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NEXT-LEVEL SYSTEM DESIGN: ADVANCED AND HIGH-PERFORMANCE SYSTEM ARCHITECTURES FOR THE FUTURE OF ELECTRIC VEHICLES

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Abstract

The transformation of the automotive industry toward electric mobility necessitates the development of advanced and high-performance system architectures to address the evolving demands of next-generation electric vehicles (EVs). With an increasing focus on sustainability, efficiency, and advanced technological integration, future EV platforms must support cutting-edge capabilities such as autonomous driving, smart energy management, and seamless connectivity. This paper investigates the design and integration of next-level system architectures that will define the future of electric vehicles. Emphasizing the need for modular, scalable, and fault-tolerant systems, the research explores how these architectures can facilitate continuous innovation, reduce vehicle obsolescence, and improve safety and reliability. Key topics include the integration of high-efficiency powertrains, advanced battery technologies, and intelligent control systems that enhance vehicle performance and user experience. Furthermore, the study highlights the role of emerging technologies such as artificial intelligence, machine learning, and vehicle-to-grid (V2G) communication in optimizing system performance, vehicle autonomy, and energy efficiency. The paper also examines the potential for adaptive architectures that can accommodate new functionalities and technological upgrades over the vehicle's lifecycle. By exploring these innovations, this research provides insights into how next-generation system designs will help electric vehicles meet the growing global demands for *performance, safety, and environmental sustainability. The findings aim to guide the development of robust, future-proof EV architectures that will shape the automotive industry's transition to a more sustainable and technologically advanced future.*

INTRODUCTION

The global shift from internal combustion engine (ICE) vehicles to electric vehicles (EVs) marks one of the most significant transformations in the history of the automotive industry. This change is driven not only by environmental concerns and regulatory pressures but also by evolving consumer expectations for cleaner, smarter, and more connected mobility solutions. While early EV development focused primarily on electrifying propulsion systems, the current landscape demands a more comprehensive redesign of vehicle system architectures to accommodate emerging technologies such as autonomous driving, smart energy management, real-time connectivity, and seamless integration with broader energy ecosystems. Traditional vehicle architectures, typically rigid and hardware-centric, are no longer sufficient to meet the demands of modern electric mobility. EVs must be built on system designs that are modular, scalable, and capable of supporting continuous innovation throughout the vehicle's lifecycle [1]. These next-level architectures must provide the computational power and data bandwidth required for AI-driven decision-making, while also maintaining safety, reliability, and efficiency under a variety of operational conditions. The contrast between ICE and EV system architectures highlights the scale of transformation required. As shown in Table 1, EVs introduce significantly greater electrical and computational complexity, necessitating new approaches to system integration and control. Unlike ICE vehicles, where the architecture is largely defined by mechanical components, EVs require tightly integrated power electronics, battery systems, thermal management units, and digital interfaces that must function harmoniously.

Table 1: Comparison of Traditional ICE Vehicles and Electric Vehicles (EVs) [2].

Feature	Traditional ICE Vehicles	Electric Vehicles (EVs)
Powertrain	Engine + Transmission	Electric Motor + Inverter
Fuel Source	Gasoline/Diesel	Electricity (Battery)
Emissions	High	Zero (Tailpipe)
Electrical Complexity	Moderate	High
Integration of Smart Tech	Limited	Extensive (AI, V2G, OTA)

The need for high performance system architectures is further escalated by the incorporation of autonomous driving technologies. Such systems depend on the data coming from the lidar, radar, cameras and ultrasonic sensors – all of which should be processed in real time with sophisticated AI algorithms. The computing infrastructure that will under-gird these operations must be highly reliable, have low latency, edge-level decision-making capabilities. Furthermore, smart energy management systems need to be able to track and optimize energy flows in real time, sustaining propulsion, climate control, infotainment, and charging subsystems in such a way to achieve overall maximum efficiency. Connectivity is another key element of future EV architectures. Continuous communication between the vehicle and external environments, such as other vehicles, charging infrastructure, and the electric grid, is a prerequisite for features such as vehicle to grid (V2G) and Over the Air (OTA) software updates [3]. These functions require strong network interfaces, secure communications protocols, and software defined vehicles, which can be updated over time long after the sale of the vehicle. To solve these needs, automotive manufacturers are changing over to unified, modular EV platforms that can accommodate several vehicle variants and provide cost-effective scalability. Examples include the Volkswagen's Scalable Systems Platform (SSP), Hyundai's Electric Global Modular Platform (E-GMP) and Renault–

Nissan CMF-EV platform among others. These architectures are intended to standardize core components but apply flexibility over body design, battery capacity, and drivetrain arrangements. As an illustrative example of Volkswagen's SSP platform, Figure 1 takes a look at all-VDI, which shows a single architecture driving a wide array of EV models.

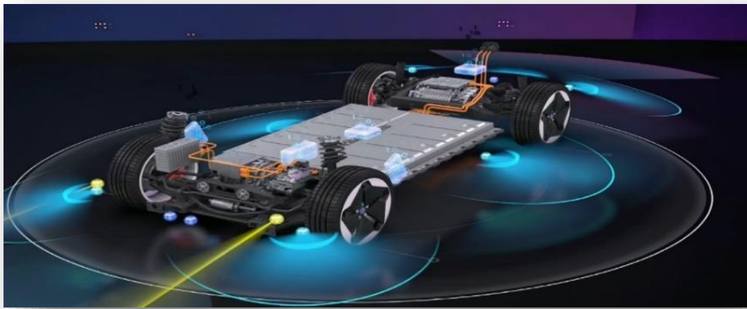


Figure 1: Volkswagen Group Scalable Systems Platform (SSP) [4].

It is worth noting; however, that the development of such architectures is not plain sailing. Designers need to balance between flexibility and performance, without letting modular systems fall behind in critical metrics such as range, safety or responsiveness. The introduction of emerging technologies (such as AI, machine learning, and V2G capabilities) brings further complexity to the table, which means the need for sophisticated software frameworks and high-bandwidth, low-latency hardware. In addition, safety standards must be observed throughout all the subsystem structures requiring redundancy, fault tolerance, and high standards of testing.

This paper seeks to explore the emerging design strategies that define next-level EV system architectures. It focuses on the integration of high-efficiency powertrains, intelligent battery management systems, and digital control units that collectively enhance performance and user experience. It also investigates how future-proofing through modularity, OTA updates, and adaptable platforms can extend vehicle lifespans and reduce obsolescence. Ultimately, the goal is to identify architectural principles that will support the development of electric vehicles that are not only technically advanced but also safe, sustainable, and adaptable to the demands of a rapidly changing mobility landscape.

