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ПРОГРАМНО-ВИЗНАЧЕНІ ТРАНСПОРТНІ ЗАСОБИ SOFTWARE-DEFINED VEHICLES. СУЧАСНИЙ СТАН ТЕХНОЛОГІЙ ТА ТЕНДЕНЦІЇ РОЗВИТКУ

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Анотація. У статті здійснено узагальнений огляд концепції програмно-визначених транспортних засобів (Software-Defined Vehicles, SDV), що формується як ключовий напрям розвитку сучасної автомобільної промисловості. Розглянуто трансформацію традиційної електронної архітектури автомобіля, особливості централізованих обчислювальних платформ, інфраструктуру зв'язку та програмного забезпечення, а також роль програмних оновлень і хмарних сервісів у забезпеченні функціональності транспортних засобів. Проаналізовано рівні розвитку SDV, їх переваги та проблемні аспекти, пов'язані з кібербезпекою, стандартизацією та інженерною складністю. Визначено перспективи поширення SDV у контексті автономного водіння, мережевої взаємодії та цифрової мобільності.

Ключові слова: Software-Defined Vehicle, SDV, автомобільна електроніка, ОС автомобіля, централізована архітектура, ADAS, кібербезпека, хмарні сервіси.

SOFTWARE-DEFINED VEHICLES. CURRENT STATE OF TECHNOLOGIES AND DEVELOPMENT TRENDS

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Abstract. The article provides a comprehensive overview of the concept of Software Defined Vehicles (SDV), which is emerging as a key direction in the development of the modern automotive industry. The study examines the transformation of the traditional electronic architecture of vehicles, the characteristics of centralized computing platforms, communication and software infrastructures, as well as the role of software updates and cloud services in ensuring vehicle functionality. Various SDV development levels, their advantages, and challenges related to cybersecurity, standardization, and engineering complexity are analyzed.

The article also outlines the prospects for the spread of SDV in the context of autonomous driving, networked mobility, and digital transportation ecosystems.

Keywords: Software Defined Vehicle, SDV, automotive electronics, vehicle operating system, centralized architecture, ADAS, cybersecurity, cloud services.

Introduction. The automotive industry is rapidly evolving in both information technologies and vehicle operation domains. The traditional vehicle model, in which core functions are determined primarily by hardware components, is gradually losing its relevance due to limited upgradeability and high modernization costs. With the increasing number of Electronic Control Units (ECUs) in modern vehicles, the conventional distributed architecture has reached its scalability limits. The implementation of Software-Defined Vehicles (SDV), based on centralized high-performance computing units, is considered a promising solution to this systemic complexity [1].

In traditional vehicles, most functions—such as acceleration, braking, or climate control—are governed by hardware-based ECUs. In contrast, SDVs utilize software to manage and enhance these functions, enabling vehicles to become more flexible, configurable, and continuously updatable. This transformation aligns with a broader cross-industry trend toward prioritizing digital capabilities and seamless connectivity. SDVs are perceived as the next generation of advanced transportation systems, reflecting the ongoing evolution of automotive innovation. Increasing attention is devoted to the in-vehicle user experience, strengthened by technologies such as infotainment systems and integrated digital services [1].

Although SDVs still require a higher degree of technological maturity before achieving widespread adoption, they offer substantial advantages over conventional vehicles. Instead of being limited to features predefined during production, SDVs can continuously update their software-based functionalities even while already in service. This capability to address issues and introduce improvements in real time drives the development of SDV technology and ultimately results in more efficient vehicle utilization [2].

As of today, fully implemented Software-Defined Vehicles (SDVs) have not yet appeared on the market; however, there are demonstrative prototypes and functional concepts, an example of which is shown in Fig. 1. Similar to autonomous vehicles, SDVs can be classified into levels 0–5. According to the Moritz scale, Level 0 is defined as *software-assisted*, referring to features such as parking assistance or adaptive cruise control. Level 1 represents *connected* vehicles and includes auxiliary mobile applications and real-time traffic updates.

