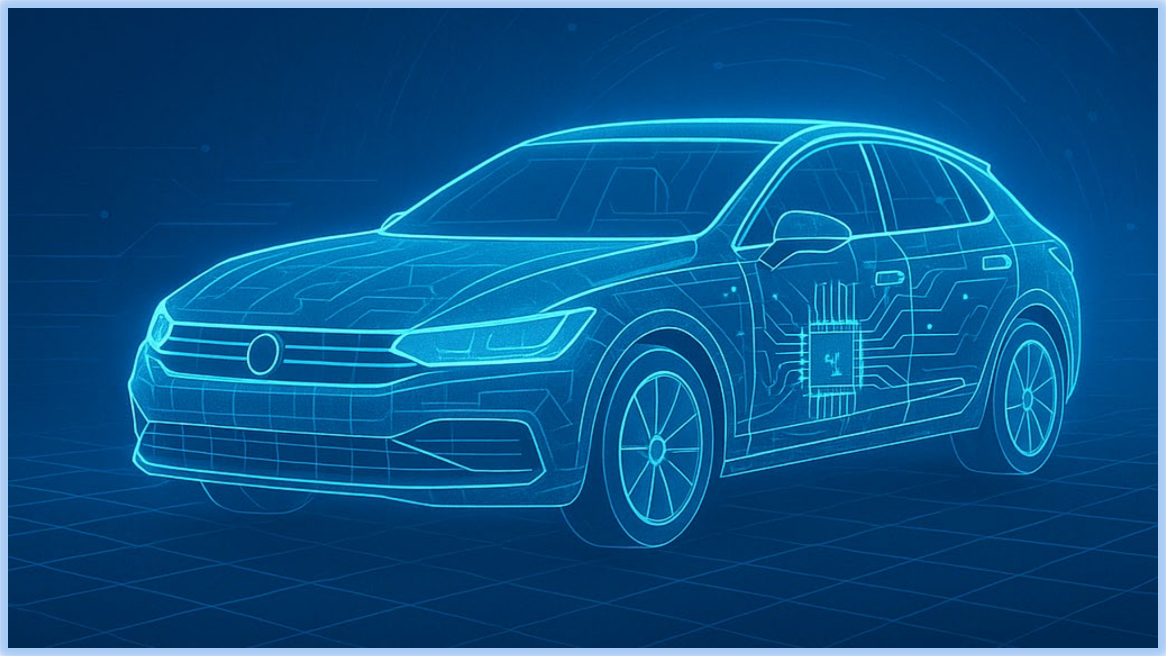
The Transformative Impact of Software Defined Vehicles on the Automotive Industry



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Glossary

Acronym	Full Form
ADAS	Advanced Driver-Assistance Systems
AI	Artificial Intelligence
AV	Autonomous Vehicle
BEV	Battery Electric Vehicle
E/E architecture	Electrical/Electronic architecture
ECU	Engine Control Unit / Electronic Control Unit
EV	Electric Vehicle
HPC	High Performance Compute
ICE	Internal Combustion Engine
IoT	Internet Of Things
ISO	International Organization for Standardization
OBD-II	On-Board Diagnostics, 2nd Generation
OEMs	Original Equipment Manufacturer
OS	Operating System
OTA Updates	Over-The-Air Updates
SDV	Software Defined Vehicle
TOPS	Tera Operations Per Second
UI/UX	User Interface
V2X	Vehicle-to-Everything

Introduction

The automotive industry is undergoing a fundamental transformation. Powertrain electrification, deployment of Advanced Driver-Assistance Systems (ADAS), and intelligent systems that move cars closer to "computers on wheels" are changing the automobile. Automotive suppliers and vehicle manufacturers are also changing, with new entrants from non-traditional automotive firms and from new regions, particularly from China. While many of these advancements are possible with a traditional microcontroller-based architecture, a Software Defined Vehicle (SDV) makes implementing these new technologies more seamless and efficient.

SDVs represent a paradigm shift in automotive design and manufacturing, driven by the increasing integration of software within the vehicle architecture. Unlike traditional vehicles that rely primarily on hardware-driven functionalities where software is hard-coded onto a microcontroller to carry out one specific function, SDVs leverage software to enable new capabilities, continuous updates, and deliver enhanced user experiences. The SDV transition has been called a "Smartphone on Wheels"[1], but the transition is far more than building an app-ecosystem with touchscreens and internet connectivity that is synced to your smartphone.

In this paper we will define SDVs, assess their impact on customer experience and vehicle architecture and explore the balance between software and hardware in enabling this transformation. Furthermore, we will explore the implications of SDVs on business models, the shifting roles of Original Equipment Manufacturers (OEMs) and Tier-1 suppliers, and strategies for sustainable value creation in this emerging ecosystem.

To understand the roots of this transformation, it's essential to look back at key milestones in automotive history. One such milestone is the Volkswagen (VW) Type 3, which in 1968 became the first car to feature an electronically controlled fuel injection system. This innovation marked a significant step towards modern automotive technology. The Type 3's Bosch D-Jetronic fuel injection system included the first mass-produced automotive Engine Control Unit (ECU), laying the foundation for computer controls in modern cars. This ECU even had limited on-board diagnostics capabilities, a precursor to today's OBD-II (On-Board Diagnostics, 2nd Generation) systems. While this board was controlled by analog electronics and sensors rather than an integrated circuit with a software engine map, it laid the foundation for software to soon enter cars. These advancements in the Type 3 highlight the historical evolution of automotive technology and its impact on modern vehicles.[2] While Japanese companies were including digital integrated circuits for wipers, locks, dashboard etc.[3], the Bosch Motronic 1.0 ECU introduced in 1979 on the BMW 7 series was arguably the first car which had a software map run on a microprocessor[4] that digitally controlled the engine timing, fueling etc., and hence could be called the first vehicle with software.

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[1] https://www.lemonde.fr/en/environment/article/2023/05/26/cars-become-smartphones-on-wheels_6028140_114.html
[2] https://www.jalopnik.com/the-volkswagen-type-3-was-in-one-important-way-the-firs-1841278026/
[3] https://www.shmj.or.jp/english/trends/trd70s.html
[4] https://www.bosch-mobility.com/en/company/milestones/

Figure 1: 1968 Advertisement by Volkswagen for the Type 3 Squareback Car with a computer[5]

Defining a Software Defined Vehicle

Software in cars is not new. While software entered cars via the engine control unit, it soon spread into various microcontrollers and components across the car. Even non-SDV cars have many lines of code carrying out various important functions in the car from controlling ignition timing, air-fuel ratio, anti-lock brakes, traction control, body control, power windows/locks, infotainment systems, etc.. However, the way this code is implemented and functions in an SDV differs from traditional architecture vehicles.

In traditional architecture vehicles, the software is hard coded onto each microcontroller/component and these units are sealed for life. Updating the software is cumbersome and requires flashing chips on the microcontroller board. The code is decentralized and there is hardly any communication among modules. Automakers could historically only add new features with a new model year/generation, as opposed to updating a vehicle already sold to the customer. This new feature would be delivered through a new module

[5] https://www.atticpaper.com/proddetail.php?prod=1968-vw-volkswagen-squareback-ad

built into the vehicle at the assembly plant. These modules were typically supplied by a Tier-1, with software embedded for life.

As cars gained more and more features, hundreds of such independent electronic control units proliferated throughout the vehicle, all doing just one (or very few) function(s). This redundancy enabled robustness, because if one unit failed, the rest could continue functioning unimpaired by that failure. However, as we will discuss, robustness can be built into SDVs without the added redundancy.