1- Research Objective:

This research aims to explore, analyze, and define the essential design principles and technological components of advanced and high-performance system architectures for next-generation electric vehicles (EVs). The specific objectives of this study are:

1. To determine essential architectural requirements for the future EV platforms' ability to support high performance, modularity, scalability and reliability that will be in line with the emerging automotive standards and customer expectations.
2. To explore the incorporation of such advanced technologies as powertrains of high efficiency, next-generation battery system and intelligent energy management architecture to enhance system efficiency and driving range.
3. To examine the role of emerging digital technologies, including artificial intelligence (AI), machine learning (ML), and real-time data processing, in enhancing vehicle autonomy, predictive maintenance, and adaptive control strategies.
4. To assess system-level design strategies that enable seamless connectivity, such as vehicle-to-grid (V2G) and vehicle-to-everything (V2X) communication, ensuring optimized energy usage and interoperability within smart infrastructure [5].
5. To evaluate adaptive and future-proof system architectures that support over-the-air (OTA) updates, component upgrades, and integration of new functionalities throughout the vehicle's lifecycle.

6. To address challenges related to safety, cybersecurity, and system redundancy, ensuring robust and fault-tolerant operation in increasingly complex and connected EV systems.

Through these objectives, the research seeks to contribute a comprehensive framework for the development of next-generation EV architectures that are not only high-performing and intelligent, but also sustainable, secure, and adaptable to future technological shifts.

2- Basic Concept of Electric Vehicles Architecture

The design and evolution of vehicle electrical/electronic (E/E) architecture is a foundational element that influences virtually every aspect of E/E system development, including technical strategies, functional requirements, design decisions, and implementation methodologies. In the context of electric vehicles (EVs), where digitalization and intelligent control are central, the E/E architecture forms the backbone that enables advanced capabilities such as autonomous driving, smart energy management, and seamless connectivity. This architecture can be understood from a physical and logical point of view. From a physical perspective, E/E architecture describes the spatial configuration and interconnections of the key elements, i.e. the electronic control units (ECUs), sensors, actuators, gateways, switches, wiring harness and power distribution system. It also speaks of how power is manipulated through the vehicle and the interconnections made between the various subsystems through in-vehicle networks like CAN, Ethernet, and LIN [6]. The other perspective, the logical perspective, deals with the flow of data between components and the orchestration of functionalities in software layers. The system is interested in signal routing, interfaces protocols, and interoperation between control logic, embedded software and data services. This mounting complexity of EVs as a result of the incorporation of autonomous capabilities and user-centric digital experience has mandated the move toward more sophisticated as well as scalable architectural models away from the traditional ECU per function approach. Originally each ECU was tasked the control of one function (ABS, airbag deployment etc), however this model has lacked to sustain as the number of features and control units have increased exponentially. In response automakers implemented domain controllers where a single controller handles a cluster of related capabilities (powertrain, chassis, infotainment) drastically reducing wiring complexity and enhancing computational efficiency.

More recently, zonal architectures have emerged as a leading paradigm in next-level system design. In zonal architectures, ECUs are organized based on vehicle regions (e.g., front-left, rear-right), with each zonal controller managing power distribution, data acquisition, and signal routing for all components in its physical zone [7]. These controllers serve as intelligent gateways and switch nodes, supporting various interfaces for sensors, actuators, and displays. Figure 2 illustrates the hierarchical shift from function-specific to zonal architectures, highlighting how computation and control have been distributed more strategically within the vehicle.

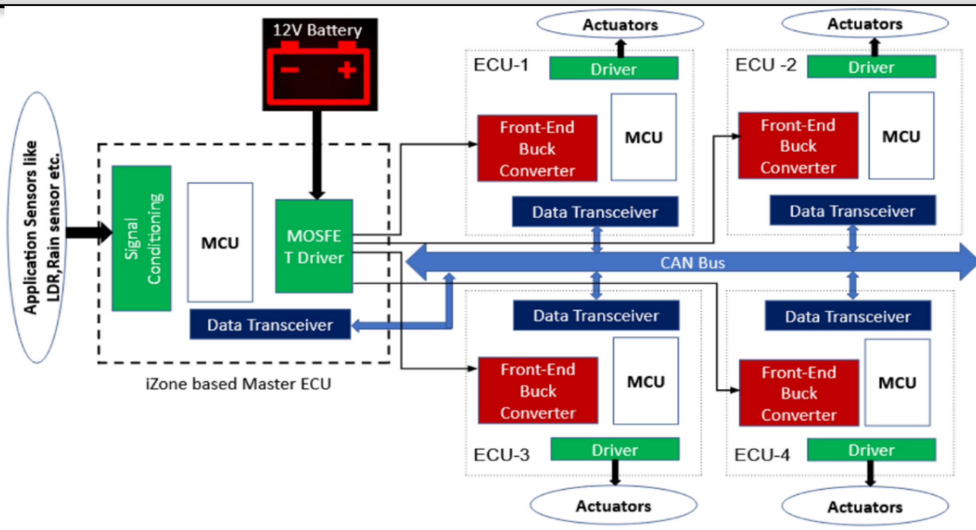


Figure 2: Evolution of ECU

Architecture in Modern EVs [8].

At the top of this architecture resides the central high-performance computing unit (HPCU), a powerful multi-core ECU that integrates multiple systems-on-chips (SoCs), GPUs, deep learning accelerators, RAM, and edge AI capabilities. The central unit is responsible for such computationally heavy applications as object recognition, path planning, and sensor fusion that are needed for advanced driver-assistance (ADAS) and autonomous driving. Further, the HPCU is often a centralized gateway and orchestration layer, working with zonal controllers and providing a vehicle-to-the-world connectivity to the external cloud services. The scalable and upgradeable nature of this solution can support over-the-air (OTA) updates, capability for cloud computing integration and adaptive AI models, making it an essential enabler of futureproof system architectures in EVs [9]. The coming together of the high demand for compute, the increase in sensor count, as well as the need for real time response has redefined the core structure of EV system design. The E/E architecture should now accommodate apart from safety-critical functions, non-critical functions like in-vehicle infotainment, game play and personalisation of the drives while ensuring that it preserves the sole of cybersecurity, latency and energy efficiency. As shown in Table 2, the transition from distributed to centralized and zonal architectures is closely tied to the broader transformation of EVs into software-defined, AI-enabled, and energy-interactive mobility platforms.

Table 2: Comparison of E/E Architectural Paradigms in EVs [10].

Architecture Type	Characteristics	Limitations	Relevance to Next-Gen EVs
Function-specific ECUs	Dedicated ECU per function; simple design	Excessive wiring, poor scalability	Limited
Domain Controllers	Grouped by functionality (e.g., chassis, infotainment)	Still partially centralized	Transitional
Zonal Architecture	Grouped by vehicle region; distributed data/power handling	Requires robust network protocols	Highly relevant
Central HPCU	Centralized compute hub; cloud and AI integration	High complexity, thermal concerns	Essential for autonomy, AI

This progression in E/E architecture aligns with the central thesis of this paper: that next-level system architectures in EVs must support modularity, scalability, and high-performance processing to enable the integration of cutting-edge technologies. From intelligent control loops to V2G energy exchange, and from edge AI to centralized data fusion, the evolution of the vehicle's electrical and electronic system is both a driver and an enabler of innovation in electric mobility. As automotive systems become more autonomous, software-defined, and cloud-connected, the role of E/E architecture becomes not just structural, but strategic shaping the future capabilities, safety, and adaptability of electric vehicles.

