A Comparative Study of Automotive Electrical/Electronics (E/E) Architectures: From Past to Present

Miray Erdogan, Mehmet Emin Sariaydin

***Abstract*—The evolution of automotive Electrical/Electronics (E/E) architectures has undergone a huge technological improvement such as aeronautics, railway architectures. These changes are started from simple mechanically focused systems to complex, software-driven platforms. This study examines the comparison study of E/E architectures of automotives on many aspects from past, distributed Electric and Electronics Architectures to present, zonal centralized architectures across the harness complexity, electronic control units' functional capabilities/complexities and their numbers in vehicles, cost-efficiency of E/E Architectures, design philosophies. As a plus, this study includes the technologies that lights the future. Moreover, the research examines the shift from distributed E/E Architectures and domain-centralized designs to new zonal and software-defined models, starting with early distributed systems that had discrete ECUs and little integration. This transition reflects the automotive industry's broader move toward software-defined vehicles, where functionality is increasingly determined by software rather than hardware. All these systems will be explained with their advantages and disadvantages.**

Keywords: Automotive E/E architectures; zonal architecture; software-defined vehicles; electronic control units (ECUs).

I. INTRODUCTION

Life conditions of world have been evolved worse day by day. Fundamental evidence that sea level is increasing, and global warming existence impact occurs. According to the UN(United Nations)'s regular emission gas report, release of gas emissions to the world are increasing each year [1]. These increasing harmful gases cause to climate change. To keep under control emission levels, governments releases emission regulations to sell officially each vehicle inside country. Almost quarter part of greenhouse gas emissions of world root cause is from Transportation sector as can be seen in Fig. 1. The result of interpreting this table, of course, plays an important role in shaping the automotive industry.

Many OEM (Original Equipment Manufacturer) 's purposes that can manage to set up connection between variable customer expectations and presented products features. Due to aggressive vehicle electronics technologies evolution and quickly changing customer expectations in global world, the realization of this purpose is harder day by day. In addition to the development of current technologies and energy regulations, general safety regulations are another reason for the development of vehicle electronics. To set an example, safety regulations are mostly pioneer to the development of ADAS (Advanced Driver Assistance System) systems and their adaptation on the vehicle.

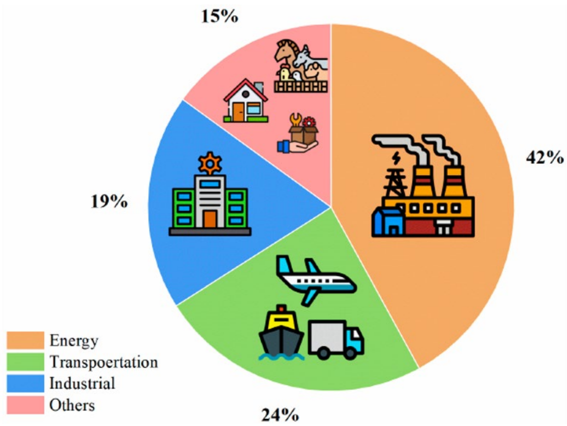

Fig. 1. Sectoral Approach for Greenhouse Gas Emissions [2]

When it is taking all into consideration, Electrical and Electronics Architecture has been evolving on many perspectives and systems which can be ADAS, Infotainment, Connectivity, etc. [3]. These evolutions are required bigger size of data and faster communication, on vehicle which is also increased complexity of EE Architecture. Next parts of this article will give detailed comparisons of Electrical and Electronics architectures which are basically related to past, current and future technologies. [1]

II. PAST EE ARCHITECTURES OF AUTOMOTIVES: DISTRIBUTED ELECTRIC AND ELECTRONICS ARCHITECTURES (BEFORE 2020)

Distributed automotive architectures, as shown in Fig. 3, assign dedicated electronic control units to handle specific vehicle functions, offering both flexibility and redundancy, and have long been a trusted and widely adopted method in the automotive industry [4]. Distributed electric and electronics architectures are still used in today's automotive industry but in literature it is accepted as the first EE Architecture from passing thought the mechanical vehicles to digitalized vehicles, therefore, in this article, this architecture type is considered in Past EE Architectures of