The three key concepts of the SDV are:

- Software is more centralized, is independent of the underlying hardware and overall is less of an afterthought
- Software can easily be updated Over the Air (OTA), improving functionality, performance and reliability of the components
- Communication among different domains or zones of the vehicle and data transfer to the cloud is much easier

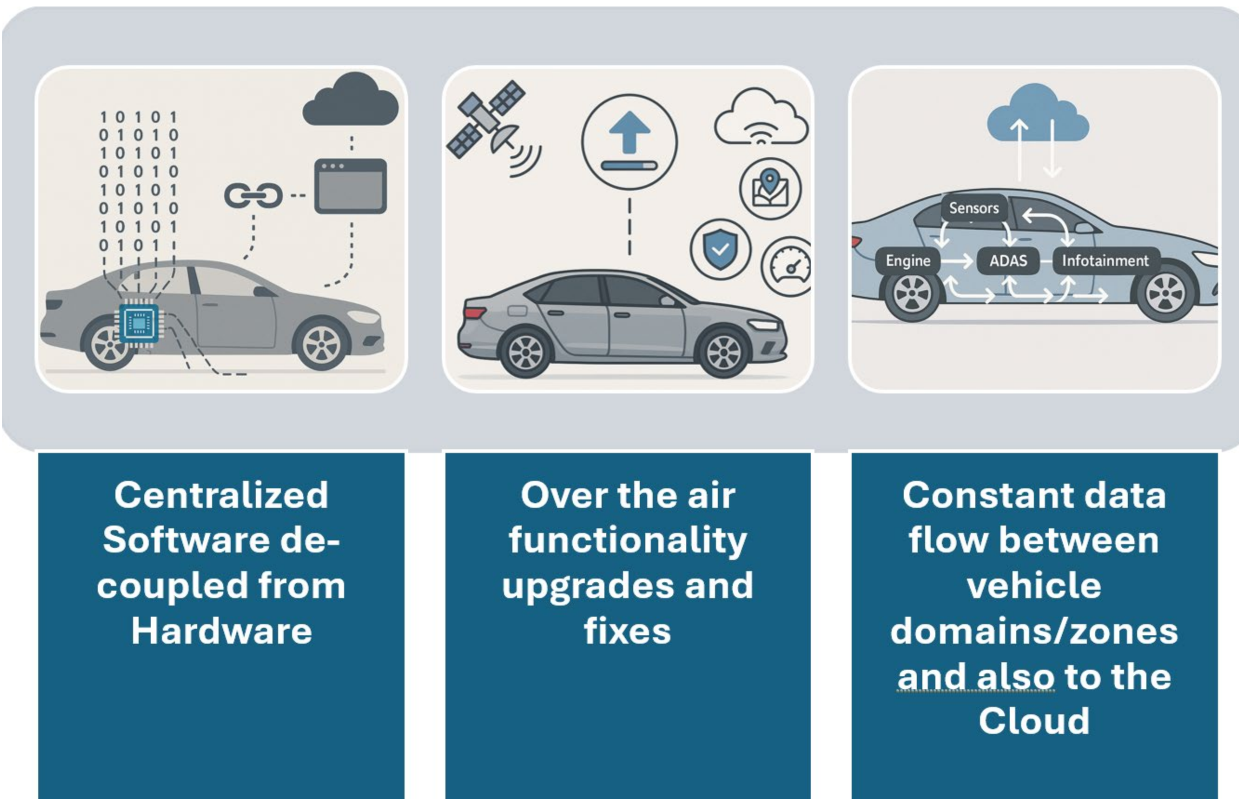

Figure 2: Key Concepts of an SDV

SDVs can be understood as automobiles where key functionalities such as performance optimization, safety features, infotainment, and autonomous driving capabilities are primarily dictated by software rather than isolated, fixed hardware components. Unlike traditional vehicles, SDVs are designed with a centralized computing architecture that allows for over-the-air (OTA) updates and feature enhancements throughout the vehicle's lifecycle. This does not preclude a vehicle with a traditional microcontroller architecture with hundreds of ECUs from delivering advanced functionality (e.g., ADAS) or some level of OTA capability. However, SDVs as an architecture platform lend themselves very well to enhanced vehicle functionality and system updates.

While there is general consensus in the automotive industry about "what is an SDV and what basic functionalities it must have", there is no one accepted definition. Some define it from the point of view of what it offers the end-customer, some define it from its architecture while some define it based on how it changes the design and build process for an OEM/Tier-1 supplier. We interviewed various OEM and Tier-1 executives and also carried out secondary research. Here are some of the definitions from different sources via secondary research:

Company	Definition
Bosch	The software-defined vehicle is a term used to describe the gradual transition from hardware-driven development to software-defined development. New functions are implemented primarily through software and can be made available to the vehicle through **regular updates**.[6]
Renault	The Software Defined Vehicle (SDV) refers to the ability to upgrade a car throughout its lifetime, through a centralized architecture, updating it and integrating new applications to enhance its functions. [7]
S&P Global	With the increasing pace of connectivity, electrification, and autonomous driving enhancements, the concept of the SDV **allows the vehicle to evolve and adapt to customers' ever-changing needs** for optimal user experience, including the latest connected services and functionality, upgraded in-vehicle apps, and enhanced safety.[8]
Aptiv	"Software-defined vehicle" is a term that describes a vehicle whose features and functions are **primarily enabled through software**, a result of the ongoing transformation of the automobile from a product that is mainly hardware-based to a software-centric electronic device on wheels.[9]
General Motors	The term software-defined vehicles refers to a fundamental trend in how vehicles are designed. The **underlying needed hardware is now serving the software enabler,** creating a shift in the profile of developed software that in turn drives new hardware requirements, but also connectivity.[10]

Our interviews demonstrated that there is no universally accepted definition of SDVs. Different companies – and even individuals within the same company – gave us different interpretations of what constitutes an SDV. Here's how different companies define SDV, the key points of which are summarized in the figure that follows the table below:

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[6] Open technology platform for the software-defined vehicle, Bosch, https://www.bosch-mobility.com/en/solutions/software-and-services/open-technology-platform-for-software-defined-vehicles/
[7] All about Software Defined Vehicle, Renault, 24.04.2023 https://www.renaultgroup.com/en/magazine/our-group-news/all-about-software-defined-vehicle/
[8]https://www.automotive-iq.com/autonomous-drive/interviews/the-state-of-the-software-defined-vehicle-market
[9] https://www.aptiv.com/en/insights/article/what-is-a-software-defined-vehicle
[10]https://www.automotive-iq.com/autonomous-drive/interviews/the-impact-of-software-defined-vehicles-on-the-automotive-industry

Definition of SDV	OEM/Tier-1
Reduced complexity in both software and hardware within the vehicle, leading to cost reduction and faster deployment.	OEM
Centralized vehicle architecture with **updatable software** over its lifetime.	Tier-1
Virtualized middleware that allows a single operating system across multiple electrical platforms, reducing software variations.	OEM
Incremental functionality added to vehicles, impacting vehicle architecture to reduce development costs and increase delivery speed.	Tier-1
Connected vehicles with a **focus on connectivity**, services, and leveraging data from the vehicle.	OEM
Centralized electrical and electronic **architecture** enabling **constant OTA** updates to make vehicles updatable and operable.	Tier-1
An opportunity to reach customers faster and provide **new services and revenue opportunities.**	OEM
SDV is defined by the **separation of hardware and software**, enabling updates and improvements over time.	Consultancy
A vehicle whose identity is determined by software. In practice, it refers to a vehicle that c**ontinuously delivers a variety of experiences to users through software**, providing value beyond just transportation.	OEM

These results highlight the diverse perspectives on SDVs across different companies. While most emphasized centralized architectures and updatable software, others focused on connectivity and incremental functionality. This variation underscores the evolving nature of SDVs and highlights the different priorities among various companies as they transition from legacy vehicle architecture to software defined vehicles.

