L&T Technology Services

Purposeful. Agile. Innovation.

From Vehicle Architecture to Engineering Intelligence

An ER&D Approach to Software-Defined Mobility

Foreword

Means of mobility have always mirrored human progress. Every turn of a wheel, every whir of an engine, and every line of code articulates our innate desire to move faster, farther, and with stronger purpose.

In this era of accelerated change, movement is primarily defined by intelligence. Vehicles are no longer just means of transportation; they are intelligent companions that sense, interpret, and evolve with us. Welcome to the era of Software-Defined Vehicles — a quiet revolution that is redefining the very essence of mobility.

Across the automotive landscape, a profound transformation is underway. Software is replacing mechanical complexity with digital intelligence. The Software Defined Vehicle is not simply a new category of vehicles, it represents a complete reimagination of engineering. Conventional hardware-driven architectures are giving way to centralized computing systems and adaptive platforms. Hardware now plays a supporting role, while software facilitates the symphony of performance, safety, and experience.

The convergence of artificial intelligence, cloud computing, digital twins, edge analytics, and advanced connectivity has given rise to something extraordinary: an intelligent network on wheels. These vehicles are capable of self-diagnosis, over the air updates, and continuous self-improvement. No longer static entities, vehicles now learn and adapt, they learn, adapt, and evolve as they progress toward new horizons.

However, this transition also introduces new challenges as combining decades of mechanical expertise with software-centric systems demands collaboration, agility, and foresight. Engineers must now design not merely components, but entire ecosystems that are modular, secure, and scalable. Organizations need to embrace new operating models that blend embedded engineering with cloud-based innovation. As intelligence deepens, accountability must keep pace, ensuring safety, transparency, and ethical utilization of technology.

Within this shift lies a deeper opportunity. Embedded within every challenge is the seed of innovation. The Software Defined Vehicle allows automakers to redefine value creation not through hardware replacement but through software upgrades. A single update can unlock new performance, efficiency, or safety features. As a result, vehicles have now become powerful digital platforms that continue to upgrade long after they leave the production line.

Building on this foundation, the transformation is ultimately guided by purpose: to make mobility safer, more efficient, and sustainable. The fusion of artificial intelligence and connected data pools can reduce accidents, optimize energy use, x minimize environmental impact. As vehicles begin to communicate with one another and with the cloud, mobility is evolving into an integrated system that learns, adapts, and elevates lives both on and beyond the road.

This book serves as a compass for navigating this transformation. Each chapter explores a vital facet of this journey — from system architecture and validation to AI integration, testing, and digital ecosystems. Together, they illustrate how software-defined mobility is reshaping the DNA of the automotive industry. This shift is collective in nature, requiring collaboration among manufacturers, suppliers, and technology innovators united by a shared vision of adaptive and intelligent mobility.

The journey is a continuous progression, shaped by rich insight and a new spark of innovation. The vehicles we design today will continue to evolve long after their creation, while the engineers behind them continue to chart the road ahead.

Mobility has never been solely about reaching the destination. It is about relentless discovery and the possibilities that emerge when human imagination and digital intelligence work in seamless harmony.

Introduction

In This Chapter

- Evolution of Software-Defined Vehicles
- Enablers of the SDV Transition
- LTTS' role in SDV transformation

From Hardware-First Control Units to Software-Defined Platforms

We live in a software-defined, intelligent world, where the full spectrum of consumer experience is enriched and elevated by new advancements in communications, data processing and data storage technology. In this new era, the future of mobility will be determined by the seamless synergy between hardware and software, emphasizing the need for a robust digital engineering paradigm.

To understand this shift, it is important to look at the history of the global automotive industry. Since the first automobile rolled out of the factory, engineers have always relied on a hardware-centric approach. While significant advancements have been made over time, the core focus has largely remained anchored in hardware design.

Each vehicle function—whether braking, steering, climate control or infotainment—was managed by a dedicated Electronic Control Unit (ECU) designed for a specific task. This segregated electronic control model meant that updating or upgrading functionalities often required physical modifications or part replacements, making innovation sluggish, expensive, and limited in scope. Moreover, most ECUs were developed by different suppliers and relied on proprietary software, further increasing the complexity, cost, and time required for upgrades.

