Position Paper

Smart Systems for Software-Defined and Hardware-Enabled Vehicles

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Introduction

The automotive industry is entering a decisive new era. Vehicles are defined not only by their propulsion performance, functional safety or interior comfort, but increasingly also by their intelligence, customization and upgradability, i.e. by the digital functionalities enabled through the seamless integration of software and hardware managing sensor signals, data and energy. The transition towards software-defined and hardware-enabled vehicles (SDVs) is reshaping the entire value chain, with smart systems at its core, from chip and sensor development to E/E architecture design, from mechatronic system and component integration to testing in real and virtual environments, autonomous driving control, energy management, entertainment systems, and on-demand mobility services.

This transformation presents Europe with a unique opportunity to combine its strengths in semiconductor technology, electric and electronic system design, vehicle dynamics know-how, safety validation and automotive engineering in a faster, more agile and more comprehensive manner to secure leadership, technological sovereignty and strategic autonomy in an increasingly competitive global market. It enables the integration of (increasingly generative and agentic) artificial intelligence (AI) and ever-growing data pools at the edge to enhance vehicle functionality. At the same time, the SDV brings massive systemic challenges: managing the different speeds of hardware and software innovation so they complement each other effectively for common solutions; ensuring safe, efficient and reliable integration across all layers, and balancing open, generic building blocks with differentiating applications, all under significant cost reduction pressure.

Against this backdrop, and in view of the measures announced by the European Commission in its Industrial Action Plan for the Automotive Industry, including the European Connected and Automated Vehicles Alliance (ECAVA), the future Automotive Partnership or Joint Undertaking under FP10, and the Important Project of Common European Interest Clean, Connected, and Automated Vehicles (IPCEI CCAV), this position paper sets out the perspective of EPoSS on SDV. It outlines how smart systems integration can enable Europe to lead the way in SDVs through an ecosystem approach, from chip via architecture to cloud, while maintaining open strategic autonomy, sustainability, and competitiveness. This builds on key reference documents that EPoSS members have contributed to, such as the ECS SRIA of the Chips Joint Undertaking, the European Software-Defined Vehicle of the Future Initiative Vision and Roadmap of the FEDERATE project, and the Strategic Research and Innovation Agendas of the automotive-related European Partnerships CCAM and 2Zero under the Horizon Europe FP9.

1. Objectives: Why focus on SW-defined and HW-enabled vehicles?

Software-defined and hardware-enabled vehicles mark a true paradigm shift in automotive technology. By decoupling rapid software development from the relatively static hardware, innovation can accelerate, functions can be continuously updated, and design can become more circular and sustainable.

The main objectives can be summarized as follows:

- **Shorter innovation cycles through decoupling**: Software can evolve rapidly and be revised through over-the-air updates, while hardware follows longer lifecycles, extending the lifetime of vehicle components through SDV principles.
- **Accelerated product development through common software foundations**: Shared, non-differentiating software layers and open standards reduce duplication of costly effort and speed up development across the ecosystem, while differentiating features build on top.
- **Safe integration of AI into vehicle control**: Deploying AI at-the-edge improves perception, decision-making, and predictive control with low latency and high reliability.

- **Circularity and upgradability**: Modular architectures allow for repairs, upgrades, and reuse of systems, thereby reducing waste and supporting Europe's circular economy goals.
- **Greater agility through aligned SW–HW development logic**: Dual-speed processes enable agile feature updates while maintaining the reliability of traditional mechatronic development.
- **Open strategic autonomy through shared platforms**: Leadership in open-source approaches in non-differentiating layers ensures agility, avoids redundant costs, and reduces dependency on hyperscalers or state-backed ecosystems from markets abroad.

Despite these promising features, a car is not simply a "smartphone on wheels." It must serve people's transportation needs from A to B in a way that is safe, sustainable, affordable, inclusive, and convenient. All these capabilities primarily rely on hardware components for propulsion, perception, energy management and versatile auxiliary functions. While decoupling enables flexibility during the use phase of a vehicle, it requires even closer alignment between hardware and software already in the design phase to ensure, the system not just works, but is also highly optimised. Fusion is the key to unlocking new digital functionalities in the car, such as bi-directional charging or automated driving in extended operational design domains. This, in turn, requires clear definitions of architectures, building blocks and interfaces to ensure that software and hardware systems and components support each other, deliver higher performance, save materials and reduce cost.

