide more comprehensive control and management of the vehicle.

Increased use of AI: The use of AI in PCM systems is becoming more prevalent, allowing for more advanced predictive and adaptive control of the powertrain. This can help to optimize performance and efficiency as well as provide a more customized driving experience.

Optimization for EVs: As the use of EVs continues to grow, PCM systems are being specifically designed and optimized for these vehicles. This includes the development of advanced battery management systems, regenerative braking, and other technologies that are unique to EVs.

Cloud connectivity: PCM systems are increasingly being designed to connect to the cloud, allowing for remote monitoring, diagnostics, and OTA updates. This can help to improve the reliability and performance of the PCM system as well as provide more convenient service and maintenance options for vehicle owners.

Increased use of data analytics: PCM systems are generating and collecting large amounts of data, and there is a growing trend toward using advanced analytics to extract insights and improve performance. This includes the use of ML algorithms to analyze data from sensors and other sources in real time and provide actionable insights to improve the performance and efficiency of the powertrain.

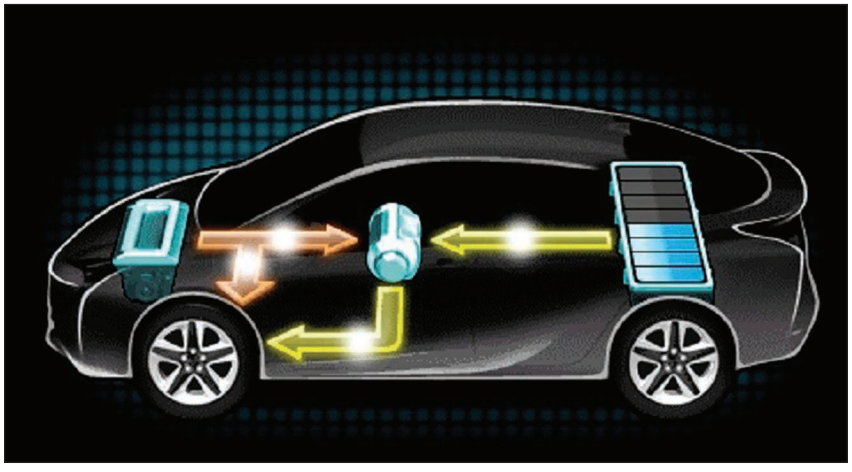

FIGURE 8 The Toyota Prius Energy Monitor provides a real-time display of the energy flow through the hybrid system. (Source: https://www.toyota.com/; used with permission.)

Lighting Systems

Lighting systems in vehicles serve multiple purposes, including providing visibility for the driver and signaling the vehicle presence to other drivers and pedestrians. Automotive lighting systems typically include headlights, taillights, brake lights, turn signals, and interior lights.

Popular types of automotive lighting systems include

Halogen headlights: These are the most common type of headlights in use today. Halogen headlights use a tungsten filament and a halogen gas to produce a bright white light.

LED headlights: LED headlights are becoming increasingly popular because of their efficiency, longevity, and brightness. LED headlights use LEDs to produce a bright white light.

Xenon headlights: Xenon headlights, also known as high-intensity discharge headlights, use a xenon gas to produce a bright white light.

Fog lights: Fog lights are low-mounted lights that are designed to improve visibility in foggy or misty conditions. They provide a wide low beam of light that illuminates the road directly in front of the vehicle.

Interior lighting: Interior lighting systems include dome lights, reading lights, and ambient lighting. These lights provide illumination for the interior of the vehicle and can enhance the vehicle appearance and ambiance.

Laser LED headlights are the newest technology in automotive headlights. They are the brightest and most efficient type of headlight, providing a longer and wider beam of light. They also use less energy than other types of headlights. However, they are the most expensive type of headlight and are not yet widely available in all vehicles. Figure 9 offers a visual comparison of various LED headlight technologies for a single car. According to BMW's demonstration with its i8 model, laser LED headlights can illuminate twice the distance compared to traditional LED technology [11].