Benefits of Software Defined Vehicles

Our interviews revealed that the evolution to SDVs can deliver benefits to multiple stakeholders, including OEMs, Tier-1 Suppliers, and End Users.

OEM	• **Brand loyalty via enhanced customer experience**: Personalized settings, predictive maintenance, and AI-driven assistance. • **Efficient bug fixes and continuous Improvement**: Over-the-air (OTA) updates allow for performance enhancements, new features, and bug fixes without physical recalls. • **New revenue streams**: Subscription-based services, feature unlocks, and connected services can generate ongoing income for OEMs. • **Improved safety and performance**: Advanced driver assistance systems (ADAS) and real-time diagnostics reduce accidents and enhance driving dynamics. • **Lower cost:** Due to consolidated hardware and reuse of software, lower bill of materials • **Competitive differentiation -** not just through hardware as was the case before, but by offering unique services, even transforming their entire business models.
Suppliers	• **Lower cost:** Due to consolidated hardware • **New business models:** Can now sell what each company needs, e.g. ECUs with embedded software, only ECU, only software • **Standardization of hardware:** Due to shift towards centralized ECU, it will be easier to standardize hardware instead of maintaining numerous versions for each partner company
End Users	• Vehicle Personalization (post sale) & Seamless Digital **Integration with their other platforms/devices** • **Reduced cost** of purchase (due to a lower cost to manufacture) and Service (lot of fixes/recalls fixed OTA) • **Continuous Feature, UI/UX & Functionality Upgrades** • **Connected Services and Integration with Infrastructure –** enabling more services and safety features

Key Concepts Deep Dive:

Centralized architecture:

We are seeing a shift towards a more centralized computing architecture in vehicles converging around four or five domain areas. These domain areas can be thought of as functional sub-systems of the vehicle, similar to human anatomy system functions such as the nervous, circulatory or lymphatic system.

Here's a brief overview of different OEMs approach. Most of the legacy OEMs seem to be currently running their traditional ICE model on older distributed architecture, while have moved to domain-based architecture for their newer battery electric models.:

OEM	Number of main domains	Domain names	Estimated SDV Models on Sale
Audi [11]	5	1. Drive system and suspension, longitudinal and lateral dynamics, 2. Driver assistance systems 3. Infotainment 4. Comfort 5. Networking and V2X connectivity	2 – A6/Q6 e-tron
BMW [12]	4	1. Driving 2. Automated Driving 3. Infotainment 4. Body and comfort	2 – i4, iX
Ford [13]	5	1. Powertrain 2. ADAS 3. Infotainment 4. Body & Comfort 5. Connectivity & OTA	2 - Mach-E, F-150 Lightning
Mercedes [14]	4	1. Powertrain 2. Autonomous driving 3. Infotainment 4. Body & comfort systems	3 – EQE, EQS, EQB
Tesla [15]	3 Zonal Control	1. Right Body Control	5 – Model 3, Y, S, X,

[11] The new Audi E³ 1.2 electronic architecture brings "Vorsprung durch Technik" to life https://www.audi-mediacenter.com/en/press-releases/the-new-audi-e3-12-electronic-architecture-brings-vorsprung-durch-technik-to-life-15925

[12] FOUR "SUPERBRAINS" FOR THE NEUE KLASSE BY BMW, BMW https://www.bmwgroup.com/en/news/general/2025/superbrains.html

[13] https://www.autoblog.com/news/ford-quietly-kills-multi-billion-dollar-software-defined-vehicle-plans

[14] Mercedes-Benz Looks to Tap into Massive Revenue Potential Linked to Software-enabled, In-Vehicle Products and Services, Kamalesh M, Manish Menon, Feb 27, 2023, https://www.frost.com/growth-opportunity-news/mercedes-benz-looks-to-tap-into-massive-revenue-potential-linked-to-software-enabled-in-vehicle-products-and-services-with-its-own-purpose-built-automotive-operating-system/

[15] https://autotech.news/wp-content/uploads/2022/07/8.png

	Modules + 1 HPC Central Compute Module	Module 2. Left Body Control Module 3. Front Body Control Module 4. Central Compute Module	Cybertruck
Toyota[16]	4	1. AD/ADAS 2. Cockpit 3. Body (not yet implemented) 4. Dynamics (not yet implemented)	1 – 2026 RAV4

While some of the interviewees believed that existing technology is sufficient to enable SDVs from an architecture perspective, others emphasized the need for significant advancements in AI, cloud native tools, and virtualization to ensure better robustness, security and reliability. Most also mentioned that Tesla and many Chinese OEMs have already achieved most of the key parameters of an SDV. Not having the car's software distributed amongst hundreds of microcontrollers has its advantages as Tesla showed during the peak of the chip shortage in 2021-22. Tesla could rewrite some firmware code and switch chip manufacturers[17], which legacy OEMs struggled to do due to the distributed and closed nature of the traditional microcontroller approach.

Although currently many OEMs are leaning towards domain-based architecture, as we shift towards SDVs, there may be greater efficiencies by migrating to zone based or zonal architecture. Migrating from domain to zonal E/E architecture offers benefits such as reduced wire-harness cost and complexity, faster communication, and fewer components leading to a lower bill of materials cost[18]. In the Tesla Model 3, for example, zonal architecture led to a 50% reduction in wiring,[19] and for Rivian it led to a 44 pound and 1.6-mile reduction in wiring[20].

Figure 3 depicts the predicted SDV architecture evolution:

[16] https://woven.toyota/en/our-latest/20250521/
[17] https://www.supplychaindive.com/news/tesla-earnings-elon-musk-semiconductor-chips-shortage/604011
[18] Renesas Strategy for E/E Architecture, Renesas, Takeshi Fuse, January 24, 2023 https://www.renesas.com/en/blogs/renesas-strategy-ee-architecture
[19] https://www.spglobal.com/mobility/en/research-analysis/can-carmakers-assail-teslas-lead-in-ee-architecture.html
[20] https://www.popsci.com/technology/rivian-zonal-electrical-architecture/