Figure 3 illustrates the historical transformation of electrical /electronic (E/E) architectures in vehicles. At first, there is a distributed E/E architecture in which ECUs specialized to unique functions are connected with a CAN bus and incorporated into a single unit by a central gateway. The inclusion of a central gateway eases controller control among ECUs, and makes functions such as adaptive cruise control viable, while allowing unrelated systems to interact [11]. Further, the domain-centralized E/E architecture is presented, with ECUs organized by functional domains. In this scenario, function specific controllers have CAN and Ethernet as forms of communicating with domain specific ECUs. A central gateway ECU remains an important element of architecture. This arrangement streamlines complicated vehicle operations and delivers cost efficiency by combining related functions of systems. An instance is a domain specific ECU for parking assistance that incorporates two function specific controllers responsible for vision processing and handling actuator command such as braking and steering. Domain-centralized architectures, as they have evolved, have become complex, now responsive to parts such as the car's wiring harness. The development of autonomous driving has given these systems even more Headache, because the deployment of additional sensors and actuators brings higher demands of data handling, network throughput and intelligent power systems. In future, zonal architecture, driven by a central High-Performance Computing Unit (HPCU) [12], will be critical in addressing the issues of prior E/E architectures. This set-up results in savings on cost and weight, facilitating next-generation vehicle functionality and innovations. The zonal architecture shown in figure 3 is composed of HPCU, zonal ECUs, and dedicated function-specific ECUs. As the primary controller within the system, HPCU controls vehicle zone data traffic and other centralized control tasks. It takes the position of the main data hub, relying upon high speed of Ethernet to transfer data between the zones in an efficient way, as it is needed to deal with the increasing amounts and bandwidth demands. Relevantly, this architecture supports virtual domains allowing embedded car operations to run in the cloud. This allows software dauloads and updates to go straight from the air to the HPCU.

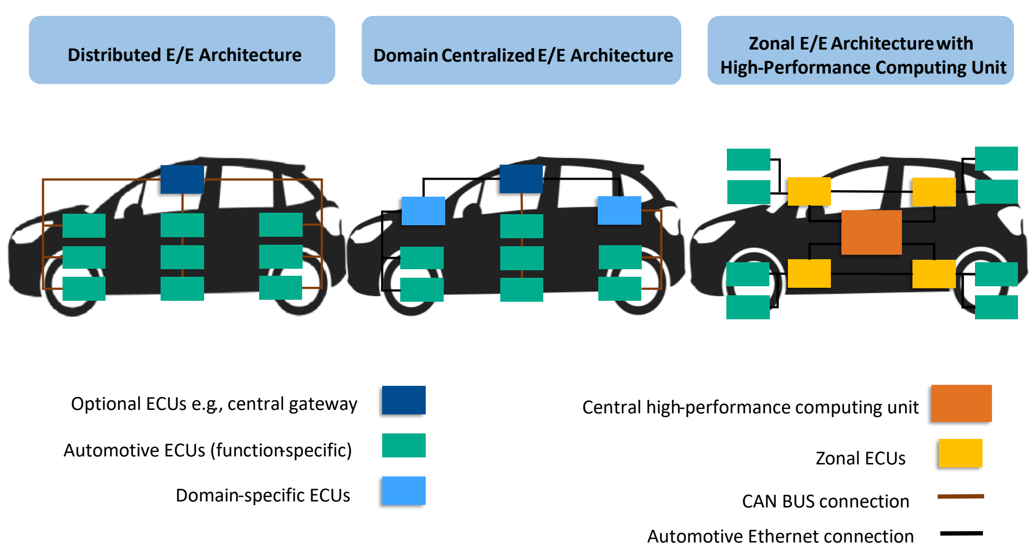


Figure 3: The figure shows how vehicle e/e architecture has changed over time. until 2019, cars mostly used a distributed e/e system. today's vehicles use a domain-centralized setup, and the future will likely use zonal architecture [13].

2.1- The Main Bottlenecks of Current E/E Architecture

Numerous vehicle specifications can be accommodated by today's E/E architectures. But now they are failing to meet the demands of self driving and future cars. As the vehicles become more complex (along with the necessity of increased compliance with safety regulations), future ECU systems will require much more energy, highly sophisticated. One major limitation of current existent systems is communication bandwidth. Although CAN-based networks have worked for years, Ethernet is much faster and can cover greater distances than traditional in-vehicle networks. Ethernet supports higher data rates, promotes system interoperability, and supports heterogeneous resource sharing which qualifies the technology to be suitable for autonomous cars which need advanced and in-depth data management [14]. Additionally, the future networks of vehicles will need to be low latency, persistent and secure in relation to data transfer, as well as robust protections against cyberhazards. New needs for connectivity from the outside such as OTA software updates or V2V communication highlight the need for high data throughput and complex security protocols. The adoption of advanced communication technologies such as automotive Ethernet for satisfying these requirements will be essential. It is also a challenging process to adapt new innovations to run on given E/E architectures. Unlike this integration process that showcases structural failings, which hampers creativity as easily scaleable. Therefore, autonomous vehicle E/E architectures should be designed with extensibility to facilitate the addition of new abilities and technologies without requiring a ground-up redefinition of the underlying system architecture. All in all, avoiding the disadvantages of existing designs requires the utilization of sophisticated computing, effective data exchange, and the implementation of rigorous automotive standards of security [15]. Meeting such features is fundamental for making it possible optimally to incorporate innovative solutions and safeguard the sustainability of future automobiles.

3- The Requirements-Driven Evolution of E/E Architecture:

Unlike previous reviews that primarily focus on technical classifications or architectural frameworks, this paper examines the evolution of electrical/electronic (E/E) architectures through the lens of evolving system requirements. In the automotive industry, shifting requirements have been a fundamental driving force behind innovation and architectural transformation [16]. As electric vehicles push the boundaries of performance, safety, connectivity, and efficiency, E/E architectures have had to evolve rapidly to meet these escalating demands.

The development of automotive technology has followed distinct phases, each marked by new performance goals and system constraints. Serving as the foundational infrastructure for managing and coordinating electronic components, E/E architectures are critical to the reliable operation of modern vehicles. The tension between emerging requirements and existing technological limitations has consistently catalyzed both incremental improvements and disruptive innovations in E/E system design [17].

The key requirements propelling the evolution of E/E architectures include:

- Seamless interconnection and integration of electronic control units (ECUs);
- Enhanced vehicle performance across braking, stability, safety, and energy efficiency;
- Reduction of overall system cost and weight in vehicle manufacturing;
- High-bandwidth, low-latency in-vehicle communication networks;
- External connectivity with cloud services, infrastructure, and user devices;
- Flexible decoupling of hardware and software to support scalability and modularity.

These requirements not only reflect market-driven imperatives but also stimulate academic inquiry into next-generation automotive architectures. In turn, breakthroughs in academic research continue to influence industry practices, creating a dynamic feedback loop that accelerates the development of advanced and high-performance system architectures for the future of electric vehicles.