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Miray Erdogan is with the Renault Group, Turkey (miray.erdogan@renault.com)
Mehmet Emin Sariadyn is with the Renault Group, Turkey (emin.sariaydin@renault.com)

Automotives. Distributed Architectures are made up of function-specific ECU (Electronic Control Units) s linked to a central gateway through a CAN (Controller Area Network) bus [3]. ECU numbers could be between 40 to 100 in the vehicles equipped with distributed architecture. This huge number of ECUs could cause a complex process and requires of reverse engineering CAN dataset [5].A broadcast is made to function at up to 1 Mbps (Megabit per second) with messages(frames) of 0–8 bytes of data are used to send data[4].Furthermore, the wiring harness needed to link all distributed ECUs has significantly expanded—from just 55 wires totaling 150 feet in 1948 to around 1,500 to 2,000 wires stretching a mile and weighing approximately 120 pounds in vehicles using distributed E/E architectures in Fig. 2 , visually compares the typical cable lengths used in different vehicle E/E architecture types [6].The high ECU number, long harness routes in distributed systems makes the E/E architecture expensive in vehicles.

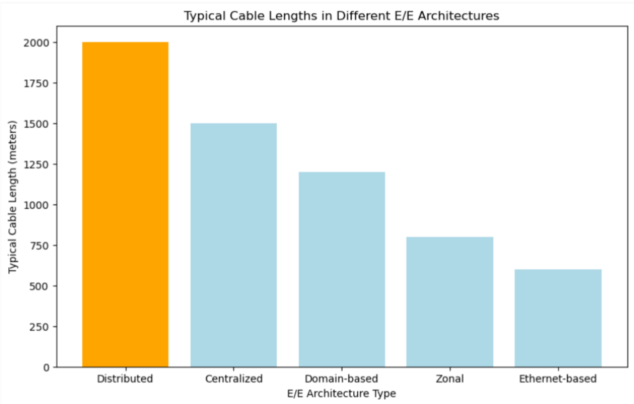

Fig. 2. Cable Lengths for each E/E Architectures [7]

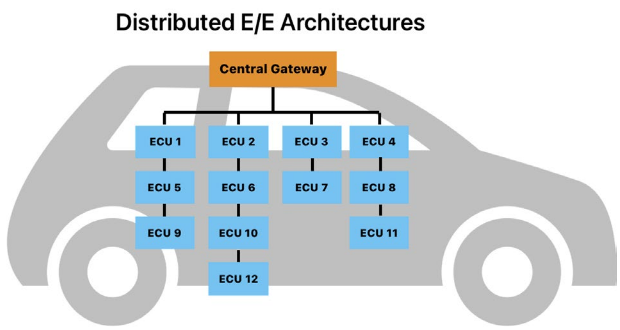

Fig. 3. Distributed E/E Architecture Schema

According to all given information in previous paragraph, it could clearly be observed that scalability of distributed E/E architectures is advantageous property. Because distributed database systems can readily add more ECUs to handle an increase in workload, they provide better scalability. Also, these systems are easily scalable vertically by raising the capacity of an ECU or horizontally by adding more ECUs. This scalability leads to optimal production and improved performance. Opportunity to update each ECUs separately makes this architecture system flexible. Moreover, it gets rid of bottlenecks and major points of failure. ECU redundancy guarantees that other ECUs can take over an ECU's responsibilities in the event of its failure.

Opposingly, being sprawl and complex, distributed E/E architecture could be hard to manage and organize. Fixing an error could take long when we compare Distributed Architecture to domain centralized and zonal architectures. Also, because data processing is dispersed among several ECUs that communicate with one another, a distributed system is more susceptible to cyberattacks [8]. Moreover, there are higher communication overhead between each ECUs.