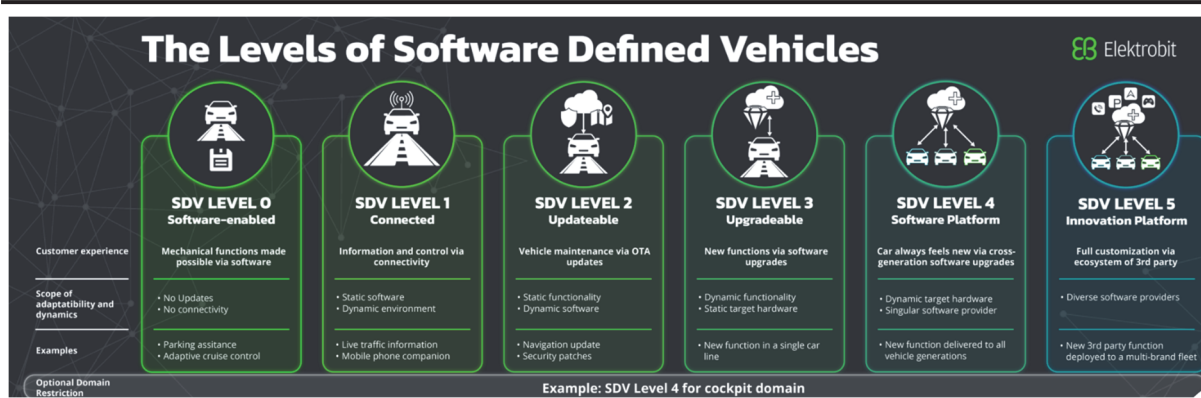


Figure 1. – Stages of Software-Defined Vehicles

At Level 2, vehicle functions become capable of receiving over-the-air (OTA) updates, although such updates remain limited to bug fixes rather than the introduction of fundamentally new features. Level 3 is described as *upgradable* and enables the deployment of new functionalities directly to vehicles already in operation. SDVs at Level 4 transform the vehicle into a true software platform in which the life cycles of hardware and software are decoupled. At this level, newly released functions defined by the original equipment manufacturer (OEM) can be deployed simultaneously to all vehicles in the OEM’s fleet—for example, Tesla’s “Boombbox” feature.

At Level 5, the vehicle becomes an open innovation platform where third-party developers can provide software functions, and the driver decides which of them to install. Although the industry is progressing toward Level 3 and Level 4 SDVs, it will take time before Level 5 vehicles appear on public roads. As with autonomous driving technologies, not all OEMs are likely to pursue Level 5 implementation, so in the future, a significant number of Level 3 and Level 4 vehicles will coexist alongside Level 5 SDVs [2].

The aim of this research is to conduct a comprehensive analysis of the concept of Software-Defined Vehicles (SDVs), to determine their key technological characteristics and architectural solutions, to evaluate their impact on the automotive industry, and to develop recommendations regarding the implementation and use of SDVs to improve safety, efficiency, and technological performance of transportation systems. This work also considers how the integration of advanced software and systems engineering ensures compatibility between hardware and software components, enhancing vehicle performance, compliance, safety, and cybersecurity while simultaneously achieving demanding cost and timeline targets [1, 2].

Materials and Methods. Software integration testing in the automotive industry focuses on verifying whether various software components function together as intended when integrated into the overall vehicle system [1].

The architectural model of a Software-Defined Vehicle is generally complex and extends far beyond the physical vehicle itself (Fig. 2) [3]. It encompasses not only the in-vehicle Electronic Control Units (ECUs) but also the supporting off-board infrastructure. This architecture includes telecommunication equipment and connectivity solutions that enable real-time data exchange between the vehicle and the cloud. Backend systems are used to store data, manage software updates, and provide critical backup functionalities, ensuring continuous interaction with the vehicle to deliver data or operational capabilities.