3.1- Point-To-Point Architecture:

The trajectory of modern electric vehicle (EV) system architectures is deeply rooted in the century-long evolution of automotive electrical systems. A huge milestone was made in 1912 when the first electric starter motor was introduced by the Dayton Engineering Laboratories Company (Delco), thus eliminating the need for manual cranking, and it started a change in usability and electrical design of the vehicles [18]. In the same year a 7V DC generator was developed for vehicle battery charging as well as powering early lighting and ignition systems. The groundwork was laid for more elaborate energy management which continued to grow in 1955 with the whole industry switching to 12/14V electrical systems an important step in accommodating and supporting the ever-increasing number of onboard electrical devices [19].

During the 1970s, the automotive industry began transitioning into an era of electrification. Electronic components increasingly replaced mechanical systems, with notable examples including transistor-based ignition systems and diode-rectified alternators [20]. At this point the idea of a defined electrical/electronic (E/E) architecture was still in its infancy largely as a result of the minimal electronic contents of cars and trucks. However, as electrical systems slowly replaced mechanical and hydraulic systems, new criteria became relevant especially need for higher electrical energy supply and improved system integration. A significant step up in the development of E/E architecture occurred after the entry and quick growth of integrated circuits (ICs). The transition from the small-scale ICs to very-large-scale integration (VLSI) facilitated development of the complex automotive networks. Electronic control units (ECUs) were progressively adapted to different vehicle areas including engine management, breaking, and airbag distribution. These innovations greatly boosted the performance as well as the safety of the vehicles. Originally, these electronic modules were linked with point to point wiring marking the onset of increased connection of separated systems into electronic world. This basic step progression is summarized in Table 3 and the important milestones are drawn in Figure 5.

Table 3: Key Milestones in the Evolution of Automotive Electrical Systems [21].

Year	Milestone	Description
1912	Introduction of Electric Starter Motor	First electric starter by Delco marked the beginning of automotive electrification.
1912	Development of 7V DC Generator	Enabled battery charging and powered basic lighting and ignition systems.
1955	Transition to 12/14V Electrical Systems	Standardized voltage to support increasing electronic load in vehicles.
1970s	Electrification of Vehicle Subsystems	Replacement of mechanical parts with electronic ignition and alternators.
1970s	Emergence of Integrated Circuits (ICs)	Enabled early ECUs and laid the groundwork for networked automotive electronics.

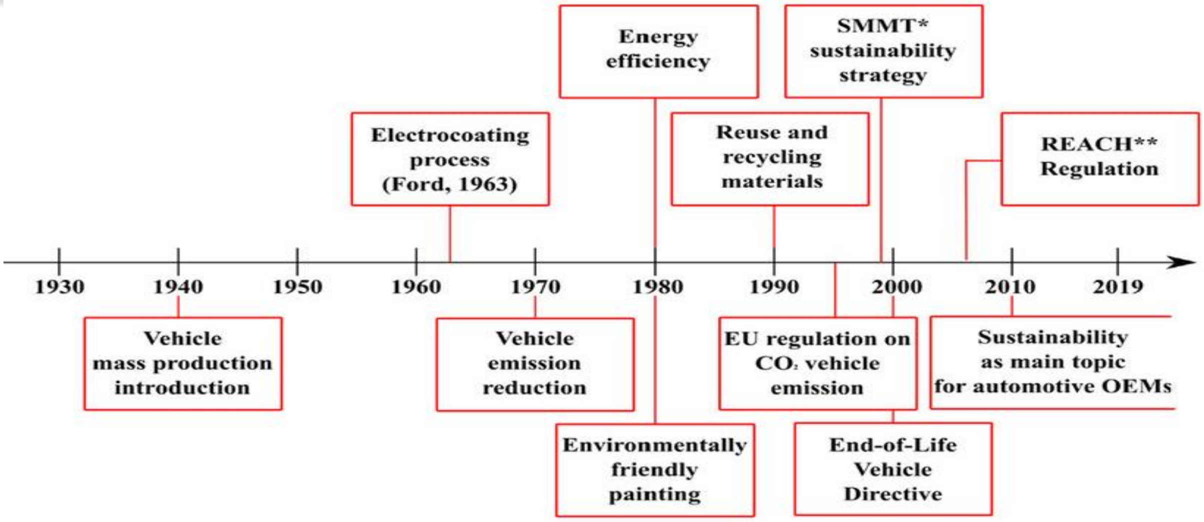


Figure 4: Timeline of Automotive Revolution [22].

Each stage in the historical evolution of automotive electrical systems has contributed directly to the architecture of today's electric vehicles. The foundational innovations in voltage systems, integrated electronics, and system connectivity have paved the way for the high-performance, scalable, and software-defined E/E architectures that are now central to the future of electric mobility.

3.2- Architecture Equipped with Vehicle Bus:

Beginning in the 1980s, the electronic transformation of automobiles gained considerable momentum, driven by increasingly stringent requirements related to vehicle safety, emissions control, and energy efficiency. In less than several years numerous electronic control systems were developed; electronic fuel injection, ignition and emission control systems, the anti-lock braking system (ABS), airbag deployment, anti-collision technology, global positioning (GPS) navigation and onboard fault diagnostics were just a sample. Major advancements in technology made it possible for many of the classical electro-mechanical and electro-hydraulic systems to be virtually replaced by more complex electronic ones [23]. At the heart of this transition was the proliferation of microprocessors into vehicles that could serve different functional needs by intelligent control. Coupling these technologies improved control precision, performance for the vehicle and provided the foundation for modern electronic/electrical (E/E) architectures [24]. But, even as electronic control units (ECUs) increased, the wiring harnesses required for wire-pairing purposes became increasingly complex. The old point to point wiring method was no longer practical, with too much bulk, too much weight, and poor maintainability and reliability.

To address these limitations, fieldbus communication systems were introduced. Fieldbus technology significantly reduced the number of physical wires required by enabling multiple ECUs to communicate over a shared digital bus. This approach allowed for real-time communication and coordinated control among vehicle subsystems using a few centralized communication lines, dramatically improving efficiency and scalability [25]. Initially, manufacturers developed proprietary bus systems, resulting in inconsistencies that hindered assembly, packaging, and interoperability. The industry responded by moving toward standardized, modular bus architectures, enabling more seamless network integration, easier design revisions, and faster mass production. A major milestone occurred in 1983 when Bosch GmbH introduced the Controller Area Network (CAN) the first standardized fieldbus [26]. CAN was formally standardized in the early 1990s and has since become the foundation of in-vehicle communication systems.

Building on this foundation, a variety of fieldbus systems were developed to address domain-specific requirements within vehicles. These include:

- ➢ Local Interconnect Network (LIN) for low-speed, cost-sensitive subsystems;
- ➢ Media-Oriented Systems Transport (MOST) for high-bandwidth multimedia applications;
- ➢ FlexRay for high-speed, fault-tolerant control systems in safety-critical domains.

This evolution is summarized in Table 4 and illustrated in Figure 6, which show the progressive shift from point-to-point wiring to bus-based modular architectures.

Table 4: Evolution of Automotive Communication and Bus Technologies [27].