TABLE I
ADVANTAGES AND DISADVANTAGES OF DISTRIBUTED E/E ARCHITECTURES

Advantages	Disadvantages
Scalability – Easy to add or remove components	**Complexity** – More difficult to design and manage
Fault Tolerance – Failure in one node does not crash the complete system	Debugging is harder due to distributed nature
Resource Sharing – Efficient use of distributed resources	**Higher communication** overhead between nodes
Flexibility – Components can be updated independently	**Increased cost** due to additional hardware and networking
Improved Performance – Tasks can be parallelized	**Security risks** due to multiple communication points
Real-time responsiveness in localized subsystems	

III. CURRENT ARCHITECTURES (2020 - 2025)

As we categorized current EE Architectures in 2020-2025, analyzed articles covers between this referred years interval in this section of article. According to segment of vehicle and number of features implemented, the ECU number could reach up to one hundred on today's vehicles. If the vehicle is high end class, the number could be up to 150 [9]. In addition to customer needs and technological developments on vehicle electronics, also General Safety Regulations and Emission regulations caused to feature increase on vehicle. To sell vehicle to target countries, automotive manufacturers must comply with these governmental regulations. Based on these regulations, evolutions could be mostly on Advanced Driving Assistance Systems (ADAS), Infotainment systems, Connectivity, Powertrain etc.

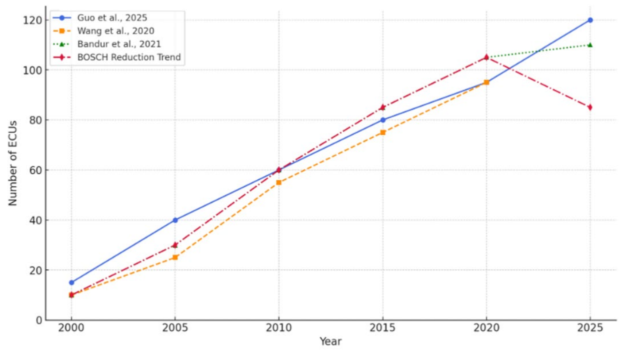

Fig. 4. Number of Electronic Control Units in Vehicle Over Time [10][11][12][13]

According to Fig. 4, ECU numbers will be increased year by year as the reasons which has been mentioned previous paragraph. However, as it could be seen on red lines, number of ECU's decreases after 2020. The fundamental reason that transformation from domain distributed E/E architecture to Domain Centralized, as shown on Fig. 5 or zonal E/E architecture, as shown in Fig. 6 which proposes powerful central computers instead of many numbers of Electronic Control Units which means that high communication network load, complexity, and more power consumption by enormous number of electronic components.

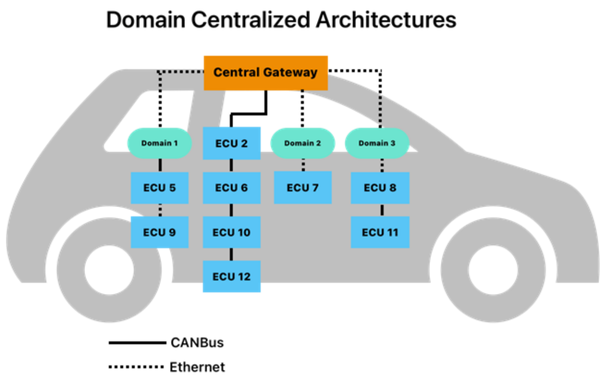

Fig. 5. Domain Centralized E/E Architectures Schema

Another modern Electrical Electronics Architectures approach examines several cross layers to decide efficiently. These methods which is called new cross-layer design, are based on to integrate function layer and architecture layer to improve feasibility and performance. They mostly focused on systems including hard deadlines. Especially, there are emphasized that it is inevitable to integrate many layers such as software, hardware, function layers. Also, it is suggested that to be implemented on aviation, cybersecurity and IOT(Internet of Things) based systems [11].

TABLE 2
DOMAIN-BASED ELECTRICAL/ELECTRONICS ARCHITECTURE IN AUTOMOTIVE

Advantages	Disadvantages
Network Load Optimisation- Fewer ECUs in domain centralized/zonal architectures reduce network load, complexity, and power consumption.	**Development Cost -** More complex centralized systems may lead to higher development costs and security vulnerabilities.
Efficiency - Cross-layer designs enhance feasibility and performance, especially under hard deadlines.	**Complexity**- Integration of multiple layers increases system complexity and potential impact of failures.
Regulation Requirements Compatibility - Better compliance with safety and emission regulations enables advanced features (ADAS, infotainment, connectivity).	
Sectoral Application-Applicable to aviation, cybersecurity, and IoT systems.	