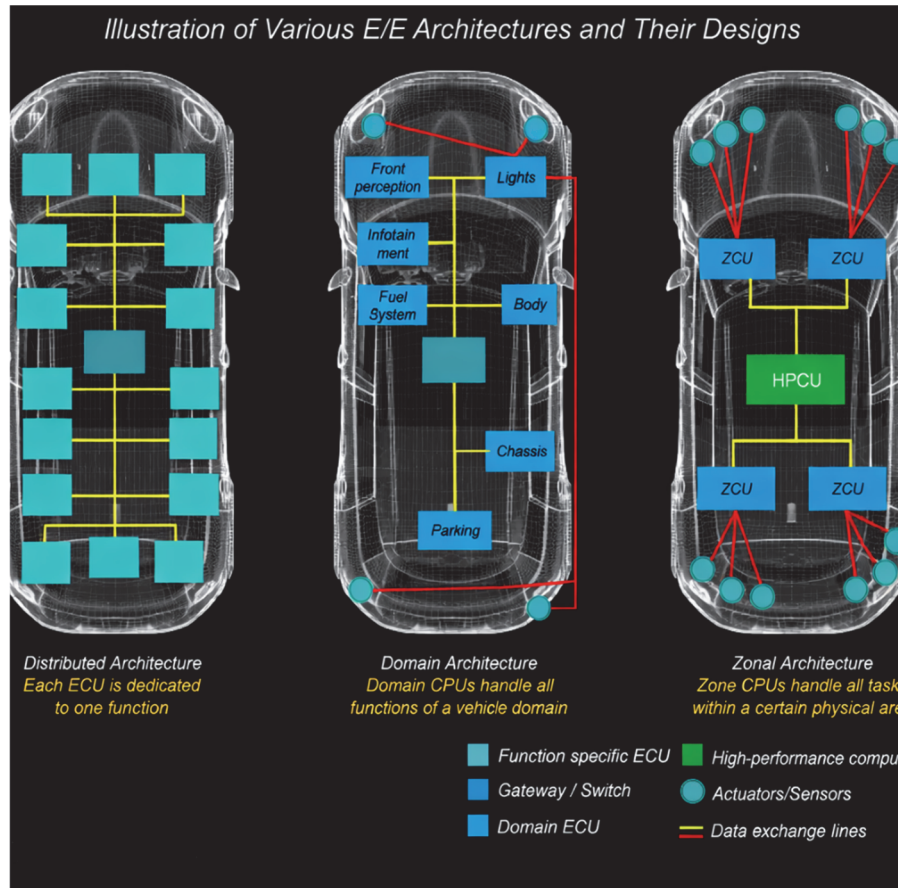


Figure 2. – Centralized Architectural Diagram

Since SDVs operate as “data centers on wheels”, high-performance computing (HPC) units and powerful Graphics Processing Units (GPUs) are required to process sensor inputs and support advanced software systems such as Advanced Driver-Assistance Systems (ADAS). Moreover, because SDVs offer significantly greater connectivity capabilities than traditional vehicles, they rely on modern communication networks-such as automotive Ethernet-to support high-speed data transfer and low-latency operation [3].

The SDV middleware layer incorporates core operating systems such as Windows or Linux, which provide internal communication with data transmission technologies. Communication subsystems connect the vehicle to external

data centers, enabling the exchange of information and forming the foundation for over-the-air (OTA) updates of onboard software as well as the integration of new functionalities. SDVs also include a wide range of user-oriented applications and software modules, including infotainment systems, digital cockpits, driver assistance systems (ADAS), enhanced vehicle control interfaces, adaptive cruise control, climate-control systems, and navigation modules. These components interact with the SDV operating system through middleware, which acts as an intermediary software layer ensuring interoperability between the OS and individual applications. Together, these functions enhance comfort, usability, and safety.

SDVs continuously monitor their own performance and plan maintenance schedules by leveraging their capabilities in data generation and analysis. Predictive maintenance allows vehicle operators to identify and resolve issues before they develop into more severe faults [3].

Intelligent control systems and motion-control functions developed by ZF are actively and strategically shaping the transition toward Software-Defined Vehicles. ZF contributes by creating a standardized, modular software architecture for the vehicle chassis and by integrating intelligent control systems such as **cubiX**, which is already in mass production and provides harmonized coordination of dynamic driving functions [4, 5].