Era	Communication Method	Key Technologies	Limitations Addressed
Pre-1980s	Point-to-point	Basic wiring harness	High complexity, weight, poor maintainability
1980s–1990s	Early proprietary buses	Manufacturer-specific protocols	Incompatibility, difficult packaging
1990s–2000s	Standardized buses	CAN, LIN	Enhanced interoperability, reduced wiring
2000s–present	High-speed & domain-specific buses	FlexRay, MOST	Real-time control, multimedia integration

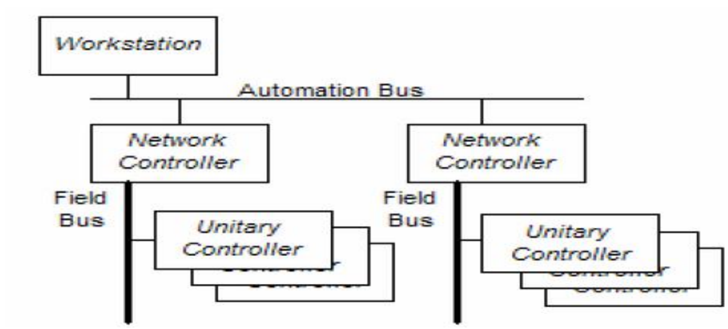


Figure 5: Transition from Point-to-Point Wiring to Fieldbus-Based Architectures [28].

By enabling reliable, efficient, and scalable communication between distributed ECUs, fieldbus systems have become a cornerstone of modern E/E architectures. Their standardization has not only improved performance and reduced cost but also facilitated the mass production of increasingly complex vehicles including today's electric and autonomous vehicles.

3.3- Architecture Equipped with Centralized Gateway:

To fully exploit the strengths of various control systems and build cost-effective, high-performance automotive networks, the use of domain-specific fieldbuses and gateway-connected architectures has become standard practice. These solutions enable modular and scalable E/E (electrical and electronic) architecture which has different control domains; powertrain, body, infotainment, and safety; interconnected through centralized gateway. Such a design is already being used by leading manufacturers for many years – for instance, in such models as the Volkswagen Passat, BMW 7 Series and Audi A8. Historically, power delivery systems were simple with the loads directly connected mechanically from the 12V battery to relay or switches which were then linked to the headrest switches. But, as the number of ECUs and electrical devices grew, their wiring harness became more complex, heavier, and costly. The introduction of high-power loads, such as electric heating systems, electric air conditioning compressors, and pumps, twice increased the load on the 12V

system, which was no longer sufficient to satisfy modern electrical needs.
In response, the automotive industry began exploring high-voltage electrical systems, notably 48V and 42V power networks, starting in the early 2000s. This gave rise to the dual-voltage power supply architecture, combining traditional 12V systems with higher-voltage buses for power-intensive components. This configuration enabled smoother integration of next-generation features while ensuring backward compatibility. Table 5 summarizes the evolution of automotive power systems, and Figure 7 illustrates the transition from centralized to decentralized power distribution systems.

Table 5: Evolution of Automotive Power Supply and Distribution Architectures

Era	Voltage System	Key Features	Limitations Addressed
Pre-2000s	12V Only	Simplicity, legacy compatibility	Inadequate for high-power applications
Early 2000s	42V / 48V Introduced	Supports power-dense systems (e.g., electric turbochargers)	High power efficiency, reduced current losses
2010s–Present	Dual-Voltage (12V + 48V)	Split architecture: control (12V) + power (48V)	Enhanced scalability and transition path

As power networks evolved, traditional junction boxes gave way to intelligent power distribution units (PDUs). Unlike their predecessors, PDUs incorporate features such as real-time diagnostics, power management, and electronic switching, reducing wiring complexity and enhancing overall system reliability. Modular PDUs allow for distributed power architecture, which places power modules closer to loads, further shortening cable lengths and reducing harness weight. Decentralized power distribution has shown clear advantages over centralized models. Studies and real-world applications in European vehicles demonstrate measurable reductions in circuit length, harness weight, and production cost.

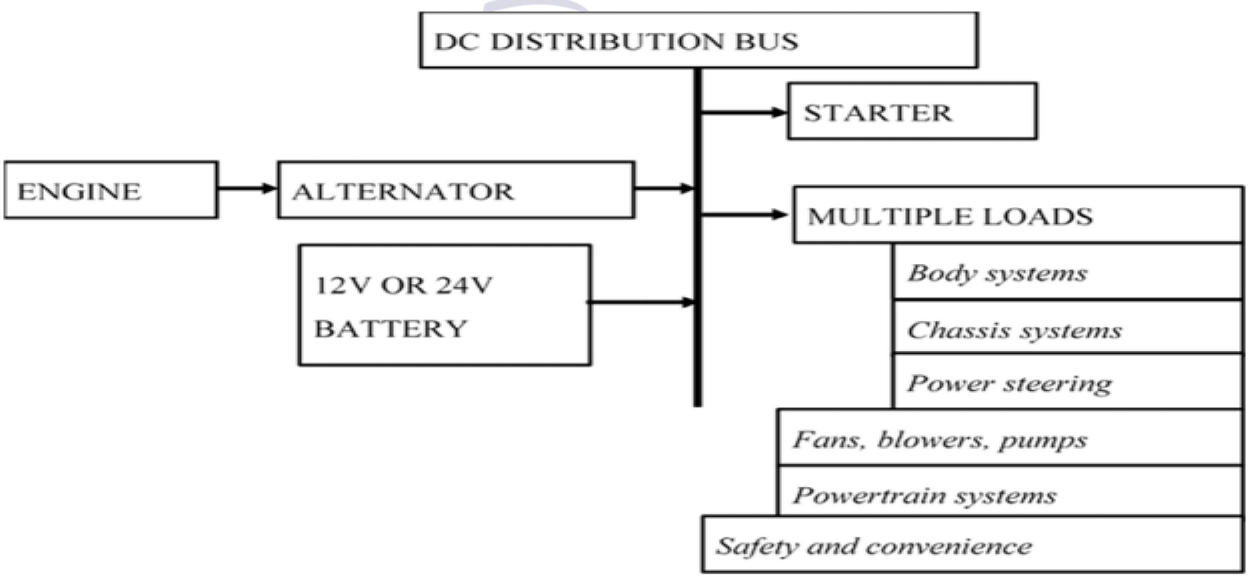


Figure 6: Evolution of Power System Architecture in Modern Vehicles [29].

In parallel, other innovations such as replacing mechanical fuses with solid-state fuses have improved reliability and simplified maintenance. These electronic fuses can be installed in less accessible but optimal locations, further reducing the physical complexity of power supply routing. Lastly, centralized gateways continue to play a vital role in managing in-vehicle communication [30]. Beyond enabling protocol conversion across subnetworks (e.g., CAN, LIN, FlexRay), they also perform essential functions such as traffic regulation, security management, and software over-the-air (OTA) updates [31]. As the number of ECUs and electric loads continues to grow, the integration of high-voltage power systems, modular PDUs, and intelligent gateways is increasingly critical to achieving a scalable, reliable, and high-performance E/E architecture suited for next-generation electric vehicles.