IV. FUTURE ARCHITECTURE

Zonal E/E Architecture includes high computational power control units that can handle many ECU's activities. Due to current ECU performance limitations and costs increase, there could not be sudden change from domain distributed E/E architecture to zonal E/E architecture in a couple of years. However, these transformations are not going to be so far. The intermediate phase of this transformation has started as Domain based E/E architecture with including Central Domain Master (CDM) units that can manage communications and activities on domain-based EE architecture, specified domain masters are occupied depending on E/E architecture of vehicle such as chassis, ADAS, infotainment etc. [3].

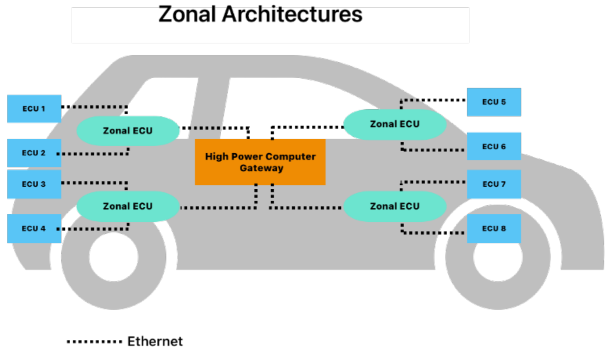

Fig. 6. Zonal Architectures Schema

According to widely used of Zonal EE Architecture, Software Define Vehicles are inevitable. The rapid progression of artificial intelligence (AI) and machine learning (ML) technologies has enabled automotive manufacturers to design and implement increasingly advanced software systems that can provide both vehicle performance and safety. Moreover, the advent of over-the-air (OTA) update mechanisms facilitates the continuous enhancement of vehicle functionalities throughout the product lifecycle, thereby introducing novel opportunities for revenue generation through the monetization of software-driven features [14]. The Software-Defined Vehicle (SDV) market is undergoing a transformative shift, driven by the increasing emphasis on software-centric innovation. This evolution is shaped by changing consumer expectations, rapid technological advancements, and a growing imperative to meet sustainability objectives. Also, Fig. 7 refers that SDV market values are expected to increase each year.

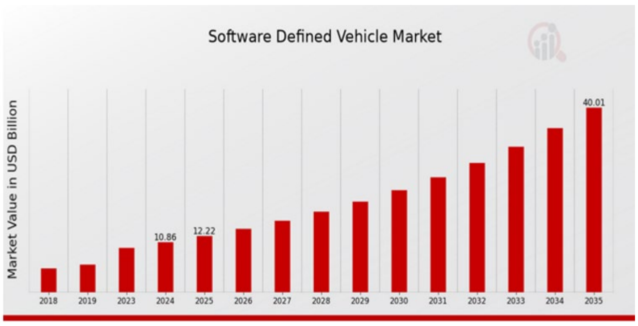

Fig. 7. Software Defined Vehicle Market Values [15]

Another approach for Software Define Vehicle is that use Virtual Machines (VM) on High Performance Computers (HPC) which is assembled on vehicle. This feature provides resource allocation on HPC. That VM enables flexibility to use resources. There is developed prioritization strategy to response vehicle needs during using VM sources [16].

V. COMPARISON

This part of the article will merge past E/E architectures of vehicles considered as distributed and current E/E architectures considered as domain centralized architectures. Distributed architectures consist of only function-specific ECUs, which are connected to a central gateway [4]. For this architecture type, 40 to 100 ECUs are used per vehicle. In contrast, domain centralized architectures utilize domain ECUs instead of a single expert gateway, with up to 150 ECUs managing a broader range of functions [17].

The shift toward domain centralized architectures is driven by increasing customer demands for ADAS features and strict regulatory requirements. To meet these demands and adapt to evolving technologies, domain centralized architectures offer a more practical solution for OEMs compared to distributed systems [18].

Another advantage of domain centralized architectures is their adaptability to software updates and regulatory changes. Instead of manufacturing new function-specific ECUs, updates can be applied more efficiently, making the system more environmentally friendly [17].