2. Concept: What is the core role of smart systems for SDV?

Smart systems provide the seamless and efficient integration of functionalities along the whole SDV stack from semiconductor chips through electronic system architecture and middleware to services. This integration allows vehicles to operate as safe, efficient, and upgradeable platforms. Software agility depends on abstraction layers, while hardware efficiency relies on optimised interaction between physical components and software toolchains. The SW/HW interface remains the critical bottleneck, where the determinism required by safety-critical hardware must be carefully balanced with the adaptability of fast-evolving software.

The role of smart systems for SDV is fourfold:

- **Integrating heterogeneous resources to accelerate performance gains:** Combining diverse compute and AI resources in systems-on-chip such as chiplets allows task-specific optimisation at the edge that can be leveraged when orchestrated by middleware**.**
- **Facilitating SW/HW integration through centralized E/E architectures**: Moving from fragmented sensors and controllers at the edge via zonal/domain network architectures to centralized control layouts not only reduces wiring complexity but enables a more robust and efficient interface between SW and HW.
- **Optimising performance by SW/HW systemic co-design**: Efficiency arises when chips, middleware, and applications are co-designed to minimize latency for real-time performance, ensure redundancy for reliability, and intelligently manage energy and data.
- **Managing trust with non-deterministic hardware and software**: AI and software introduce uncertainty, requiring functional safety standards (ISO 26262, SOTIF) to be complemented by evidence-based validation of SDV stacks including training, testing, and digital twin simulations.

Seen from a comprehensive smart systems perspective, SDVs are thus built on centralized electronic architectures based on high-performance computing (HPC) platforms connected by fast, low-latency interconnects such as automotive Ethernet. These platforms integrate diverse chips, CPUs, GPUs, AI accelerators, and neuromorphic processors into heterogeneous hardware components such as chiplets that deliver cohesive, high-level functions. Maintaining trust and safety requires continuous, system-wide validation frameworks that link chip-level safety features with software behavior, incorporating both traditional functional safety standards (e.g., ISO 26262) and AI-and-software-specific verification. While this layered integration of hardware, software, and validation will form the foundation of reliable software-defined and hardware-enabled vehicle architectures in the future, the current SDV market has not yet reached this full vision.

3. Gap analysis: Which topics require more research and innovation in the future?

The transition towards software-defined and hardware-enabled vehicles not just requires further technological progress in isolated domains, but above all a systemic alignment of hardware, software, and architectures. Gaps exist wherever layers do not play together seamlessly, from chips and sensors, to middleware and E/E architectures, to applications and cloud integration. Addressing these gaps is crucial to achieve the performance, safety, and sustainability goals of future mobility.

Hence, the following research and integration needs are imminent:

Smart hardware component development

- Low-power neuromorphic chips aligned with software frameworks for energy-efficient AI inference.
- Event-based cameras or quantum-enabled devices, to enhance perception in real-world conditions.
- Sensor cluster optimisation to balance latency, cost, efficiency, and SOTIF compliance.
- Predictive maintenance and lifespan monitoring at chip, sensor, and actuator level.
- Chiplets enabling modular upgrades, distributed performance, and on-chip function partitioning.
- Low-power programmable logic embedded in AI processors for adaptability and reconfiguration.
- Chiplet-based real-time debugging and tracing for in-field observability and reliability assurance.
- Processors for high-performance automotive computing to support centralized and zonal controllers, leveraging company-neutral, open architectures such as RISC-V.

Smart systems integration

- Transformation of on-board network architectures to centralised and zonal layouts.
- Standard definition of building blocks and interfaces, both in hardware and software.
- Extension with cloud-based computing power and edge IoT integration for scalable functions and fleet learning.
- Cybersecurity, trust, and reliability concepts to secure highly centralised systems against risks.
- Integration of robotics, cobotics, and mobotics functions, reflecting the convergence of mobility with automation.
- V2X and cooperative functions linking vehicles, infrastructure, and cloud.
- Vehicle-level function definitions, e.g. propulsion, comfort, and system monitoring dynamically adapted by software.
- Real-time dynamics models connecting SW-defined functions with the performance characteristics of underlying hardware.
- Test environments for SDV functions relying on 5G/Multi-Access Edge Computing (MEC).

