Multi-Partner Project: Shaping the Vehicle of the Future - How FEDERATE and HAL4SDV are steering Europe's Software-Defined Vehicle Ecosystem

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Abstract*— The FEDERATE and HAL4SDV projects aim to address the growing importance of software in the automotive industry, positioning Europe as a leader in the software-defined vehicle (SDV) domain. FEDERATE focuses on building a cohesive European SDV ecosystem by coordinating stakeholders such as OEMs, tiers, semiconductor companies, and research institutions. It supports the agile development of a non-differentiating automotive software platform through open-source collaboration, fostering a vibrant SDV community and providing guidance for ongoing and future SDV projects. Meanwhile, HAL4SDV aligns with the ECS Strategic Research and Innovation Agenda to develop technologies and processes needed for SDV advancement beyond 2030. HAL4SDV's objectives include creating a unified software interface, hardware abstraction, and Over-The-Air updates, while focusing on cybersecurity, real-time capabilities, and seamless integration of new software functions and modified software building blocks into the target vehicle system. Together, these projects aim to drive innovation, scalability, and sustainability in the SDV area.

***Keywords*—Vehicle of the future, software defined vehicle, hardware abstraction layer, artificial intelligence (AI), edge computing, embedded intelligence.**

I. Introduction

The automotive industry is undergoing a transformation, with the software-defined vehicle (SDV) emerging as a key innovation. This paper explores the SDV's potential to redefine the vehicle ecosystem, focusing on Europe's strategic position in this competitive market. It delves into the electrical/electronic (E/E) and SW architectures abstracted by the SDV, examines technical challenges, and build on results of projects in the domain and is bosted by the FEDERATE Coordination and Support Action (CSA), which fosters collaboration and aligns Open Source software (OSS) initiatives, research projects, as HAL4SDV (among others) that addresses critical hardware abstraction challenges. Together, these initiatives aim to establish a robust European SDV ecosystem.

II. The Rise of the Software-Defined Vehicle

The automotive industry is transitioning from HW-centric engineering to software-driven innovation, leading to the emergence of the SDV. SDV technologies abstract hardware through software layers, enabling modularity, real-time updates, and improved and extended functionality throughout a vehicle's lifecycle. This paradigm shift is driven by advancements in connectivity, artificial intelligence (AI), and edge computing, which have redefined how vehicles are developed, maintained, and integrated into broader digital ecosystems. The global automotive market is rapidly adapting to this transformation, with key players like USA and Chinese automakers setting benchmarks for the SDV. Europe, traditionally a leader in automotive innovation, faces significant competition in this domain. According to a McKinsey report, European automakers must adapt quickly to remain competitive, focusing on areas like software modularity, open-source collaboration, and over-the-air (OTA) updates [1].

III. The European and Global Automotive Market

Europe's automotive industry, a major economic contributor with over 7% of GDP and millions employed across the value chain, faces a transformative shift as it adapts to the SDV approach. This transition presents both opportunities and significant challenges. The large European automakers and the transport domain are working to align with this new era, recognizing the growing importance of software integration, electric drivetrains, and advanced connectivity in shaping the vehicles of tomorrow. However, they are grappling with increasing competition from both established and emerging players. European automakers face significant challenges from Tesla's dominance in software and autonomous capabilities, setting high performance and consumer expectations, and the aggressive expansion of Chinese automakers in Europe. Supported by government policies, cost advantages, and advanced EV capabilities, Chinese companies leverage economies of scale and competitive battery manufacturing to produce lower-cost electric vehicles [2][3] in combination with advanced software capabilities. The European automotive industry is also impacted by geopolitical tensions and macroeconomic pressures. Rising energy costs, supply chain disruptions, and inflation pose risks to European manufacturers' ability to stay competitive. In particular, labour costs and productivity issues are making it harder for European automakers to maintain profitability in the face of global competition [2][4]. Chinese brands, with lower production costs, and significant governmental subsidies have successfully gained traction in both domestic and international markets, significantly increasing their share in Europe. In addition, they massively build on their governmentally regulated economy using huge orchestrators like Alibaba, Tencent, Haier, etc. digitizing their industry [1].

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In response, European automakers must embrace innovation, focusing on software development, modular SW vehicle architectures, and advanced electric drivetrains. They need to rapidly scale their capabilities in areas such as autonomous driving, high-performance processors, and real-time data management. This transformation is essential for regaining their competitive edge amid the accelerating global push for electrification [2][4]. To secure leadership in this domain, Europe must invest in open-source collaboration, standardization, and software R&D. The European Chips Act and Horizon Europe programs are fostering these efforts, with KDT/Chips JU projects like FEDERATE and HAL4SDV serving as critical enablers.