As vehicles became more advanced, the number of ECUs grew significantly. This led to a highly complex network of electronic components, making maintenance more difficult and limiting the ability to scale or add new features efficiently.

However, the landscape began to change with the integration of advanced computing, connectivity and sensor technologies. The introduction of High-Performance Computing Units (HPCUs) made it possible to centralize control, replacing numerous individual ECUs with fewer but more capable computing systems. This reduced hardware dependency and simplified overall vehicle electronics.

This evolution has paved the way for Software-Defined Vehicles (SDVs), a new automotive paradigm in which software becomes the primary driver of functionality, personalization, and end-user safety. This change simplifies the complexity of vehicle electronics, enabling over-the-air (OTA) updates and eliminating the need for costly and time-consuming recalls. Manufacturers can introduce new capabilities, fix issues and enhance performance without the vehicle ever visiting a service center, significantly reducing time to market for new features and innovations.

By consolidating hardware functions and enabling continuous software-driven upgrades, the industry is creating vehicles that can adapt to future requirements. This approach supports emerging technologies such as autonomous driving, AI-based personalization and predictive maintenance, ensuring that cars remain relevant and compliant with evolving regulations and customer aspirations.

Beyond its technological implications, this shift is also transforming the automotive business model. OEMs are moving from one-time vehicle sales to continuous value delivery, unlocking new revenue streams through software-enabled upgrades, connected services and data monetization. The ability to deploy features remotely reduces warranty costs and accelerates innovation cycles, giving early adopters a decisive competitive advantage.

Software-Defined Vehicles — A Closer Look

An SDV represents a significant evolution in automotive technology, where the majority of the vehicle's functions are controlled and managed by software. In this model, the hardware acts as a versatile and upgradeable base rather than being fixed to specific tasks. This separation allows for greater flexibility in adapting to technological advancements and changing customer requirements throughout the vehicle lifecycle.

A key enabler of this flexibility is the hardware abstraction layer, which separates the software applications from the specific hardware components. By decoupling these layers, the same software can be used across different hardware configurations, improving portability and reusability. This approach reduces dependency on any single hardware architecture and accelerates the pace at which new features can be introduced.

In essence, an SDV undergoes continuous evolution throughout its lifecycle. This unlocks new business models such as subscription services, feature-on-demand and personalized user experiences that were not feasible under traditional hardware-bound architectures.

Central to the SDV architecture is the use of a centralized compute platform that consolidates multiple vehicle domains into a single, unified system. Functions that were previously managed by separate control units such as the powertrain, safety mechanisms and infotainment are now integrated. This enables better coordination, reduced complexity, scalability across vehicle platform and more efficient performance management.

The adoption of a Service-Oriented Architecture (SOA) further enhances this flexibility. In an SOA framework, software is organized into independent modules or services, each responsible for a specific function. These modules can be developed, updated and deployed individually, without impacting the entire system, enabling faster rollout of enhancements and more efficient issue resolution.

Cloud connectivity plays a vital role in the SDV ecosystem by enabling continuous data exchange between the vehicle and external systems. This connectivity supports real-time diagnostics, performance monitoring and optimization, ensuring the vehicle remain up-to-date and operate at peak efficiency. It also supports predictive maintenance and the delivery of new features without requiring physical service interventions.

Finally, the use of microservices architecture within the SDV platform promotes faster development cycles, scalable performance and seamless integration of additional functionalities. Just as smartphones can receive updates and unlock new capabilities after purchase, SDVs can evolve well beyond their initial specifications, delivering, improved safety and enhanced driving experiences throughout the vehicle's lifespan.

For automakers, SDVs represent a shift from product-based revenue to service-led growth. They enable OEMs to extend customer relationships beyond the point of sale, enhance loyalty through updates and personalized experiences, and create recurring income via feature-on-demand models.

Key Drivers of the SDV Transition

Software Updatability

The vehicle's software can be updated remotely through OTA systems, eliminating the need for physical service visits. This ensures quick deployment of new features, security fixes and performance enhancements.