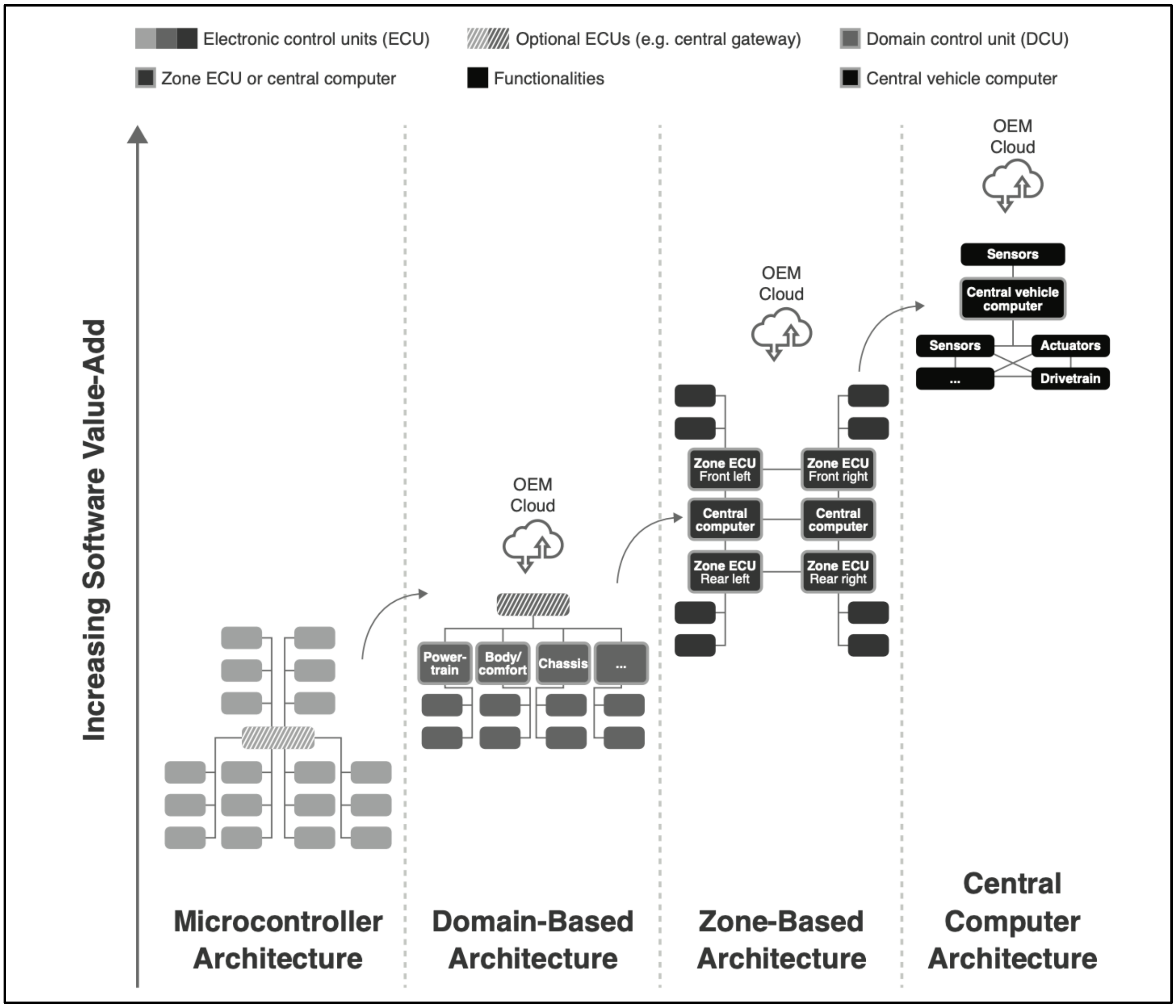

Figure 3: E/E Architecture Evolution | Source - The Flagship Experience, Evangelos Simoudis[21]

Timelines for shifting from traditional microcontroller architecture to domain-based and/or zone-based architecture differ among OEMs, however many companies agree that by 2030 most cars will be SDVs with a few models running highly centralized compute architecture. A few OEMs mentioned in the interviews that over the past few years within the same model generation itself they have shifted from microcontroller to domain-based architecture and reduced the number of ECUs and wiring. This change may not be visible externally for consumers, but under the hood a lot has changed. Most of them mentioned approximate timelines of 2026-28 for moving most of their models to SDV architecture, and confirmed that they all had ongoing efforts developing such platforms. All the interviewees agreed that Tesla has been a pioneer of SDVs starting with the Model S – the world's first SDV car introduced in 2012[22]. Many also mentioned the newer Chinese OEMs, such as Nio, Zeekr, Xpeng, that have full SDV model lineups.

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[21] The Flagship Experience, Evangelos Simoudis - How AI and Software-Defined Vehicles Will Revolutionize the Automotive Customer Experience

[22] https://www.motortrend.com/features/tesla-model-s-code-software-design-craig-carlson-interview

OTA (Over the Air) Updates:

1. Increased Necessity of Regular OTAs for SDVs

In the rapidly evolving landscape of Software-Defined Vehicles (SDVs), Over-the-Air (OTA) updates have become essential for ensuring customer satisfaction through the continuous improvement of vehicle systems. As SDVs rely heavily on software for functionality, performance, and safety, regular OTAs are necessary to update critical systems, enhance features, and fix software bugs or vulnerabilities. OTA updates enable manufacturers to provide timely improvements without requiring expensive physical recalls or service visits, enabling a seamless and more efficient user experience. One study suggests that 43% of vehicle recalls could be avoided with OTA[23]. Of course, while OTAs can fix many shortcomings of the product via software patches, they cannot compensate for vehicle hardware failures that sometimes necessitate recalls such as stress fractures, incorrect fasteners/glue, faulty seals etc. However, an SDV with multiple sensors and regular data transfer to the cloud could predict the failure of a vehicle hardware component, which does not prevent a recall/service visit, but could prevent an even more expensive vehicle hardware failure.

Containerization is essential for OTA updates, enabling modularity, scalability, security, and efficient software integration. Containerization packages software code, along with its dependencies, libraries, and configuration files, into a single unit called a container. These containers can run consistently across different environments—whether in the cloud or inside a vehicle. They isolate applications from each other, reducing the risk of one malfunctioning service affecting others. Containerization supports running mixed criticality applications on shared hardware and facilitates the transition to centralized architectures, ensuring functional safety and compliance with industry standards. In order to maintain different versions of code for different customers, we might see the use of containerization in the cloud, as has been common in most software architectures in recent years. Testing how different software versions and feature updates perform is critical. This testing can now be done perhaps more efficiently at the cloud level on a digital twin that mimics different hardware/software combinations that are in existence.

2. Ensuring Security and Reliability of OTAs

Various approaches for ensuring secure and reliable OTA updates were mentioned in our interviews, including bidirectional verification, private IP tunnels, and robust frameworks. To guarantee the security and reliability of OTAs, several key practices must be implemented. First, robust encryption and authentication mechanisms are essential. By utilizing end-to-end encryption, secure boot processes, virtual private networks, OTAs can be safeguarded from unauthorized access and tampering. Additionally, regular security patches are critical to mitigate vulnerabilities in the system. Frequent OTA updates ensure that the software remains up to date and resilient against emerging cyber threats.

Penetration testing and simulation further strengthen the security framework. These proactive cybersecurity measures involve continuous testing to identify and address potential threats before the updates are deployed, reducing the risk of vulnerabilities. Adhering to regulatory standards, such as ISO 21434 for automotive cybersecurity, ensures compliance with industry's best practices and legal

[23] https://www.bearingpoint.com/files/Software_over_the-air_study_BearingPoint.pdf

requirements. Finally, failsafe mechanisms need to be implemented to guarantee that vehicles remain operational even in the case of a failed update, preventing downtime and maintaining safety.

Most legacy OEMs are conservative with OTA updates, ensuring significant testing before deployment to meet customer expectations of quality and uphold their brand image. This approach contrasts with more software-forward automotive companies that have more frequent updates. Some interviewees suggested that the software-forward OEMs are perhaps using their customers as beta-testers in the quest for speed.

3. Compatibility of OTAs with Existing Hardware

A common benefit for OEMs is the potential for cost reduction through software reusability and consolidated software development. However, compatibility with existing computing hardware is paramount for OTAs to work seamlessly across a variety of systems on OEM fleets. Each OEMs fleet includes newer and older vehicles and standardized communication protocols ensure that both legacy and new systems can communicate effectively, facilitating smooth integration.

Edge computing integration plays a crucial role by offloading processing tasks to localized units, improving the efficiency and speed of OTAs while minimizing the load on central servers. Scalability considerations are also important, as hardware must be designed to accommodate future software functionalities. This forward-thinking approach ensures that the system remains adaptable as new features are introduced, optimizing performance and extending the life cycle of both the hardware and software. The challenge lies in creating a future-proof internal software update management system.