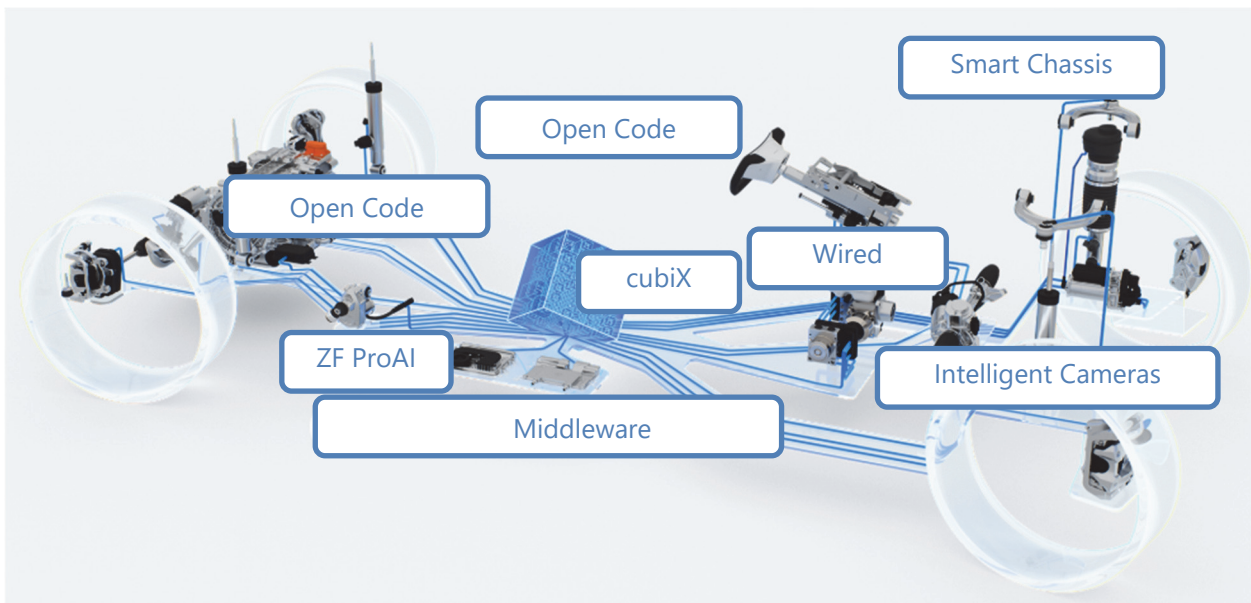


Figure 3. – Software Development Process

Thanks to data-driven services and innovative technologies such as Steer-by-Wire and Brake-by-Wire, ZF is accelerating the digitalization and connectivity of modern vehicles. New hardware platforms, such as **ProConnect**, enable seamless diagnostics and over-the-air (OTA) software updates, allowing

manufacturers to design vehicles with future requirements and operational efficiency in mind (Fig. 3) [4].

The foundation of future vehicle architectures is built on high-performance **zonal controllers**, which host the vehicle's central software. Similar to how the human brain is connected to every part of the body, the central computers of an SDV interact with all sensors and actuators, providing an unprecedented mobility experience in automated driving, electromobility, vehicle motion control, and integrated safety functions. Various types of vehicles can be incorporated into this mobile-chassis platform, which consists of high-performance controllers, continuous damping-control systems, braking systems, steering systems, and electric drive units [5].



Figure 4. – ZF ProAI Central Computer

ZF ProAI is an automotive-grade central computer (Fig. 4) designed to support all vehicle platforms, software applications, and electric-drive configurations—from cost-efficient entry-level models equipped with front-facing cameras or basic parking-assist features to high-performance comfort configurations used in Level 2–3 Advanced Driver-Assistance Systems (ADAS) and premium-segment vehicles.

The development of a Software-Defined Vehicle integrates several essential layers: the physical platform (powertrain, battery, suspension), the electronic architecture (sensors, control units), the software stack (operating systems, applications), and user-oriented design. Together, these components form a unified digital driving experience.