Regulatory Compliance

Automotive designs must continuously adapt to evolving global safety, cybersecurity and emissions regulations. Flexible architectures allow compliance without major hardware redesigns.

ECU Complexity Reduction

By replacing numerous function-specific ECUs with fewer High-Performance Computing Units (HPCUs), automakers can reduce wiring, hardware redundancy and integration challenges. This leads to lower manufacturing costs, optimizes the overall product cost and easy maintenance.

Emergence of Generative AI as an Enabler in SDV Engineering

By embedding GenAI into the SDV lifecycle, automakers and technology providers can create smarter, more adaptive vehicles capable of learning from their environment and continuously improving.

Consumer Expectations

Modern drivers expect vehicles to offer smartphone-like experiences, including real-time updates, personalized settings and seamless connectivity. Meeting these demands boosts customer satisfaction and strengthens brand loyalty.

Collectively, these factors are compelling automakers to reimagine their R&D and go-to-market strategies. Companies that can accelerate the transition to SDV architectures stand to capture higher margins, reduce development timelines, and enhance regulatory agility.

LTTS supports OEMs in deploying Feature-as-a-Service and subscription frameworks, helping monetize software capabilities and enhance customer lifetime value.

LTTS' Involvement in SDV Transformation

L&T Technology Services (LTTS) is playing an important role in enabling the global shift toward software-defined mobility, offering end-to-end capabilities that span the SDV technology stack and product lifecycle. These strengths position LTTS as a global technology provider and strategic transformation partner, helping OEMs and Tier-1 suppliers navigate the complex transition to SDVs.

LTTS' SDV Capabilities

E/E Architecture Transformation

Data Management and Analytics

Platform Software and Integration

Cybersecurity and Compliance

GenAI-Powered Engineering

Feature Monetization Models

Chapter 1

SDVs — A Transformative Step Forward

In This Chapter

An SDV is built on the core methodology of software-hardware decoupling. In this architecture, hardware serves as a flexible platform, while the software determines the vehicle's core functionalities. This decoupling enables the same software applications to run across diverse hardware setups. As a result, functions such as infotainment, powertrain control and safety features can now be updated independently of the physical components, enhancing flexibility and reusability.

Offering an Elevating Experience

The shift toward SDVs affects nearly every functional domain of a vehicle, redefining how performance, safety, and user experience are delivered.

1 Powertrain and Energy Management

Software now optimizes energy efficiency in Electric Vehicles (EVs) through advanced battery management systems and regenerative braking algorithms. OTA updates can enhance range and performance without physical modifications.

2 Safety and ADAS (Advanced Driver Assistance Systems)

Software-driven safety systems such as lane-keeping assist, adaptive cruise control and collision avoidance rely heavily on real-time data processing from sensors and cameras. In SDVs, these features can be continuously improved through regular software updates.

3 Infotainment and Connectivity

Infotainment systems are transitioning into software-driven platforms that deliver personalized, app-based experiences. Cloud connectivity supports seamless integration with smartphones, navigation services and entertainment ecosystems.

4 Comfort and Personalization

Features such as seat positioning, climate control and ambient lighting can be individual driver preferences through software-defined profiles. This level of personalization enhances comfort and creates a more engaging in-vehicle experience.

5 Fleet and Commercial Applications

In logistics, SDVs support telematics, remote diagnostics, and predictive maintenance, reducing downtime and operating costs for fleet operators.

Across all these domains, leading engineering firms are enabling OEMs to scale digital experiences securely. LTTS, for instance, has helped global manufacturers embed AI analytics, developing in-vehicle software platforms, implementing digital twin–based validation, and integrating robust cybersecurity frameworks. These capabilities accelerate development timelines while ensuring compliance, safety, and system reliability.

SDV Maturity Levels

The evolution of SDVs can be understood as a progressive journey across distinct stages.

Hardware-Defined Stage

In a traditional car, every function has its own ECU. Therefore, if we want new features, you have to replace or physically upgrade the hardware, making maintenance expensive and time-consuming.