3.4- Domain-Based Architecture:

Traditionally, electronic control units (ECUs) have been designed to handle specific applications within the vehicle, such as electronic power steering or brake control. Although some of the ECUs cooperate with each other (for ex. of brakes/airbags) to promote integrated safety of the vehicle, a lot of ECUs operate individually, processing sensor data and running the algorithms locally. The number of ECU added for each newly introduced automated driving function results in an exponential increase in system complexity as the quantity of automated driving functions increases. Excessive decentralization leads to complex wiring, ineffective networking performance, and slower speeds of communication for the important information. All components and sensors in the traditional centralized gateway-based architecture are connected to a single central gateway. Intradomain and cross-domain communications all go through this gateway where it typically becomes a bottleneck at high data throughput where bandwidth and latency demand continue to grow. Further, failure by the centralized gateway can undermine the entire network, thereby experiencing severe operational problems.

To address these challenges, leading automotive suppliers such as Bosch, Continental, and Delphi have introduced Domain Control Units (DCUs) to help manage system complexity and reduce the burden on gateways. DCUs serve to compartmentalize the vehicle's network into functional domains, each handling a specific set of ECUs with shared communication access. The adoption of DCUs has alleviated some of the stress on the network by providing localized processing within each domain, reducing reliance on the central gateway and improving system performance and information security [32]. Still, domain-based architectures implementation complicates the system design at a more expensive level. Furthermore, it is incumbent upon future E/E system development that an Ethernet backbone is incorporated for inter-domain communication. The isolation of ECUs depending on their functions is a vital advantage of domain-based architecture that increases performance and network management. In this system, the gateway acts as an interface to different domains, and coordinates the communication between multiple subsystems. In fact, domain-based architectures are now widely implemented in the contemporary automobiles. These architectures are also usually classified into key domains including Body, Powertrain, Chassis, Infotainment, ADAS (Advanced Driver Assistance Systems), and Telematics, as shown in Table 6 [33]. In particular, the ADAS domain has grown rapidly, stimulated by the growing market interest in autonomous driving possibilities as well as safety aspects. DCUs for the ADAS domain are commonly based on high performance computing processors and provided by solution providers like NVIDIA, Infineon, Renesas, TI, NXP and Mobileye.

Table 6: Commonly Applied Automotive E/E Domains

Domain	Key Components	Key Functions
Body	Body control ECUs, lighting, door modules	Lighting, door locks, windows, comfort
Powertrain	Engine control, transmission, battery management	Engine, powertrain control, fuel efficiency
Chassis	Anti-lock braking, suspension, steering systems	Safety, stability, suspension control
Infotainment	Navigation, multimedia, voice control systems	Entertainment, communication, media
ADAS	Radar, cameras, ultrasonic sensors, ECUs	Autonomous driving, lane assist, safety
Telematics	GPS, communication ECUs	Vehicle tracking, remote diagnostics

Despite its advantages, domain-based architecture comes with challenges. When local processing is insufficient, delays between the sensor and actuator must be carefully managed to ensure deterministic system behavior. In this regard, automotive Ethernet and Ethernet switches are key enablers, but careful consideration of communication latency and guaranteed delays is required for critical functions. Table 7 provides an overview of the benefits and challenges of domain-based architectures

Table 7: Advantages and Challenges of Domain-Based E/E Architecture

Advantages	Challenges
Reduced complexity in wiring and network management	Increased cost and system design complexity
Improved communication efficiency with domain isolation	Need for high-performance processors in some domains (e.g., ADAS)
Enhanced security and reliability with local processing	Potential delays if local processing is insufficient
Scalability for new functions and technologies	Need for guaranteed deterministic delays in critical systems

In conclusion, domain-based E/E architecture represents a significant advancement in automotive network design, effectively addressing the growing complexity and performance demands of modern vehicles. By decentralizing control and adopting high-speed communication technologies like Ethernet, these systems offer scalability, improved reliability, and better handling of the increasing number of automated driving functions. However, challenges related to communication latency and processing delays remain critical considerations as the industry moves toward fully autonomous and connected vehicles.

3.5- Zone-Based Architecture:

To minimize wiring costs and weight, Brunner introduced the zone-based architecture, which integrates components based not only on their functional domains but also on their physical location within the vehicle. This method departs from the categorization of the parts merely on their function and hence the need to re-examine the automotive software and hardware platforms. The key benefits of this architecture reside within reduced engineering time and costs via re-use of components as well as easy cross vehicle integration of systems. The zone-based architecture as well provides an advantage to power supply system. Within this configuration, area controllers are able to act as both communication center and source of power to their respective' peripheral' elements thus negating the need for separate wiring systems [34]. Whereas conventional systems used separate networks for communication and for power, the introduction of Ethernet technology allows the merging of these networks resulting in less cabling as well as less cost while providing more flexibility in the overall design of the network.

One prominent advancement in this area is Power over Ethernet (PoE), a technology that allows power to be transmitted alongside data over an Ethernet cable. The first PoE standard, IEEE 802.3af, introduced in 2003, supported up to 15.4W, while the later PoE+ (IEEE 802.3at) standard increased the power capacity to 25.5W [35]. Nevertheless, traditional PoE technology does not fit directly in the automotive Ethernet, since PoE uses a 4-pair cable system whereas automotive Ethernet uses BoardR-Reach which uses unshielded twisted-pair, a single pair of wires. In an attempt to fix this, the IEEE 802.3bu standard developed Power over Data Lines (PoDL), a new power delivery standard that is specific to automotive and industrial. Overall, the zone-based architecture drastically minimizes cabling requirements, in particular, for Ethernet-based systems that unify both power and communication. Nevertheless, it also implies heightened requirements for software platforms in response to the necessity for efficient management of location-based clustering of components. The table showing the Comparison between different E/E architectures can be seen from Table 8

Table 8: Comparison with different E/E architectures

Type	Features	Strength	Weakness
Point-to-point architecture	Electronic devices were connected directly with the actuator.	Isolated mechanical or hydraulic systems were connected.	Only few components were electrified and connected
Vehicle bus based	The signal transmission between all ECUs can be completed through a few buses	Standardization and modularization of vehicle bus made the E/E architecture easier	A great variety vehicle bus and the data transmission speed were low
Centralized gateway based	Different subnetworks with different vehicle buses were connected with a centralized gateway	The gateway converts different protocols and regulates network traffic, security of the automotive bus system is improved	As the number of ECUs increase, functions of the gateway could be very complex, which is harmful for security
Domain-based	DCUs integrate a portion of the ECUs, contain specific software components and reduce the material costs and weight in automotive manufacturing	DCU effectively improved the gateway load and ECU bottleneck problems, the complex and cost could be decreased	Additional delays that may be introduced between the sensor and the actuator.
Zone-based	Electronic components can be integrated based on their physical location in the vehicle.	Zone-based architecture is greatly beneficial in reducing cabling, especially for Ethernet, with the combination of communication and power.	The architecture entails higher requirements for software platforms owing to the location clustering.