Smart SW–HW co-design

- Co-design of sensors/actuators and their control-unit software to ensure efficiency across layers.
- Chiplet design capabilities and reliability strategies to support distributed yet safe performance.
- Data integrity and OTA update frameworks integrated at hardware, middleware, and system.
- Edge computing aligned with centralised HPCs to balance latency and efficiency.
- HW-independent SW stacks to ensure portability across platforms and vendors
- Modular engineering toolchains (CI/CD pipelines, Digital Twins) covering the entire SDV lifecycle.
- Interfaces and standards for SDVs, comparable to the role of PC hardware standards
- Methods and frameworks for validation, ensuring trust in non-deterministic AI-enabled systems.

True software-defined vehicles will only succeed if all layers, from chips to applications, interact seamlessly within a centralised, co-designed on-board network architecture and effectively support the core functionalities of safe and efficient driving. Smart sensors and controllers set the deterministic ceilings for compute, latency, and energy; middleware provides the abstraction and orchestration needed to manage complexity, to bridge the different innovation speeds of hardware and software, and to isolate safety-critical from non-critical functions; and applications create real-time value for users and mobility services. While abstraction may seem less critical in centralised architectures, it remains essential for OTA updates, portability across heterogeneous chips, and preventing vendor lock-in.

4. Innovation pathways: How to reach ideal SW/HW support of green and digital vehicles?

The biggest challenges for Europe lie in making all layers work together within highly integrated SW–HW architectures based on centralised network and E/E designs, high-performance computing platforms, and chiplet-based processors interacting with the sensors and actuators to deliver safe and efficient vehicle functions. Addressing these challenges is essential for building an effective roadmap.

The following action fields require particular attention:

- **Innovation cycle synchronisation**: Automotive hardware evolves over long cycles, while software moves in weeks. Without foresighted co-design, this mismatch risks becoming a bottleneck.
- **Trust and safety assurance**: Centralised nodes are powerful but vulnerable, requiring new redundancy concepts, advanced cybersecurity, and validation methods for AI-enabled, non-deterministic functions using digital twins and tests in real world.
- **Complexity management at scale**: Heterogeneous systems offer performance gains but demand unified interfaces, debugging capabilities, and observability tools to avoid fragmentation.
- **Holistic instead of siloed development**: Defining vehicle-level functional requirements, and developing and validating them, require a holistic approach where all key automotive systems are developed collectively across the SW/HW interface. This requires novel organizational approaches.
- **Edge, HPC, and cloud balancing**: Deciding which functions stay on-board the vehicle, which run at the edge, and which rely on the cloud to shape overall efficiency, safety, and supply chain harmonization, particularly for AI deployment.
- **Standardisation gap closing:** Without common APIs, middleware, and SW/HW reference architectures, Europe risks duplication, interoperability failures, and slower innovation in SDV.

Meeting these challenges requires smart systemic coordination across the full lifecycle:

- **Agreement on comprehensive SW/HW reference architecture**: a layered SDV stack (chip → e/e architecture → middleware → application) should serve as a common baseline across the industry.
- **Clear understanding of differentiators**: Generic processors and middleware provide common services, while differentiating components and applications deliver brand-specific value.
- **Push–pull alignment with digital and green trends**: Integrating smart batteries, bidirectional charging management, and predictive diagnostics into digital mobility functions ensures that SDVs support sustainability goals.
- **Lifecycle integration**: Design, development, use, maintenance, and recycling must be treated as one chain, with predictive diagnostics and OTA updates extending lifetimes and reducing waste.
- **Balancing cooperation and autonomy**: Europe must maintain sovereignty in HW and SW stacks as well as AI and data for SDV while participating actively in global standardisation and automotive markets, in line with the principles of open strategic autonomy.
- **Rethinking engineering**: Moving from separate automotive component and subsystems development processes followed by system-level integration, validation and verification toward agile, sprint-based and circular co-design approaches, testing schemes and toolchains inspired by DevOps pipelines in software-development that allow updates in weeks rather than months.