Partially Software-Defined Stage

As technology advanced, OEMs began partially decoupling software from hardware. Certain updates—primarily related to infotainment and navigation—could be delivered via OTA mechanisms. However, most core vehicle functions remained tightly bound to hardware, limiting overall flexibility.

Domain-Centralized Stage

In this stage, multiple ECUs are consolidated into domain-specific controllers. For example, powertrain-related functions may be managed by one controller, while infotainment is handled by another. This approach reduces system complexity and improves coordination within domains. However, these domains largely continue to operate in silos, limiting cross-functional integration.

Zonal Architecture and High-Performance Computing Units (HPCUs)

The next stage in this evolution involves consolidating multiple domains into a smaller number of highly capable computing systems known as HPCUs. These systems function as the central 'brain' of the vehicle, managing operations across defined zones—such as the front, rear, and interior. This transition reduces hardware duplication, improves system efficiency, and enables faster data processing. Similar to smartphones, a unified system controls the majority of functions.

Fully Software-Defined Vehicle

Building on this foundation, the industry is moving toward fully software-defined vehicles, where nearly all functionalities are controlled by software rather than fixed hardware. These systems are based on a Service-Oriented Architecture (SOA), enabling modular design, continuous updates, and the integration of AI-driven decision-making.

This approach allows features to be added, enhanced, or monetized throughout the vehicle lifecycle, much like applications on a smartphone.

Engineering partners such as LTTS have guided OEMs through each phase—deploying semicon-agnostic toolchains, virtualization frameworks, and continuous-integration pipelines tailored for functional safety requirements. These capabilities help reduce risk and accelerate release cycles.

System-Level Architecture

At the system level, an SDV is built on a few key components that work together to make it flexible, upgradable, and intelligent. The architecture integrates a central computing platform, modular software layers and secure communication interfaces to ensure seamless interaction between sensors, control units and cloud services. By leveraging virtualization and standardized APIs, the system enables frequent updates, customized features and robust safety mechanisms. This interconnected design supports dynamic scalability, remote diagnostics and adaptive functionalities that respond to user needs and evolving technology landscapes. Together, these elements provide a foundation for continuous innovation and optimized vehicle performance within a rapidly changing automotive ecosystem.

SDVs Gaining Prominence Across Segments

SDVs are now in the spotlight, but their adoption varies by vehicle type and application segments.

Passenger Vehicles

The growing adoption of SDVs is driven by consumer demand for infotainment, personalization, safety and autonomous features. OEMs focus significantly on user experience and recurring revenue models features-on-demand.

Commercial Vehicles

Adoption is guided by efficiency, fleet optimization, predictive maintenance and regulatory compliance. Software plays a key role in telematics and logistics.

Off-Highway Applications (construction, agriculture, mining)

Early adoption is seen in autonomous machinery, predictive diagnostics and energy optimization. Although adoption is relatively gradual compared to passenger vehicles, these segments are leveraging SDVs to enhance productivity and reduce downtime.

LTTS Insights Across Passenger, Commercial, and Off-Highway Vehicles

LTTS observes that passenger vehicles rapidly moving toward becoming software-driven platforms. Features such as personalized in-car experiences, advanced driver assistance and over-the-air updates are creating a 'smartphone-like' ecosystem inside cars. With growing consumer demand for safety, comfort and connectivity, LTTS enables OEMs to embed intelligence through AI, digital twins, In-Vehicle platforms, and secure and scalable architectures. The focus is on making vehicles future-ready, while keeping ownership flexible through subscription and pay-per-use models.

In the commercial space, the shift is driven by efficiency, safety and fleet management. LTTS supports OEMs with AI-powered telematics, predictive maintenance and smart route planning to cut downtime and improve operating margins. These capabilities enhance fleet visibility, minimize idle time, and ensure regulatory compliance. By embedding cybersecurity and real-time data analytics, LTTS is helping businesses transition from traditional ownership models to Mobility-as-a-Service, delivering sustained operational and cost benefits.