While developing the first generation of SDVs, Audi leverages the advantages of the Volkswagen Group. For example, the Group has established a joint venture with the American automotive manufacturer Rivian. Together, the companies will develop a shared electric and electronic architecture, and the joint venture will accelerate software development, thereby stimulating innovation across the broader Group (Fig. 5) [6].

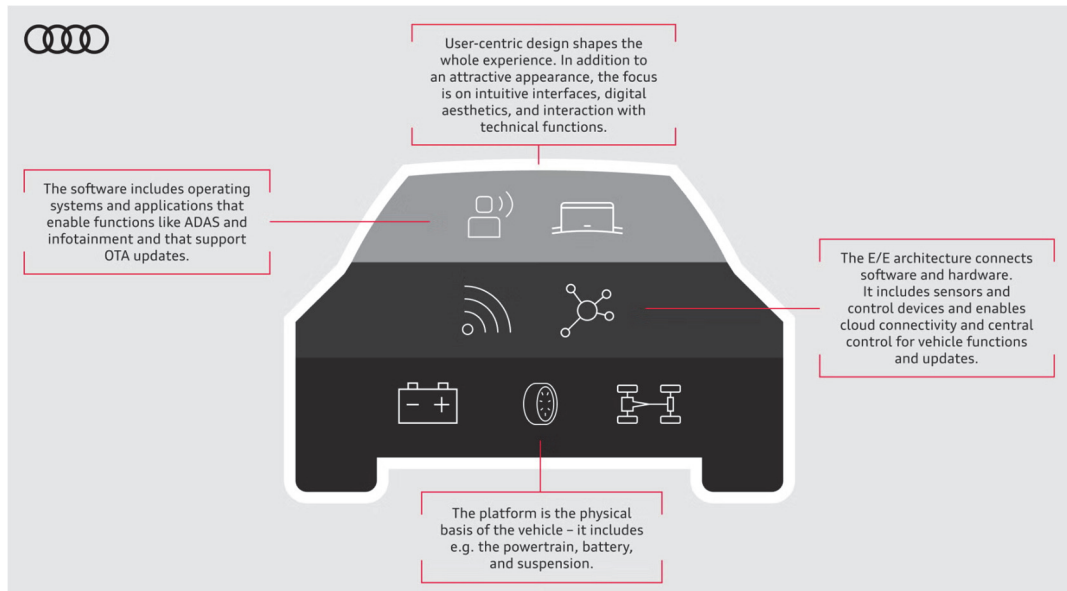


Figure 5. – First Generation of Audi SDV

In the future, SDV architecture will be standardized and scalable across all vehicle models. This will allow it to be developed independently of individual model line-ups and product cycles. The key advantage is that Audi vehicles will be able to receive new functions throughout their entire lifecycle, easily and cost-effectively, through over-the-air (OTA) updates [6].

Advantages and Disadvantages of SDVs. Like any vehicle architecture, Software-Defined Vehicles have both advantages and challenges. SDVs require a higher degree of system complexity due to the diversity of software platforms and software architectures. Therefore, ensuring compatibility with both conventional and advanced hardware becomes a key requirement [3].

Among the positive aspects, the following can be highlighted: improved powertrain performance enabled by enhanced monitoring; continuous software updates and the ability to introduce new features and capabilities; vehicle self-monitoring through telematics and diagnostics, along with the possibility of predictive maintenance; a personalized experience for every passenger, ranging from customized instrument clusters to infotainment options; and enhanced passenger comfort driven by an expanded portfolio of infotainment services.

The technology of Software-Defined Vehicles represents a significant step forward in the automotive industry, but it also requires overcoming several

drawbacks. Strengthening cybersecurity measures is essential to protect vehicles from cyber-attacks; in addition, there is a shortage of technical expertise. The industry must attract and develop a new generation of specialists with experience in software development, cybersecurity, and data-management systems [7].