Some of the key players in the automotive lighting systems industry are:

- *OSRAM:* A global supplier of lighting products and solutions for the automotive industry (https://www.osram.pt/cb/applications/automotive/index.jsp)
- *Philips:* A Dutch multinational corporation that produces a wide range of lighting products, including automotive lighting systems (https://www.philips.co.uk/c-e/au/car-lights/headlight-bulbs/led-headlight-bulb.html)
- *HELLA:* A German automotive supplier that produces a variety of lighting products and systems for the automotive industry (https://www.hella.com/lighting/en/)
- *ZKW Group:* An Austrian company that specializes in automotive lighting systems (https://zkw-group.com/).

There are several ongoing developments in automotive headlights, including matrix LED headlights, laser headlights, adaptive headlights, organic LED (OLED) headlights, and AR headlights.

Matrix LED headlights: These headlights use several individual LEDs that can be controlled independently to adjust the light beam. This allows for precise illumination of the road ahead while avoiding glare for oncoming drivers.

Laser headlights: These headlights use laser diodes instead of traditional bulbs to produce light. Laser headlights can produce a brighter and more focused beam of light than traditional headlights while also being more energy efficient.

Adaptive headlights: These headlights use sensors to detect the car speed, steering angle, and other factors to adjust the direction and intensity of the light beam accordingly. This improves visibility and safety while driving at night or in adverse weather conditions.

OLED headlights: OLEDs are more energy efficient and can be made into very thin and flexible panels, allowing for more design flexibility and unique lighting patterns.

AR headlights: These headlights use projection technology to display information directly onto the road ahead, such as navigation directions, speed limits, and hazard warnings. This technology is still in the early stages of development but has the potential to revolutionize the way we interact with our cars and the road.

Recent developments in automotive lighting systems are important for safety reasons. Headlights, for example, play a critical role in allowing drivers to see the road ahead and avoid potential hazards. The development of advanced lighting technologies, such as LED and laser headlights, has improved visibility and made driving at night or in poor weather conditions safer. Additionally, adaptive lighting systems, such as adaptive front-lighting systems and dynamic bending light systems, can adjust the direction and intensity of the headlights in response to driving conditions, further enhancing safety on the road.

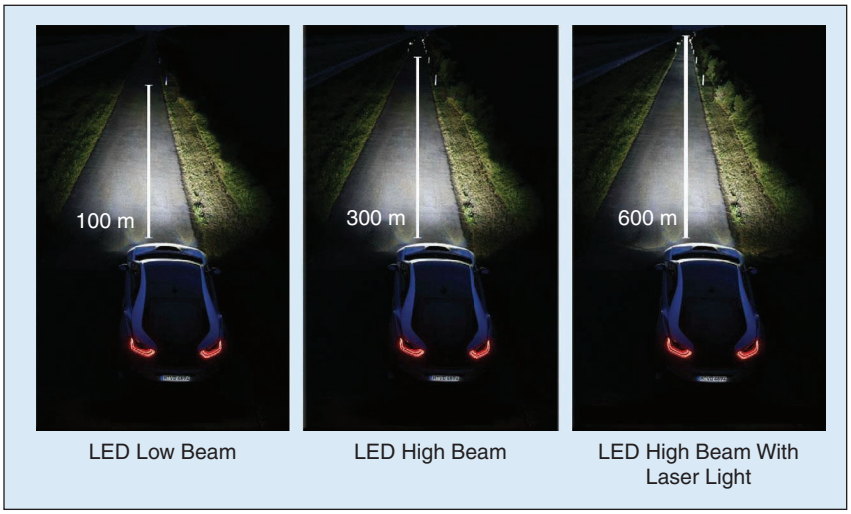

FIGURE 9 A comparison of headlight technologies for the BMW i8. (Source: https://www.bmw.com/; used with permission.)

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