For off-highway segments (construction, agriculture and mining), LTTS focuses on rugged digital solutions that ensure reliability in demanding environments. The Company's platforms enable autonomous operations, smart diagnostics and advanced safety systems, tailored to heavy machinery. By combining edge computing with connected platforms, LTTS delivers greater uptime, reduces maintenance costs and enhances operator productivity. These insights position LTTS as a key partner in shaping the future of industrial mobility beyond conventional road vehicles.

Chapter 2

Engineering and Business Challenges in SDV Programs

In This Chapter

- Software-Hardware Integration Challenges
- Legacy Systems Compatibility
- Real-Time Safety and Performance Constraints
- Cost, Complexity, and Talent Shortages
- Adapting Organizational Structures and Ecosystem Collaboration

The journey toward SDVs presents both transformative opportunities and complex challenges. OEMs need to navigate the integration of hardware and software, ensure safety and compliance and adapt their organizational structures while managing cost and talent gaps. This chapter explores the key engineering and business hurdles that define the SDV transition.

Software-Hardware Integration Challenges

Diverse Software Sources

Modern vehicles rely on software developed across multiple sources, including in-house teams, technology partners, and open-source communities. Each follows distinct development practices, standards, and release cycles, making integration into a unified ecosystem inherently complex. Achieving alignment requires strong governance, well-defined integration frameworks, and standardized protocols.

Complexity of Control Systems

Vehicles today are built on numerous specialized systems, ranging from engine and transmission controllers to advanced driver-assistance systems (ADAS). Integrating these highly specific modules into one unified platform demands meticulous planning and flawless execution to ensure seamless communication and avoid system conflicts.

Over-the-Air (OTA) Updates

OTA updates have become a standard expectation, enabling manufacturers to fix defects, address security vulnerabilities, and introduce new features remotely. However, coordinating updates across multiple software components without interrupting vehicle operations or introducing new vulnerabilities is a complex and sensitive task.

Long-Term Software Lifecycle Management

Unlike consumer electronics, vehicles remain in operation for a decade or more. Over this lifespan, software must be maintained, updated and eventually phased out in a structured way. Effective lifecycle management requires disciplined version control, change management, and a reliable support infrastructure.

Data Integration and Analytics

Vehicles generate massive amounts of data from sensors and electronic control units. Unlocking value from this data, such as enabling predictive maintenance or offering personalized in-car experiences, requires robust data architectures and advanced analytics capabilities capable of handling scale and complexity.

Testing and Validation

Testing is the foundation of successful vehicle integration. It begins at the most granular level, with verification of individual software modules, and extends through to full-vehicle trials under real-world conditions. Each stage plays a critical role in ensuring that the vehicle performs safely, reliably, and as intended. However, as vehicles become increasingly software-driven, the traditional testing methods that once sufficed are no longer adequate. The complexity of modern architectures demands advanced, scalable testing frameworks that can validate entire systems holistically, accounting for the wide range of scenarios a vehicle may encounter over its lifecycle.

Legacy Systems Coexistence

When OEMs transition toward software-driven vehicles, they cannot simply discard existing systems. Most vehicles in operation today still rely on traditional electronic control units (ECUs) and hardware architectures that were not designed for modern software platforms. This creates a significant challenge, as new software must operate seamlessly alongside legacy systems with different constraints, standards, and capabilities. Achieving this interoperability increases development complexity, cost, and time.

At the same time, companies need to build new hardware that can handle today's needs and also support updates and new features in the future. This often requires building systems that exceed present-day needs to ensure long-term relevance. As a result, engineers have to carefully test how new software will interact with older systems, while also planning for future changes. Balancing these competing demands makes the shift to software-defined vehicles much harder.

Real-Time Safety and Performance Constraints

Software Bugs and Glitches

Unlike mechanical components, software is inherently more prone to errors. Even a small coding mistake can trigger significant faults in a vehicle's operation, potentially compromising safety. To minimize these risks, OEM rely on rigorous testing procedures such as integration testing and system-level testing. These steps are crucial to identify, isolate, and resolve bugs before the software is deployed in vehicles.

Redundancy and Fail-Safe Mechanisms

In safety-critical functions like braking, steering and acceleration, redundancy is non-negotiable. Backup systems are designed to take over instantly if the primary system fails, ensuring that the vehicle remains under control during emergencies. These fail-safe mechanisms require careful planning, robust engineering and repeated testing to confirm they can function effectively when needed most.