Development Prospects and Expected Outcomes. According to analytical forecasts, vehicles equipped with Level 2 ADAS may account for up to 52% of all vehicle sales by 2030 (Fig. 6) [8]. Safety regulations requiring new vehicles to incorporate more sensors used in Level-2 ADAS are expected to drive a significant portion of this market growth. As adoption increases, the overall cost of the required hardware and software components is likely to decrease.

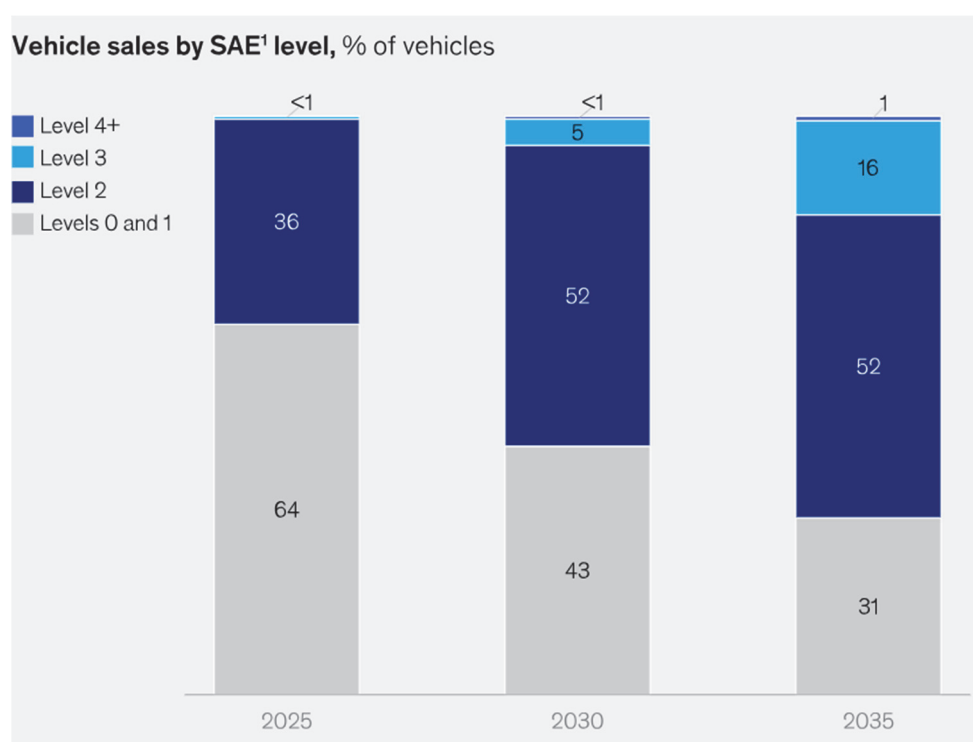


Figure 6. – Forecast Dynamics of Vehicle Sales by SDV

For example, original equipment manufacturers (OEMs) are now offering Level-2 ADAS packages at significantly more affordable prices than in the past. Meanwhile, the growing advantages and increasing customer willingness to purchase vehicles equipped with automated-driving (AD) capabilities may raise the share of Level-3 AD vehicles to 16% of total vehicle sales by 2035, compared to less than 1% in 2025. Anticipating this shift in customer purchasing behavior, readiness for such technologies continues to rise, as OEMs are actively developing the software and algorithms required to support Level-3 AD functionality. In contrast, only 1% of vehicle sales in 2035 is expected to consist of vehicles capable of Level-4 AD or higher [8].

Conclusion. The conducted research has made it possible to analyze Software-Defined Vehicles (SDVs), which represent a key direction in the transformation of the automotive industry by combining a hardware platform with flexible, upgradable software. SDVs open opportunities for continuous feature enhancement, personalization, and integration with digital ecosystems, improving vehicle safety, efficiency, and user comfort. At the same time, their implementation is accompanied by a range of challenges—from technical complexity and the need for standardization to cybersecurity concerns and workforce-readiness issues.

Purchasing a vehicle may increasingly resemble subscribing to a service, where new features and updates are delivered over time through applications. This transition is expected not only to change the way we drive vehicles but also to redefine mobility and the way users interact with their transport systems.

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