4- State-of-the-Art E/E Architecture:

SAE divided automated driving into 6 different levels. The levels of the diversity represented by the degrees of vehicle automation are differentiated. With the vehicle system assuming human driver responsibilities, the need for improved sensing and fallback to more intelligent decisions increases. The architecture's capability to improve perception and processes of decision-making is an essential part of the architecture for autonomous intelligence development. It requires a vehicular E/E architecture that has a high bandwidth; low latency; high flexibility, and high scalability.

In this way, the existing bottlenecks of automotive E/E architecture can be summarized as follows:

1) Bandwidth bottleneck: As a result of the proliferation of sensors, which has led to a resultant data volume surge, the bandwidth in traditional in-vehicle systems has been limited.

2) Wiring complexity: Fattened wiring complexity and harness bulk resulting from expanded nodes are problematic for car repair, counterproductive for weight loss, and impair power performance and economy.

3) Low deterministic latency: Intra-domain and cross-domain communications volume continues to increase; meanwhile the existing bus technologies are not capable to meet the requirements for low deterministic latency in highly concurrent and heavily trafficked environments.

4) Flexible architecture and scalability: The process of controlling online upgrades, maintenance, scalabilities, and the dynamic network configuration of vehicle equipment is complex.

To the outlined bottlenecks, standardization groups together with OEMs, suppliers, and academia researchers are collaborating towards E/E platforms development and refinement, as shown in Fig.2 that will be described below.

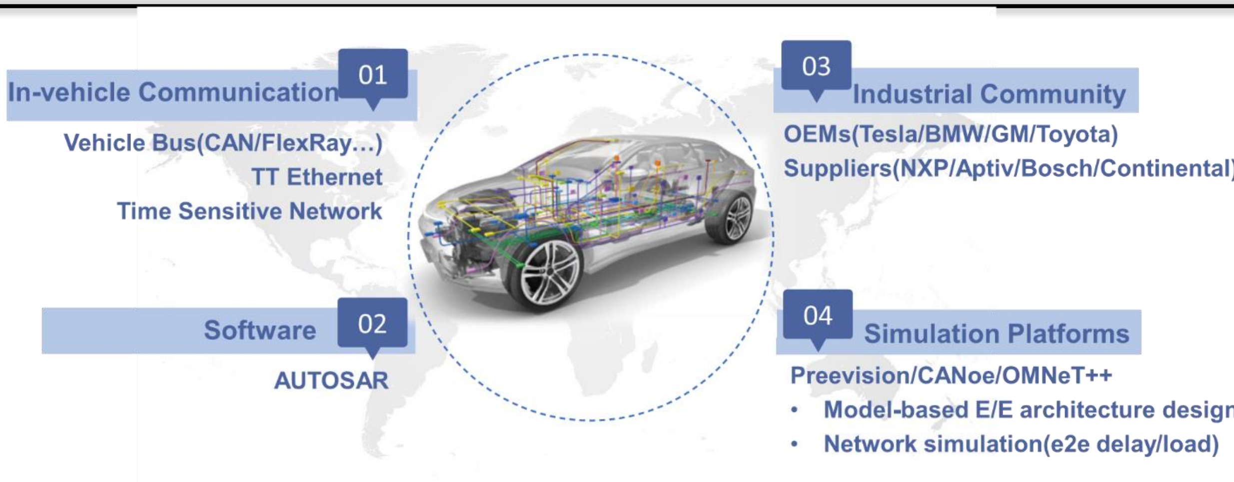


Figure 7: State-of-the-art E/E architecture [36].

5- Prospective Trends for E/E Architecture:

The automobile of the future is increasingly being conceptualized as a "computer on wheels," reflecting the deep integration of electronic systems across all vehicle functions. As such, the innovation of electrical/electronic (E/E) architecture is not just necessary it is inevitable. The E/E architecture is expected to evolve into a “communication-control-computation” platform, serving as the foundational layer for advanced functionalities such as autonomous driving, connected services, and intelligent energy management.

There are constship trends behind this change, which are promoted by continuous improvement of the technology. These are developments in the overall system architecture, in-vehicle communication networks, the power supply systems and the software platform that are all projected to experience massive upgrading over the next decades. Figure 9 shows how these evolving aspects are depicted in the future-oriented versions of next-generation E/E architectures. With the emergence of automated driving technologies, we expect to see an exponential increase in the number of electronic components including ECUs, sensors, actuators, and processors. It is inferred from a fully autonomous (SAE Level 5) vehicle that more than 4,000 electronic nodes could be integrated into the system [37]. The complexity at this level necessitates high-performance computing and high bandwidth low latency communication networks for real time data processing and control. In addition then, future systems need to support converged transmission of both power and data to counteract the increasing complexity and weight of the established wiring configurations. Such an approach not only eases the design of the harnessing mechanism but also improves efficiency and flexibility in the vehicle design in general.

5.1- Architecture:

Domain-based E/E architectures will continue to dominate the automotive landscape today, and in the future. This is largely as a result of the relative maturity of intelligent driving technologies and the limitations of the existing platforms of vehicle production. Nonetheless, some progressive automotive manufacturers have started to take to adopting zone-based architectures, which are generally felt will be the direction for the industry in the next decade or so. With continued increase in computing power, there is enhanced likelihood of a centralized computing platform. Future cars are supposed to operate more like mobile servers, being able to operate over large data volumes and perform computation heavy duties. At the same time, progress in cloud technologies is supposed to accelerate the virtualization of E/E architectures and turn them into more dynamic and software-equipped constructions. However, with the huge volume of senser/control data, along with the high latency demands of real-time applications (and especially the autonomous driving), a hybrid architecture of centralized and edge computing will be necessary. This distributed approach enables local data processing near the source (e.g. at the sensor or actuator level) thus; minimizing communication latencies and fast system responses [38]. Such a hybrid architecture improves the flexibility of ECU virtualization as that some functions can be dynamically assigned and executed at the edge. It also ensures resilience and security of the entire system by addressing the central processor dependency problem. In this model even in case where the central computing platform is compromised or fails, essential vehicle functions can continue to operate locally.

5.2- In-Vehicle Communication:

With the advancement of intelligent driving technologies, modern vehicles are increasingly equipped with a diverse array of sensors to meet the functional demands of automated driving. These sensors include cameras, LiDAR, ultrasonic sensors, and inertial measurement units (IMUs), among others. The integration of such sensors enables sensor fusion, which significantly enhances the reliability and comprehensiveness of environmental perception. However, this also has a stringent demand on the in-vehicle communication network, such as a higher bandwidth, grown reliability and deterministic low latency, which can serve little other than real-time computing platforms residing at higher-layer computing platforms. For example, cameras take a key role in object detection, recognition and classification. Cars can use various types of cameras including front-view, surround-view and interior cameras. A solitary 1080p 60fps camera might theoretically need up to 3Gbps bandwidth; while a 4K 60fps HD camera may require more than 10Gbps. These figures are a clear indication that Ethernet-based in vehicle networks are the necessary solution that will be used to satisfy the communication needs of future vehicles [39].