Multipurpose / Virtual Hardware and Digital Twin

Despite the transition to a more software focused vehicle, basic vehicle hardware like sensors to sense the surroundings are still necessary. Software can replace some vehicle sensors. For example, whether a door is closed or not can be tracked using different communication signals in the vehicle -- a separate sensor is not required. Some interviewees mentioned the idea of virtual sensors, where existing vehicle hardware like cameras and microphones are repurposed for additional functionalities without the need for additional vehicle hardware, thereby reducing overall cost.

Another advantage of moving to SDVs is that it's much easier to simulate them in a Digital Twin environment since the entire software stack can be run virtually. Digital twins enable developers to create digital replicas of vehicles, reducing the need for extensive real-world trials and enhancing the overall development process. Erik Coelingh, VP of product at Zenseact, an ADAS developer owned by Volvo, noted " we develop this in-house now, so instead of relying on suppliers with long lead times and long process and sending requirements back and forth, we develop the software".[24]

An interviewee from a Tier-1 supplier discussed the importance of using cloud native tools for trusted verification and validation, highlighting the role of digital twins in modeling real vehicle and compute hardware in the cloud. This approach allows for efficient and cost-effective testing of software updates and new features in a virtual environment before deployment, ensuring reliability and security.

[24] https://arstechnica.com/cars/2025/03/volvo-reconstructs-crashes-with-ai-in-virtual-worlds-to-make-safer-cars/

Role of Open-Source in SDVs

Open-source solutions can reduce development time through shared platforms (such as Automotive Grade Linux or Eclipse SDV foundation), enhance interoperability with common frameworks promoting cross-OEM compatibility, and lower costs by reuse of code and reducing dependency on proprietary software. We are already seeing startups like Li Auto launching their own Open-Source Automotive OS: Halo OS [25]. However, challenges to adopting Open-Source software include intellectual property concerns, ensuring quality and security in community-driven projects, and managing software dependencies and update cycles. While open-source software drives innovation and efficiency, companies balance its use with proprietary solutions for critical functionalities. From the interviews we learned that there is a growing openness to using open-source software, especially for non-differentiating layers like middleware[26] and operating systems, and for the other layers, OEMs will likely customize and branch off these solutions to meet their specific needs. This saves time, cost, and can improve performance and connectivity for future applications. A description of the various differentiating and non-differentiating layers are shown in Figure 4.

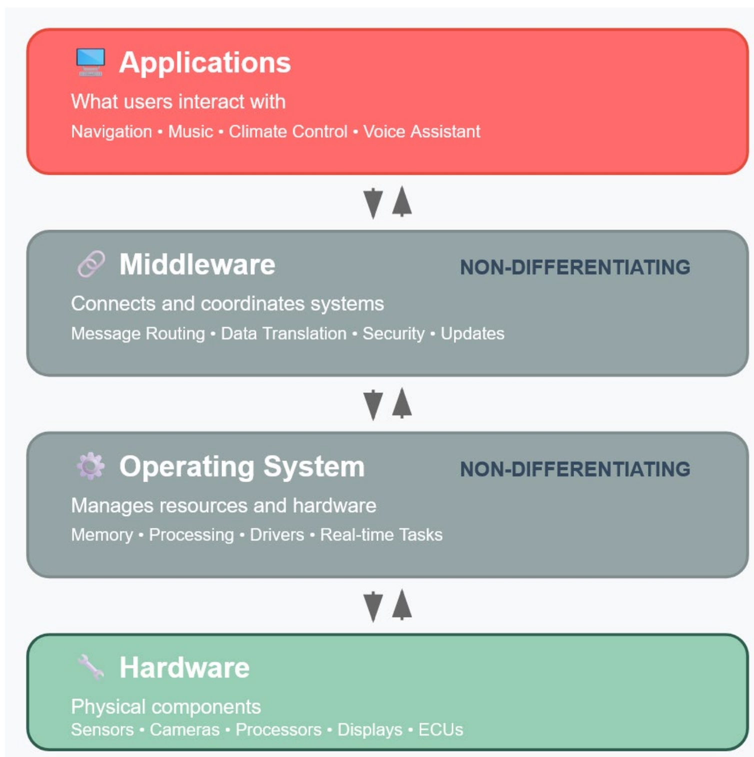

Figure 4: Architectural Layers of an SDV

[25] https://www.chinaevhome.com/post/li-auto-breaks-ground-by-launching-world-s-first-open-source-automotive-os-li-auto-halo-os

[26] https://azure.microsoft.com/en-us/resources/cloud-computing-dictionary/what-is-middleware/

Shifting Dynamics between OEMs & Tier-1 Suppliers

The Software-Defined Vehicle (SDV) ecosystem is evolving rapidly, with multiple stakeholders adapting to new roles and responsibilities. OEMs, Tier-1 suppliers, tech companies, and regulators are all navigating the shift towards software-centric vehicles with distinct responsibilities and strategies.

OEMs are transitioning from vehicle hardware manufacturers to software integrators, which is a new role for them. For many decades, OEMs specified component or sub-system requirements and the Tier-1 suppliers engineered these components and supplied them to the OEM to integrate into the vehicle. SDVs disrupt this pattern as OEMs are responsible for software reliability, functionality updates, data privacy, cybersecurity compliance, and customer service for software-related issues.

A common theme from the OEM interviews was that navigating relationships with traditional Tier-1s and new tech partners is a critical challenge as OEMs take more control of software development. **Tier-1 suppliers** are focusing on providing high-quality, secure, and compatible hardware while adapting to new demands. They are ensuring seamless integration with OEM software frameworks and bearing liability for system failures caused by component defects. Instead of selling black-box systems, Tier-1 suppliers are becoming co-developers or integrators of OEM software on new domain controllers (e.g., Valeo providing the ADAS controller and some software to BMW). It was quite clear from all the interviews that while OEMs will take more control and aim for some vertical integration, they will continue to rely on Tier-1 expertise and support for core hardware components.

Some new frameworks of collaboration are listed below:

1. **Co-Developing Platforms:** Traditionally, an OEM would involve a supplier once a vehicle program was underway with defined component needs and specifications, oftentimes in a transactional way. With the SDV transition, because software and electronics define so much of the vehicle experience, many OEMs are bringing Tier-1 suppliers into the development process and collaborating with them much earlier, shifting from a transactional relationship to a partnership. This ensures the supplier's expertise is leveraged in the initial design phase, and the OEM's overall system-level goals for the SDV platform are understood by the supplier, like this SDV co-development partnership between Renault and Valeo[27]. However, shifting business culture is often easier said than done and will test the agility and adaptability of both OEMs and suppliers.

2. **Clear Interfaces and Modularity:** Defining clear software interfaces (via APIs and other methods) and responsibilities is crucial for effective collaboration on a complex software-defined platform. OEMs can help by providing standardized interfaces for suppliers – e.g., a common operating environment or middleware that the OEM defines, on top of which all supplier components must run. This allows multiple Tier-1s to work on different features without interfering with each other, since everyone understands how their piece plugs into the whole. Some OEMs use industry-standard middleware (such as AUTOSAR Adaptive for certain domains) so that Tier-1 contributions are modular. A Tier-1 can collaborate by being flexible and compliant with these interfaces, rather than insisting on proprietary ones. When each party's responsibilities are well-delineated (for example, OEM provides the vehicle OS and OTA system, Tier-1 provides the application that performs a function and its internal logic), collaboration is smoother and troubleshooting is easier.