IV. The Software Defined Vehicle of the Future

A. Key Trends in the SDV Architecture

The automotive industry's transformation is driving a shift in vehicle electrical and electronic (E/E) architectures from decentralized to centralized and modular designs. Traditional architectures, with numerous ECUs for specific functions, were flexible but resulted in greater complexity, weight, and cost. Modern architectures consolidate key SW functions like ADAS, infotainment, and vehicle control into fewer, more powerful ECUs, reducing wiring complexity and enabling efficient resource sharing. Modularity further enhances scalability, flexibility, and updates, while standardized interfaces and software platforms simplify the integration of new features and technologies. While E/E architectures are central to shaping the requirements of future vehicles, SW abstraction from these architectures is critical to independently advancing future SDV.

Moreover, to manage the increasing complexity of vehicle systems, domain and zonal controllers are being introduced. *Domain controllers* are powerful ECUs that are responsible for managing specific vehicle domains, such as powertrain, chassis, and body. They consolidate multiple functions, reducing the number of ECUs and simplifying system integration. *Zonal controllers* are smaller ECUs handle specific zones within the vehicle, such as the cockpit or the rear passenger compartment. They are responsible for local functions like seat adjustment, climate control, and lighting.

High-performance processors are essential for advanced driver-assistance systems (ADAS), electric drivetrains, and autonomous driving, as they support real-time sensor data processing, complex algorithms, and sophisticated SDV software functions. They must also provide resources for additional new SW features installed over the air during the operational lifetime of a car.

Sensors and their hardware abstraction, designed to reduce reliance on single suppliers, are vital for monitoring the vehicle's environment and internal state. Cameras, radar, lidar, and ultrasonic sensors supply critical data for ADAS, autonomous driving, and advanced features.

High-speed communication networks are then essential for transmitting data between different ECUs and sensors. Ethernet-based networks, such as Automotive Ethernet, are becoming increasingly popular due to their high bandwidth and flexibility.

Cloud and edge computing are reshaping vehicle E/E and SDV architectures. Cloud computing handles large-scale data processing remotely, while edge computing enables real-time data processing within the vehicle. Together, they provide the computational power and connectivity needed for advanced vehicle features.

These trends are driving the automotive industry toward safer, more efficient, connected, and adaptable vehicles, serving as both key enablers and integral parts of the SDV.

B. Technical Challenges of the Software-Defined Vehicle

While the SDV promises the necessary innovation required by the vehicle of the future, it presents several challenges.

SDVs need modular and scalable architectures to manage growing software complexity, evolving HW/SW features, and increasing data processing demands while maintaining cost efficiency. Modularity and scalability simplify the integration of new (e.g. autonomous driving) algorithms and addressing challenges of tightly coupled systems. Current SDV efforts focus on non-differentiating, non-safety-relevant open-source components, but the goal is to manage safety-critical, differentiating elements seamlessly, ensuring safety, security, shared memory access, and freedom from interference.

Challenges include ensuring modularity for easy feature addition or replacement without system disruption, managing massive data flows from sensors and cameras, balancing performance, cost, and scalability in designs, including all safety-related and differentiating elements, and supporting service-oriented architectures for efficient SDV implementation. Such scalable SDV architectures enable microservices, edge computing for distributed processing, AI and continuous software integration and testing pipelines, while benfitting form cost efficiencies.

SDVs rely on connectivity, incorporating systems like V2X, IoT, and cloud services which increase the vulnerability to cyberattacks such as ransomware, OTA update tampering, and protocol hacking. Key cybersecurity challenges include securing the expanded attack surface, ensuring safe communication between vehicles, infrastructure, and the cloud, protecting sensitive data during transmission, and enabling secure external data processing for AI. Mitigation measures like robust encryption, intrusion detection systems, firewalls, secure software design, and regular audits can address these threats. However, these technologies can delay the real-time loops critical for ADAS and automated driving, requiring further research and tailored solutions to balance security with performance.The SDV relies on sophisticated abstraction layers to decouple hardware from software, enabling modularity and compatibility across diverse platforms. Hardware abstraction layers (HAL) are essential to prevent performance issues from hardware mismatches or inefficient resource use. Key challenges include developing a unified HAL for software-hardware communication, ensuring compatibility across various hardware configurations, and maintaining performance and reliability despite hardware diversity. Achieving this requires standardized HALs, robust testing frameworks, and collaboration among OEMs, semiconductor companies, and software developers to establish cross-industry standards.

Many SDV functions, like collision avoidance or adaptive cruise control, depend on real-time data processing for critical decision-making, where delays in sensor data processing can result in incorrect or late responses. Ensuring real-time capabilities demands ultra-low latency communication between hardware and software, real-time AI algorithm execution, and bottleneck-free data pipelines under high system loads. These needs can be met with high-performance processors, advanced communication protocols, and optimized data handling frameworks.