Despite their differences, both architectures share a common feature: the use of CAN communication. However, domain centralized architectures are enhanced with Ethernet communication, enabling faster data transfer when high-speed information is required [17]. This added capability, along with high-performance ECUs and increased functional integration, results in higher power consumption compared to distributed systems.

Distributed architectures offer benefits such as independent updates, localized real-time responsiveness, flexibility, redundancy, and ease of scalability [4]. However, domain centralized architectures provide modular scalability, flexible integration, and the potential for network-level redundancy by concentrating functions regionally, despite the risk of localized failures due to interdependencies within domains [18].

From a hardware perspective, distributed architectures require lengthy wiring harnesses and numerous ECUs, which increase vehicle weight, wiring complexity, and production costs [4]. On the other hand, domain centralized architectures reduce the number of harnesses and ECUs by consolidating functions and collecting them in specific domain region, thereby lowering vehicle weight and production costs. Less Weight could lead to gain, the vehicle, being environmental friendly. For instance, one domain ECU can replace two to three function-specific ECUs used in distributed systems [17].

In terms of fault tolerance, distributed architectures are more resilient. A failure in one ECU typically does not affect others. In contrast, a failure in a domain controller can impact all ECUs within that domain [4].

Finally, domain centralized architectures offer improved cybersecurity. In distributed systems, all ECUs are accessible via the central gateway, increasing vulnerability. Domain centralized systems, however, isolate communication through domain layers, reducing exposure and enhancing security [18].

TABLE 3
DISTRIBUTED VS. DOMAIN CENTRALIZED ARCHITECTURE COMPARISON

Aspect	Distributed Architecture	Domain Centralized Architectures
ECU Organization	Separate ECU for each function (e.g., ABS(Anti-lock breaking System), lights, windows)	Functions grouped by domains (e.g., ADAS, infotainment, powertrain)
Number of ECUs	40–100 (sometimes more)	100–150 with more integrated functions
Network Structure	CAN network via central gateway	CAN + Ethernet between domain controllers
Data Rate	Up to 1 Mbps via CAN, 0–8-byte frames	Higher bandwidth via Ethernet for systems like ADAS
Wiring	Very long and complex; up to 1 mile, 120 pounds	Shorter, reduced length and weight
Flexibility	Each ECU can be updated independently	Domain-based updates; more integrated
Fault Tolerance	High; failure of one ECU doesn't affect others	Moderate; domain controller failure affects entire domain
Cybersecurity Risk	High; many ECUs and communication points	Lower; centralized control improves security
Cost for a function	High; many ECUs and complex wiring	Low; Lower ECUs and shorter wiring for domains
Performance	Good real-time local responses, but complex overall	More integrated systems with higher processing power
Scalability	High; easy to add ECUs vertically or horizontally	Moderate; expansion within domain structure possible
Energy Consumption	Lower; many ECUs operating continuously	Higher; high energy needs for high communication network load, complexity
Manageability	Difficult; complex system and long debugging	Easier; centralized domain grouping simplifies management

VI. CONCLUSION

The evolution of automotive electrical/electronic architectures from distributed systems, domain-based architectures to zonal, software-defined platforms, which are expected to develop more widely, highlights the technological changes in the automotive industry. With the increasing complexity of vehicle functions and stringent regulations to meet consumers expectations for connectivity and automation, automotive electrical and electronics systems have become the cornerstone of contemporary vehicles.

Distributed architectures working with multiple ECUs and aiming individual functions offered flexibility but also causes some challenges in terms of scalability, maintenance, cybersecurity, and overall vehicle complexity. The development of domain centralized architectures addressed some of these subjects by organizing functions, improving integration, cybersecurity, and system synchronization.

In the future, it is envisioned that domain centralized architectures will be continuously transformed into Zonal or software-defined vehicles (SDVs). These will offer flexibility, over-the-air updates, cost-effectiveness, and advanced capabilities such as autonomous driving technology and advanced cybersecurity protocols. With these types of architecture, fundamental focus is modified from hardware-based vehicles to software-based vehicles.

Finally, the continuous evolution of automotive E/E architectures emphasizes the automotive industry's goals to deliver innovation, efficiency, and exceptional driving experiences. The interrelationship between hardware, software and system integration will be vital to effectively capitalize on the capabilities of future vehicle designs.

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