[27] https://www.valeo.com/en/renault-group-and-valeo-sign-a-partnership-in-software-defined-vehicle-development/

3. **Shared Platform Collaboration:** Collaboration can also take the form of shared platforms where a group of stakeholders, including key OEMs and Tier-1s, develop a software platform or OS or API standard and then offer it to the industry. This approach is a step up from the previous interface and modularity method. An OEM might decide to adopt that platform rather than create its own from scratch. This is effective when the platform is highly complex and would be inefficient for each OEM or Tier-1 to duplicate. Examples include GM/Magna/Wipro's SDVerse Marketplace[28] or the Eclipse SDV Project[29]. OEMs need to have confidence that these platforms won't prevent them from differentiating their products.

4. **Establishing and Maintaining Long-Term Relationships:** The more software-intensive cars become, the more involved the Tier-1 supplier must be during the development of the car and the more OEMs depend on their suppliers' code and parts for vehicle safety and performance. Both sides must trust that the other will uphold quality, timelines, and confidentiality. Further, it will not be easy to shift suppliers midway through the production of the car given how closely involved the first supplier was in the development of the car. Hence, OEM–supplier collaborations in the SDV era are likely to move towards longer-term relationships or alliances rather than single-contract deals.

An OEM will value a supplier that commits to support and upgrade its software in the field (since ultimately the OEM bears the brunt of any field issues). In some cases, Tier-1s may embed engineers on-site at the OEM and vice versa to act as liaisons, which greatly enhances mutual understanding. The net result is more of a partnership model (sometimes dubbed "Tier 0.5") where the supplier is almost an extension of the OEM's own team.

Big Tech Companies Relevance

We are seeing increasing interest from Big Tech companies and chip manufacturers in the automotive industry. For example, Amazon is selling whole packages to automotive companies and integrating Alexa with the car's infotainment system. Revenue generated through such integrations is shared by Big Tech companies and OEMs[30]. Amazon's SDV package includes solutions for use cases such as Vehicle Data Collection, Cybersecurity, OTA updates, and Virtual Engineering Workbench[31]. Other leading technology companies like Qualcomm, Nvidia, and MediaTek are also making significant strides in advancing software-defined vehicle (SDV) capabilities through cutting-edge platforms and strategic partnerships.

Qualcomm has emerged as a major player with its Snapdragon Digital Chassis platform, recently introducing its most powerful "Elite" line powered by second-generation Oryon processors, Adreno GPUs, and Hexagon NPUs, securing ten new automotive design wins in Q3 2024 alone[32]. This digital solution consists of 4 platforms: Auto Connectivity, Cockpit, Snapdragon ride, and Snapdragon CarToCloud, similar to the domains we discussed earlier in this paper. Qualcomm has collaborated with Qorix to integrate

[28] https://www.globenewswire.com/news-release/2024/03/05/2840326/0/en/General-Motors-Magna-and-Wipro-Team-Up-to-Develop-Automotive-Software-Marketplace-SDVerse.html
[29] https://sdv.eclipse.org/projects/.
[30] https://www.aboutamazon.com/news/company-news/amazon-hyundai-partnership
[31] https://aws.amazon.com/automotive/software-defined-vehicle
[32] https://www.qualcomm.com/products/automotive/snapdragon-digital-chassis

specialized middleware into their Snapdragon Ride and Cockpit platforms, addressing integration challenges while providing scalable solutions for OEMs and Tier 1 suppliers[33].

Nvidia has established itself in the SDV space with its DRIVE platform, whose Orin SoC (System on a Chip[34]) delivers an impressive 254 TOPS (tera operations per second) of computing power -- a substantial increase from the 32 TOPS of its previous generation [35]. Nvidia's partnership with Volvo demonstrates real-world implementation, with the automaker's all-electric EX90 SUV built on the DRIVE Orin system-on-chip.

MediaTek has introduced its comprehensive Dimensity Auto platform, encompassing solutions for cockpit systems, connectivity, autonomous driving capabilities, and automotive-grade components[36]. MediaTek has also formed a strategic partnership with Nvidia, combining their Dimensity Auto ARM-based processors with Nvidia's GPU and AI chiplets to leverage the increasing platform capabilities of Nvidia's automotive-focused assets[37].

The growth from the automotive sector for many of the traditional semiconductor suppliers has slowed, while the newer players into this space such as Nvidia and Qualcomm are seeing higher growth as the table below shows.

Semiconductor Company	Type	FY24 Revenue ($m)	YoY Growth
Infineon	Traditional	$9,100[38] (converted $ value)	2%
Renesas	Traditional	$4,881[39] (converted $ value)	6.4%
NXP	Traditional	$7,151[40]	-4%
Qualcomm	New	$2,900[41]	55%
Nvidia	New	$1,700[42]	55%
Horizon Robotics	New	$332[43] (converted $ value)	53.6%[44]

On the software side we are seeing a lot of activity in terms of high growth, new partnerships, and acquisitions. Independent automotive software integrators are seeing high demand due to their ability to help OEMs and Tier-1's cope with the massive software workload of SDVs. This is reflected in high growth of business and partnerships at companies such as KPIT (18% growth in annual Revenue FY 24 to 25[45]), Elektrobit (partnering with Cognizant for their SDV solution[46]), and also via acquisitions by traditional

[33] https://www.autonomousvehicleinternational.com/news/software/qorix-and-qualcomm-partner-for-software-defined-vehicle-development-solution.html
[34] https://linearmicrosystems.com/system-on-a-chip-soc-in-automotive-systems/
[35] https://www.automotiveworld.com/articles/centralised-compute-will-ignite-sdv-innovation-says-nvidia/
[36] https://corp.mediatek.com/news-events/press-releases/mediatek-introduces-dimensity-auto-empowering-smart-vehicle-technology-innovation
[37] https://www.fierceelectronics.com/sensors/mediatek-partners-nvidia-stake-smart-vehicle-market
[38] https://www.infineon.com/dgdl/2024-11-12-q4-fy24-analyst-call-v01-00-en.pdf?fileId=8ac78c8b92bced6201931ce640ed0050
[39] https://www.renesas.com/en/document/rep/earnings-report-year-ended-december-31-2024
[40] https://investors.nxp.com/news-releases/news-release-details/nxp-semiconductors-reports-fourth-quarter-and-full-year-2024
[41] https://s204.q4cdn.com/645488518/files/doc_financials/2024/q4/FY2024-4th-Quarter-Earnings-Presentation.pdf
[42] https://energydmgroup.com/nvidias-automotive-strategy-and-market-position-what-5-28-2025-earnings-report-means-to-its-automotive-business/
[43] https://pitchbook.com/profiles/company/156723-13#timeline
[44] https://autonews.gasgoo.com/icv/70036442.html
[45] https://www.kpit.com/documents/annual-report-2024-25/
[46] https://www.elektrobit.com/newsroom/cognizant-and-elektrobit-collaborate-to-accelerate-development-of-software-defined-vehicles/

Tier-1's as in the case of NXP's acquisition of TTTech Auto for $625 million[47] in 2025. Similar to how NVIDIA, Qualcomm, and Horizon Robotics are redefining the hardware/semi-conductor layer, we will likely see SDV platforms being co-developed by such firms in collaboration with OEMs, tier-1s, cloud providers, and hardware vendors.

These innovative solutions collectively demonstrate how technology leaders are enabling the automotive industry's transformation toward more intelligent, connected, and software-defined vehicles. Our interviews revealed a difference of opinion in how OEMs view their relationships with traditional Tier-1 suppliers versus new tech partners like Google, Apple and Amazon. Some see the need to maintain strong partnerships with traditional suppliers, while others are more inclined to collaborate with Big Tech companies for software solutions as legacy OEMs have struggled and continue to struggle with developing software. Traditional OEMs are leveraging tech partners like Nvidia, Qualcomm, Mobileye, and Google to catch up with their software capability, while also nurturing internal software teams or subsidiaries (e.g., CARIAD+ Rivian for VW, "Woven by Toyota" for Toyota). Newer OEMs like Tesla have taken a full-stack approach that required significant upfront investment and development time. It is easier to start with software focused vehicles for companies like Tesla, Lucid, Rivian, than it is to shift from traditional hardware focused infrastructure to a more software focused system. However, many of the new EV upstarts have struggled with manufacturing a quality product at scale. Tesla went through "manufacturing hell" in 2018[48] and newer companies such as Rivian and Lucid are also struggling to achieve profitability[49].