The SDV evolves throughout its lifecycle, relying on OTA updates to deliver new features, bug fixes, and security patches. Ensuring these updates are seamless and secure is challenging, as failed updates can disable a vehicle or allow malicious code injection. Key challenges include minimizing downtime, ensuring updates don't disrupt real-time operations, guaranteeing data integrity and authenticity, and managing diverse hardware and software configurations. Addressing these requires fault-tolerant mechanisms, robust validation processes, and fallback strategies for updates.

Regulatory and standardization challenges arise as SDVs redefine automotive systems, with global standards lagging behind, leading to fragmented development. Adhering to diverse safety, cybersecurity, and environmental regulations across regions while ensuring interoperability between SDVs is difficult. Balancing innovation with compliance in a shifting regulatory landscape adds complexity. Mitigating these issues requires collaboration with regulators, participation in standardization initiatives, and proactive compliance-focused design. Connecting diverse platforms in the European automotive industry into a shared system with standardized platforms, robust security, and modular architectures will be crucial. Success depends on ecosystem-wide collaboration among OEMs, software developers, semiconductor manufacturers, and regulators.

V. FEDERATE: Coordinating the EU SDV Ecosystem

FEDERATE [5] is a Coordination and Support Action (CSA) that plays a pivotal role in Europe's vehicle of the future, driving the European SDV evolution and fostering collaboration among OEMs, tiers, OSS initiatives and research institutions, and policymakers to establish a cohesive SDV ecosystem, as enforced by the manifesto signed by executives from major European automotive players.

A. Towards a Euorpean SDV ecosystem

FEDERATE envisions a collaborative, open, and innovative European Software-Defined Vehicle (SDV) Ecosystem that addresses critical societal challenges by enabling clean, affordable, and safe mobility solutions. By fostering a unified ecosystem, it aims to drive the adoption of sustainable technologies that reduce environmental impact, enhance transportation accessibility, and ensure the safety of all users. This vision aligns closely with the goals of the European Green Deal, contributing significantly to decarbonization and the advancement of green mobility. Moreover, the successful realization of this vision will reinforce Europe's sovereignty in chip manufacturing and automotive software, strengthening its leadership in a competitive global landscape.

FEDERATE's mission is to unite key stakeholders from diverse sectors, including the mobility industry, the open-source software community, the semiconductor sector, and public authorities, to collaboratively accelerate the development of a robust SDV Ecosystem. The project aims to cultivate a vibrant and inclusive European SDV community, where stakeholders actively engage in knowledge sharing, innovation, and standardization. By orchestrating research and innovation activities, FEDERATE seeks to streamline the advancement of SDV technologies, foster open-source collaboration, and provide strategic guidance for current and future projects. Through this mission, FEDERATE aspires to position Europe as a global leader in the SDV domain, enabling the seamless integration of cutting-edge automotive software solutions and sustainable transportation systems.

B. Collaboration and innovation for competitiveness

FEDERATE aims to enhance the global competitiveness of the European mobility and semiconductor industries in delivering the SDV. Its key objectives include: (1) Orchestrate research, aligning existing and future SDV projects to avoid duplication of efforts; (2) Develop roadmaps, creating a joint strategic vision to guide European SDV R&D; (3) Create a vibrant and collaborative community, building partnerships, engaging the European key players to drive open source development and knowledge sharing, and include complementing partnerships like CCAM [8] and 2Zero [9]. The EC together with FEDERATE established the SDV Sherpa group, a network of expert decision makers across SDV fields, to foster collaboration and innovation through knowledge exchange on technologies, solutions, and best practices. It also developed a strategy to communicate and disseminate project activities and results, ensuring broad engagement and impact in the SDV ecosystem.

On a strategic level, the project develops and updates a roadmap for creating non-differentiating building blocks within an open SDV ecosystem, recommending research funding programs to address gaps in tools and technologies. It assesses trends like automated driving, edge2cloud applications as park&pay, plug&charge, and Edge AI to forecast SDV developments and derive high-level requirements for stakeholders. Common building blocks, such as SW components, containers, SDKs, and services, are designed to be reusable, scalable, and aligned with stakeholder requirements and insights from the SDV Sherpa group.

On a technical level, FEDERATE aims to create a shared understanding of building blocks within a layered service-oriented architecture (SoA), including harmonized interfaces and features, supported by the community. Through iterative requirements and technology analysis, the project defines modular software building blocks and aligns them with industrial SDV initiatives. Strategic partners review and prioritize the building block backlog quarterly.

VI. HAL4SDV: Pioneering Hardware Abstraction for the Software Defined Vehicle

HAL4SDV, the first project of the European SDV roadmap, addresses the need for HW abstraction to decouple HW from SW, enabling portability and modularity. By unifying interfaces and methodologies, it supports automatic SW configuration independent of HW, advancing SDV in both safety-critical and non-safety-critical applications.