In general, it should be noted that the shift towards SDVs, the decisive factor alongside driving safety and performance, significantly changes the roles of players in the automotive supply chain throughout the vehicle's lifetime. While co-design of hardware and software is essential in the pre-deployment phase, ensuring that chips, E/E architectures, and applications are aligned for safety, performance, and efficiency, after deployment, decoupling becomes key. Software then evolves independently of hardware through updates, diagnostics, and in-operation validation. This enables OEMs to deliver continuous improvements to users, while suppliers of hardware and software remain engaged in monitoring, testing, and enhancing system functions across the entire lifecycle. As a result, all players transition from one-off delivery models to shared lifecycle responsibility and agile upgradability, requiring close collaboration and business models based on continuous value creation within an ecosystem. This systemic and accelerating implication of smart systems integration in software-defined, hardware-enabled vehicles is important for Europe, given its tiered supply chains.

5. Funding: What implications does smart systems have for the FP10 partnership?

During Horizon Europe FP9, software-defined and hardware-enabled vehicles (SDV) were established as a research and innovation priority in the Chips Joint Undertaking, in cooperation with the European Partnerships on Connected, Cooperative and Automated Mobility (CCAM) and Towards Zero-Emission Road Transport (2Zero). Cross-references in the respective roadmaps, the ECS SRIA and the CCAM and 2Zero SRIAs, identified a range of call topics, including hardware abstraction layers, RISC-V microprocessors, heterogeneous integration, and engineering toolchains in the "Software-defined Vehicle of the Future" (SDVoF) initiative of the Chips JU. In parallel, perception systems, E/E architectures, and generative AI-related topics were covered under the CCAM and 2Zero Partnerships, and all this led to projects such as the CSA FEDERATE, the RIA HAL4SDV, and EEA4CCAM.

Looking ahead, the EPoSS initiative to foster the SDVoF ecosystem by strengthening relations across the triangle of automotive software stack, electronic hardware, and application domains such as electrification and automation has been taken up to a large extent in the measures of the European Commission's Industrial Action Plan for the Automotive Industry. All three funding instruments currently in preparation reflect this idea: the European Connected and Automated Vehicles Alliance (ECAVA), which has just been launched, the future Automotive Partnership/Joint Undertaking under Horizon Europe FP10 (from 2028), and the potential Important Project of Common European Interest on Clean, Connected and Automated Vehicles (IPCEI CCAV).

In this context, the following aspects are of particular importance:

- **Highlighting the enabling role of smart systems integration for SDV** as a key competitiveness factor in strategic discussions across all new instruments.
- **Developing a common reference SW/HW reference design for SDV** to establish a company-neutral framework for the systemic architecture and co-design, smart electronic components, and interfaces of future software-defined and hardware-enabled vehicles.
- **Emphasising the decisive role of SW/HW co-design** for efficient, safe and convenient SDV technology solutions.
- **Acknowledging the need for progress in the zero-emission and automated vehicle domain** at transport systems and services level as well as with AI, circularity, manufacturing and production.
- **Reflecting the tension of fast SW development cycles vs. long-term HW decisions for SDV** in the assessment of acceleration potentials and value chain cooperation challenges.
- **Growing the European SDV ecosystem** to create a level-playing field for the entire smart system enabled value chain, supported by AI and data in the cloud-edge continuum, while safeguarding open strategic autonomy.

Europe's leadership in SDV and smart systems will depend on ensuring that all funding instruments, ECAVA, Automotive Partnership or JU, and IPCEI CCAV complement each other along the value chain, build upon and continue the achievements of 2Zero and CCAM, and relate to the successor of the Chips JU, creating strong, synergetic funding levers. This must also create spillover potential into AI, robotics, cobotics, industrial automation, and dual-use domains. Achieving this requires close ecosystem collaboration and shared governance between public and private actors, strong involvement of both the European Commission and Member States, all coordinated through a comprehensive ECAVA–Automotive JU/Partnership–IPCEI CCAV framework along common roadmaps.

Conclusion

Europe's future competitiveness in the automobile sector in general, and in software-defined, hardware-enabled vehicles (SDV) in particular, will be decided by its ability to achieve smart systemic integration from chips, sensors and processors to centralised E/E architectures, and services. Success depends on aligning HW and SW innovation cycles, co-designing safe and efficient systems, and enabling continuous lifecycle improvements through decoupling after deployment. If Europe secures common reference architectures, open standards, and aligned funding instruments, it can build a strong SDV ecosystem that combines sustainability, competitiveness, and open strategic autonomy.