We are seeing many new partnerships arise due to the shift to SDV. Some are listed in the table below:

Partners	Date	Highlights
Rivian and Volkswagen SDV partnership (17 to 7 ECUs)[50]	Jun 25, 2024	Rivian and Volkswagen formed a 50/50 joint venture to develop next-gen software-defined EVs, with VW investing $5 billion in Rivian. VW will use Rivian's software and platform, while Rivian gains capital and scale.
Volvo Group and Daimler Truck[51]	Oct 28, 2024	Volvo Group and Daimler Truck have signed a binding agreement to establish a new 50/50 joint venture to develop a software-defined vehicle platform for heavy duty vehicles and drive the industry transformation.
Ford and Google[52]	Feb 1, 2021	Ford and Google have launched a six-year partnership where Google Cloud becomes Ford's preferred cloud provider, embedding Android with built-in Google services in Ford

47 https://www.tttech-auto.com/newsroom/nxp-accelerates-transformation-software-defined-vehicles-sdv-agreement-acquire-tttech-auto
48 https://www.forbes.com/sites/lensherman/2018/12/20/tesla-survived-manufacturing-hell-now-comes-the-hard-part/
49 https://finance.yahoo.com/news/rivian-lucid-burn-cash-challenges-120000535.html
50 https://futurride.com/2024/06/25/rivian-and-volkswagen-announce-software-defined-vehicle-joint-venture/
51 https://www.volvogroup.com/en/news-and-media/news/2024/oct/volvo-group-and-daimler-truck-sign-binding-agreement-for-joint-venture-to-develop-software-defined-vehicle-platform.html
52 https://corporate.ford.com/articles/products/ford-and-google-to-accelerate-auto-innovation.html

		and Lincoln vehicles starting in 2023
BYD and TSMC[53]	Nov 20, 2024	BYD Semiconductor, collaborating with TSMC and MediaTek, is developing a high-performance smart cockpit chip based on a 4 nm automotive process. Featuring ARMv9 architecture, 5G support, DDR5 memory interface, and the ability to drive up to 11 screens
Mercedes-Benz and Nvidia[54]	Feb 23, 2023	Mercedes-Benz and Nvidia have formed a wide-ranging partnership to integrate Nvidia's DRIVE Orin AI computing and software into all upcoming Mercedes-Benz vehicles, enabling centralized, updateable software-defined architecture for automated driving and smart cockpits starting in 2024
General Motors (GM) & Qualcomm[55]	Jan 25, 2021	General Motors and Qualcomm have extended their partnership by integrating Qualcomm's 3rd-generation Snapdragon Automotive Cockpit Platforms into GM's upcoming vehicles, enhancing digital cockpits, telematics, and ADAS systems.
Toyota & Renesas[56]	Oct 26, 2021	Renesas' automotive chips power Toyota and Lexus's next-gen multimedia system—featuring a customizable, high-res up to 14″ touchscreen, voice recognition, over-the-air updates, and secure connectivity—debuting in the Lexus NX (Nov 2021) and rolling out across other models
Toyota and Nvidia[57]	Jan 6, 2025	Toyota, Aurora, and Continental have partnered with Nvidia to adopt its DRIVE AGX Orin platform and DriveOS in next-gen vehicles.

53 https://www.digitimes.com/news/a20241119PD230/byd-mediatek-smart-cockpit-4nm-development.html
54 https://blogs.nvidia.com/blog/mercedes-benz-digitalization/
55 https://www.qualcomm.com/news/releases/2021/01/general-motors-and-qualcomm-extend-long-standing-relationship-transform
56 https://www.renesas.com/en/about/newsroom/renesas-innovative-automotive-chips-drive-next-generation-multimedia-system-toyota-lexus
57 https://nvidianews.nvidia.com/news/toyota-aurora-continental-nvidia-drive

Liability and Responsibility

With SDV projects involving long development timelines and heavy upfront investment, some OEMs and Tier-1s are entering into deals to share both the risks and rewards. Instead of a simple fixed price for a component supplied by the Tier-1 to the OEM, there might be milestone payments for software development, or incentives if a certain target is met or exceeded. In some advanced cases, revenue-sharing models have been discussed, e.g., if a Tier-1's contribution helps in the creation of a new subscription service, the supplier might receive a royalty per subscription. These creative commercial arrangements, while not commonplace yet, can motivate suppliers to think beyond unit sales and focus on the end-user value. These risk and revenue sharing models encourage deeper collaboration to ensure the product/feature/service is a success in the market, and not just delivered as per the OEM specification, as was the case earlier.

While OEMs generally take responsibility from a brand recall and image perspective for any issues, the final monetary compensation is derived from the supplier who supplied the defective component. There is some debate on how liability should be shared with Tier-1 suppliers, especially as the role of system integrator becomes more complex and with different levels of software and hardware integration being offered to different OEMs by Tier-1s. The line of who does what, and whose code caused the error will need to be carefully defined, to avoid such issues, and is definitely a concern with top OEMs. From the interviews it was clear that OEMs will be taking full responsibility for any issues as they own the brand (and will continue to even with SDVs), with Tier-1s covering costs for recalls if their components are at fault.

Business Models for SDVs

SDVs enable various business models, including:

- **Subscription-based services** for advanced features like autonomous driving and enhanced infotainment to generate recurring revenue
- **Software updates and feature unlocks** as revenue streams.
- **Data monetization strategies**, leveraging connected vehicle insights.
- **Extended software support models**, balancing cost with regulatory requirements.

An industry expert from one of the largest US carmakers mentioned in the interview: "One of the fundamental shifts for the company is to stop thinking of total addressable market as units sold per year, but start thinking of the total addressable market as units in operation. So, you can in theory have quite a bit more vehicles out there generating revenue for you than even your sales are supporting each year." They further added that "We found fleet management companies in the commercial space, over a 10-year period, hadn't really grown the total number of units they were managing by that much, but their revenues had grown 5-fold. They've done it entirely by finding new services and new ways to provide value to those customers."

The interviewees were also a bit cautious. While there is enthusiasm for new business models like subscription services and features on demand, there is also skepticism about whether consumers will be willing to pay for certain features, with some OEMs becoming more realistic about what functions can be monetized. Freemium models may work well for mobile phone apps, but when it comes to an automobile, which most people take pride in owning, they may not take too kindly to being made to pay to enable a feature already present in their far more expensive car (as compared to a smartphone).

While there's no winning formula here, we have seen OEMs trying different models to create recurring revenue. Below is a list of features that we have seen monetized recently with both one-time and monthly/yearly payment options[58]:

OEM	Features being monetized
BMW	• Drive Recorder feature costs $149 for the lifetime of the vehicle or $39 per year. • Traffic camera information is available for $25 annually.
Ford	• BlueCruise (Ford's hands-free driving system) costs $495 a year or $49.99 a month.
GM	• Super Cruise (GM's hands-free driving system) costs $2,200 up front for three years on Chevrolet and GMC vehicles and $2,500 for Cadillacs, after which it's $25 a month or $250 per year via subscription.
Mercedes-Benz	• Mercedes Me Connect (live weather, traffic and connected navigation) for a $150 annual subscription • Acceleration Increase costs $1,200 a year.
Tesla	• For a one-time payment of $8,000, or $99 per month, new owners get access to Tesla's Full Self-Driving system. [59]
Toyota	• Remote start costs $80 a year or $8 a month.