A. Sustainable technology leadership

HAL4SDV aims to transform future mobility and reinforce Europe's leadership in the automotive industry by advancing connectivity, efficiency, and sustainability, driving automotive sector toward a more integrated and environmentally responsible future. It also addresses the need for technological investment to ensure growth and maintain global competitiveness. Focusing on vehicles beyond 2030, it introduces innovative methods, technologies, and processes driven by advancements in microelectronics, communications, SW engineering, and AI. It prioritizes systems, safety, security, and SW to shape the next generation of automotive solutions and provides seemless integration of SW applications and middleware components.

B. *Project objectives*

HAL4SDV aims to develop an open SoA-based platform for both safety and non-safety applications. Its core concept is the HAL, featuring a "System + SW" architecture with standardized interfaces for sensors, actuators, computing, and storage, supported by hypervisors and SW updates.

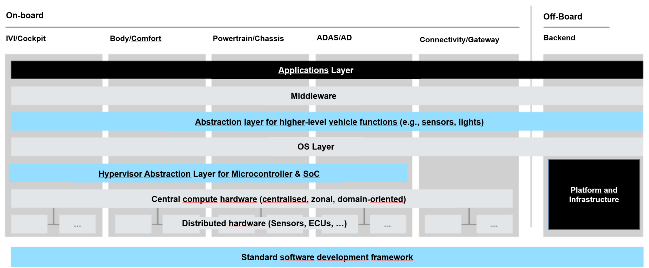

Figure 1- SW architecture with hardware abstraction layer (HAL).

HAL4SDV has identified the following objectives:

1) A SW Platform Architecture enables in-vehicle updates and new feature upload, transforming the vehicle via SW while retaining its HW. It supports interoperable safety and non-safety SW components aligned with COVESA VSS [10], Eclipse Foundation OSS SDV [11] and SOAFEE [1].

2) Abstraction from HW, virtualization, memory management, and AI, thorugh interfaces/APIs to decouple sensors and actuators. It handles task assignment to computing nodes, supporting virtualization, shared memory management, AI, etc.

3) HW support for different component, sensors, actuators, micro computers, safety controllers, GPUs, etc. including RISC-V based solutions for automotive.

4) Automated integration of in-vehicle applications, hypervisors, different OSs, built on a service oriented architectural approach for mixed criticality applications.

5) Support of safety features (i.e.: freedom from Interference, etc.) providing the basis for a platform serving SDV approach plus, in the long run, highly automated driving functionality, potentially up to SAE level 5.

6) Dedicated SW measures to guarantee a suitable security level to allow safety-relevant features to be updated, downloaded, enhanced and added via the edge (e.g. secure enclaves to build up zero-trust concepts).

7) Solutions to "outsource" functions to the edge and use "results" provided "Over the Air" within the vehicle.

8) Engineering support accelerates SDV design, development, and testing through advanced methodologies, tools, virtualization, simulation, cloud-based prototyping, system modeling, and data analytics.

C. *Reseacrh and development activities*

HALSDV will deeply analyze automotive HW and SW architectures to capture the requirements of the HAL, architecture, open-source software, IP solutions, and tools for SDV engineering. This includes studying of differentiating and safety-relevant developments, their requirements, and how they must integrate to meet overall safety standards. Modeling and simulation will support the SW design of the platform and its components. The design and development of safety & non-safety-relevant components is conducted in parallel, focusing on the interface to the open-source world and how to separate non-safety-relevant from safety-relevant parts of the SDV platform to comply with the safety requirements. The outcomes will be applied in diverse use cases, simulating real-world environments to demonstrate project results: the developed technologies will be showcased in real vehicle implementations through demonstrators addressing innovative use cases. These will cover areas such as chassis, powertrain, battery/charging, ADAS/AD, execution environments, and security, highlighting systems integration and platform performance. Their implementation will include analyzing architectural considerations for safety-relevant aspects of the HAL4SDV platform, laying the groundwork for follow-up activities targeting safety-critical components.

VII. Conclusions

The FEDERATE and HAL4SDV projects are pivotal to Europe's leadership in the SDV ecosystem. FEDERATE promotes collaboration among industry, policymakers, and researchers, focusing on an SDV roadmap, open-source development, and strategic alignment to accelerate sustainable, affordable, and safe mobility solutions. HAL4SDV complements this by developing a HW abstraction layer (HAL) to enable modularity, scalability, and SW portability across platforms. It addresses challenges like cybersecurity, real-time processing, mixed-criticality systems, and regulatory compliance, supporting advancements in autonomous driving, V2X connectivity, and OTA updates. Together, these initiatives aim to position Europe as a global SDV leader, driving innovation and fostering a more Efficient, competitive, and sustainable automotive sector.

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