Concurrently, the safety-criticality of decision-making processes in autonomous vehicles is making low & predictable latency in transmission of data imperative. The compromise of certain real time response capabilities of the vehicle can occur due to any delay or jitter in communication of important messages. With in-vehicle data traffic becoming more complicated, traffic scheduling and control mechanisms must be developed such that both critical and non-critical data streams meet their individual latency and quality of service (QoS) requirements. Furthermore, dynamic changes in the network topology and dynamic traffic patterns are characteristic of the growing complexity in automotive systems, which require redesigned static configurations. Modern vehicles have to be able to dynamically re-configure their in-vehicle networks to accommodate the incorporation of new sensors, ECUs or software-defined capabilities [40]. In this regard, Software-Defined Networking (SDN) has become an enticing solution. SDN provides dynamic network management of central surveillance, analysis, planning, and executing mechanisms. It can still provide QoS guarantees in situations where the network topology changes or new devices are added in. The use of SDN in automotive E/E systems is receiving growing attention in academia and industry, providing flexible and intelligent solution on how to orchestrate the network in future generation vehicles.

5.3- Power Supply:

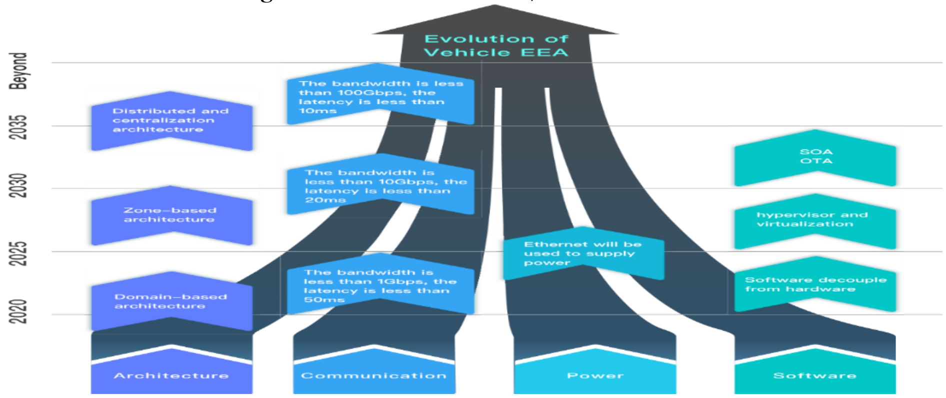
As vehicle systems become increasingly complex, the design of in-vehicle wiring harnesses is gaining significant attention. Optimizing wiring to reduce length and weight is critical for achieving vehicle light weighting, which directly contributes to improved fuel efficiency, enhanced electric vehicle (EV) range, and ease of maintenance. In this context, technologies such as Power over Ethernet (PoE) present a promising solution by allowing power and data transmission over a single cable, thereby minimizing wiring complexity. At the same time, the ongoing electrification of vehicles imposes more stringent demands on the power distribution network, particularly in managing electromagnetic interference (EMI) from high-voltage systems [41]. To ensure safety and signal integrity, special attention must be paid to shielding, filtering, and the strategic routing of cables. Proper electromagnetic compatibility (EMC) design is essential to maintain reliable communication and prevent signal degradation across the vehicle's electrical and electronic systems.

5.4- Software Platform:

Software has become an increasingly critical component in modern automotive systems, and this trend is set to accelerate as vehicles become more software-intensive. As a result, software engineering is becoming a core element of automotive electrical/electronic (E/E) architecture. Traditionally, automotive software updates were performed at vehicle service centers through a direct connection to the On-Board Diagnostic (OBD) interface [42]. However, the advent of SOTA has removed a number of the geographical and temporal limitations that attach to such updates. SOTA allows for the secure transmission of vehicle ECUs of the software packages developed by OEMs over Wi-Fi, cellular networks or satellite communications. This approach helps to fix software bugs and system weaknesses while minimizing warranty and recall costs, as well as enhances vehicle serviceability. Although these and other benefits seen, safety and operational availability of vehicles during OTA (over-the-air) updates continue to be a priority [43]. Vehicle downtime or even update failure may occur when communication failure or lack of battery power during the update process interrupts the latter. It means that power and system stability requirements during the deployment of software are therefore very important in SOTA implementation.

In parallel, the automotive industry is increasingly adopting Service-Oriented Architecture (SOA) as a flexible and scalable approach to manage complex software systems. SOA is a software design paradigm originating in the IT sector that facilitates the integration of distributed and heterogeneous components through standardized interfaces. One of the fundamental tenets of SOA is decoupling of services from applications, which allows the process of decoupling software from hardware is most relevant in dynamic automotive settings. SOA helps the modularization of applications into small, reusable services which can be easily shared, reconfigured and adapted across various platforms [44]. This high level of interoperability and reusability increases development efficiency and speeds up integration of new features. Its impact has been demonstrated in various industries including finance, industrial automation and the fields of transportation. In the automotive domain, SOA brings a promising end-to-end integration system for heterogeneous application and service management in the E/E system. But as more and more features exercised on the vehicles applications becomes more flexible, and the functionality increases so are the requirements for communication bandwidth and computational power. This has caused a convergence of SOA with automotive Ethernet, which enables the required infrastructure for high speed reliable in-car communications. Studies made by Gopu indicate that SOA can be implemented on automotive embedded systems successfully i.e modifying existing communication protocols or developing new standards [45]. For instance, AUTOSAR architecture supports SOA integration by means of SOME/IP enablers, enabling Service based Application deployment without penalizing legacy systems. In view of the further development of automotive Ethernet and the growing utilization of connected vehicle services, SOA should be becoming a building block of the future vehicle E/E architecture. Such automakers as BMW are already implementing SOA principles into their next-generation systems. Their approach initiates from service abstraction, strict encapsulation, and hierarchical architecture which minimizes complexity and improves scalability.

Figure 8: Future trends E/E architecture.



Conclusion:

The shift toward electric mobility represents not only a technological transformation but also a fundamental redefinition of vehicle architecture and system design. This paper has examined the critical components and emerging trends that will shape the next generation of high-performance electric vehicles (EVs), emphasizing the importance of modularity, scalability, intelligence, and connectivity in future system architectures. By integrating advanced powertrains, intelligent control systems, and cutting-edge technologies such as artificial intelligence, vehicle-to-grid (V2G) communication, and adaptive software platforms, EVs can achieve greater performance, efficiency, and user-centric functionality. Moreover, the study highlights the growing need for architectures that are not only high-performing but also resilient, upgradable, and secure capable of evolving alongside rapid technological advancements and shifting industry requirements. The integration of real-time analytics, predictive maintenance, and autonomous capabilities further positions EVs as dynamic, software-defined platforms rather than static mechanical products. Ultimately, the insights presented in this research underscore the critical role of advanced system design in driving the sustainability, reliability, and innovation of the automotive industry. As EV adoption accelerates globally, next-level system architectures will be essential in building vehicles that meet both the technical challenges and environmental imperatives of the future.

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