Challenges in Achieving SDV Goals

Our interviews with automotive and technology executives revealed an array of interconnected challenges for SDVs to achieve their full potential, which we have organized into six buckets below:

1. **Software Complexity versus Performance Compatibility:** A major hurdle is the sheer complexity of the software, which requires integration of millions of lines of code while maintaining security and performance. Legacy system compatibility compounds this challenge, requiring new software frameworks to work seamlessly with existing vehicle hardware. The lack of uniform standards across OEMs and Tier-1 suppliers complicates integration efforts, yet achieving standardization in interfaces and becoming more agnostic with regards to other components is a challenge. This is especially critical for Tier-1's as they must understand and integrate various products from hundreds of smaller Tier-2 and Tier-3 suppliers.

2. **Financial Constraints**: Automakers must balance investment in innovation with financial sustainability. The transition to SDVs is not the only massive investment required from the legacy OEMs; they are also making huge investments in powertrain electrification and ADAS and autonomous systems. Hiring expensive software professionals and upgrading to expensive silicon

[58] Nickeled and Dimed? Why Automakers Are Moving to Vehicle Subscriptions, MotorTrend, Alan Muir, Oct 17, 2024, https://www.motortrend.com/features/car-subscriptions-why-pay-for-features-services/
[59] https://electrek.co/2024/04/21/tesla-lowers-price-of-full-self-driving-to-8000-down-from-12000/

(albeit lesser in number) imposes huge costs for the legacy OEMs. Efforts to develop unified software architectures, such as Ford's FNV4 project[60], have encountered difficulties resulting in project cancellations. The FNV4 initiative was designed to streamline software integration across both electric and gasoline-powered vehicles. It promised cost reduction, improved quality, and new revenue from software-enabled features in the long run. However, the project was scrapped due to escalating costs and development delays. This shows yet again that the race to develop SDVs is costly, with billions invested and no guaranteed success.

3. **Organizational Inertia and Constraints**: Organizational and resource constraints that slow software execution are a major challenge for legacy OEMs, due to their highly specialized and interconnected development processes that require lengthy consensus-building. This theme was heard multiple times during the interviews: the biggest change needed at the legacy OEMs is organizational rather than technological. This includes consolidating siloed groups into a single software development company to enable a holistic view and consistent planning. Toyota's subsidiary "Woven by Toyota" after more than 5 years of development, launched the Arene automotive OS in May 2025 on the latest Toyota RAV4 vehicles[61]. Even this launch has only two domains (AD/ADAS & Cockpit) out of four planned for the Arene OS (Body & Dynamics are still independent). This highlights the challenge of implementing an all-new software and SDV platform even for a behemoth like Toyota after 5 years in development by a dedicated subsidiary. A slow, but staged approach will meet with eventual success for legacy players, but could prove to be too expensive in terms of money and time for a few.

4. **High Costs of Updates for Cybersecurity**: Cybersecurity threats are heightened with SDVs due to the increased exposure in connected software environments. Substantial investments and close collaboration among OEMs, Tier-1s and tech partners are required for ongoing software maintenance. In the smartphone market, the industry norm is three years of feature updates and five years of security updates. In comparison to smartphones, cars are on the road much longer, are much more expensive, and can cause much more damage if something fails. Providing security updates over the lifetime of the vehicle will be expected from the OEM in order to maintain basic vehicle functionality and security for an SDV, as any software glitch will render the vehicle non-functional or a danger on the road. This is both expensive and difficult as cars are on the road for an average of 16.6 years in the US[62], with many being on the road for over 20 years. With vehicle prices increasing people are holding onto their cars longer, so this problem will only get worse[63].

5. **Uncertainty of Monetizable Features and Services**: In September 2023, BMW had to drop its heated seats subscription due to customer backlash. Customers were asked to pay $18 per month or $180 per year, $300 for three years, or $415 for unlimited access to heated seats [64]. Although SDVs allow OEMs to provide the required hardware with the car but restrict the access to those features using software, it remains to be seen what consumers will pay for. One of the industry interviewees mentioned that 75% of respondents in a survey regarding customers' willingness to pay for AI features in vehicles indicated no willingness to pay for such features. Consider a scenario where companies are trying to monetize essential safety features such as ABS or Traction Control

[60] https://finance.yahoo.com/news/exclusive-ford-kills-project-develop-222459573.html
[61] https://www.autonews.com/toyota/an-toyota-arene-software-operating-system-rav4-woven-0521/
[62] https://iopscience.iop.org/article/10.1088/1748-9326/aaf4d2#erlaaf4d2f1
[63] https://www.claimsjournal.com/news/national/2025/04/21/330147.htm
[64] https://www.autoevolution.com/news/bmw-drops-controversial-heated-seats-subscription-no-extra-money-for-onboard-features-220775.html

Systems. What happens if the customer forgets the payment or there's some issue with the payment method? Who is liable in this case if something happens to the car and the safety features don't function as intended?

6. **Data Privacy:** SDVs are powered by data. OEMs can gain insights, push OTAs, offer new services and much more with these data. However, concerns are quickly emerging related to cybersecurity, data privacy, and liability. People are increasingly aware that their cars generate a lot of data, and this awareness is only increasing as we transition to SDVs. Consumers are increasingly demanding that they are informed and asked for their consent to share information that is potentially sensitive, such as home address, trip origin, destination and path, hard braking and rapid acceleration incidents. General Motors faced a consumer backlash with the sharing of telematics data from its cars to the firm LexisNexis and cut all ties with the firm[65]. As tensions rise around data ownership, liability distribution, and software innovation, clear agreements on liability allocation and insurance models will be critical to managing risks and ensuring the success of the SDV ecosystem.

Recommendations for Sustainable Value Creation

Although there were differences of opinion among our interviewees, most converged around the following recommendations for OEMs to ensure sustainable business models:

- Offer genuine value through software enhancements without alienating customers with excessive monetization.
- Define clear policies on software update support duration to maintain vehicle reliability.
- Collaborate via long-term partnerships with Tier-1 suppliers and tech firms to optimize innovation and efficiency.
- Adopt open-source software and platforms in non-differentiating areas like middleware to save on development cost and time.

Conclusion

Software Defined Vehicles (SDVs) represent a fundamental transformation in the automotive industry, shifting the focus from hardware to software-driven innovation. This evolution offers substantial benefits, including enhanced customer experiences, improved vehicle architecture, and new business models. Through a series of interviews with key industry leaders, we have hoped to present valuable insights into the definition, benefits, technological advancements, challenges, and future directions of SDVs in this report.

The SDV shift enables continuous delivery of new experiences and services to users, transforming cars into intelligent, connected devices. For end customers, SDVs offer post sale personalization, continuous updates, enhanced safety features, and personalized/connected services, akin to the evolution from feature phones to smartphones. For OEMs, SDVs provide opportunities to save costs, reduce complexity, and offer differentiation to consumers through unique services and the transformation of business models, leveraging AI and deep learning technologies. However, industry stakeholders must navigate challenges such as cybersecurity, hardware compatibility, liability, cost, organizational inertia, data privacy, and long-term value creation. OEMs and Tier-1 suppliers must adapt to this evolving landscape, ensuring that SDVs not only enhance technological capabilities but also create sustainable economic value. Collaboration between these stakeholders and open-source communities will be essential in shaping the future of SDVs.

[65] https://www.freep.com/story/money/cars/general-motors/2024/03/22/gm-data-firms-lexis-nexis/73057931007/