Functional Safety Standards (ISO 26262)

ISO 26262 is the global benchmark for functional safety in automotive electronics and software. It outlines stringent guidelines to ensure systems are designed, tested and validated for safe operation throughout a vehicle's lifecycle. Compliance requires comprehensive hazard identification, detailed risk assessments, and extensive validation before vehicles reach production, safeguarding both drivers and passengers.

Safety of the Intended Functionality (SOTIF)

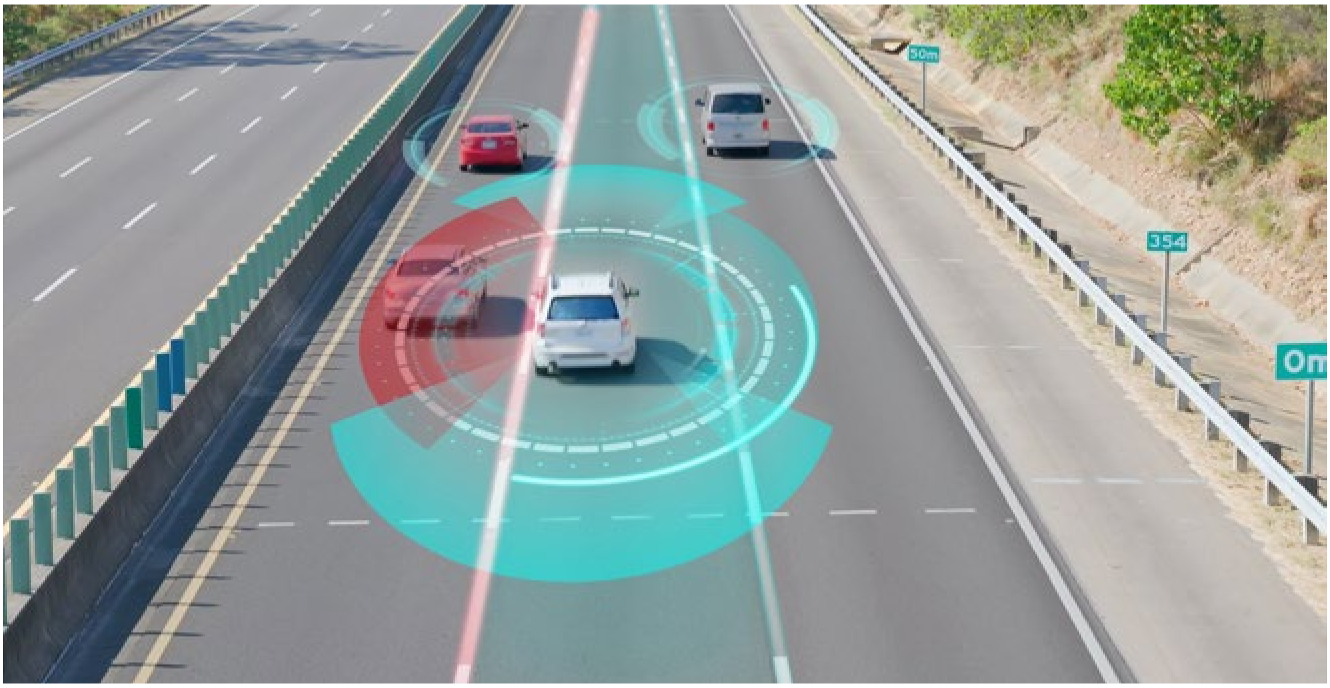
Beyond traditional safety measures, Safety of the Intended Functionality (SOTIF) focuses on ensuring that ADAS and autonomous driving features perform safely in unpredictable real-world conditions. SOTIF addresses potential limitations in sensing, perception and decision-making, helping to reduce unintended risks and ensuring these technologies deliver the intended level of safety.

Real-Time Operating Systems (RTOS)

Modern vehicles rely on real-time operating systems to manage tasks that demand immediate execution. For example, functions like airbag deployment or collision avoidance cannot afford delays. RTOS ensures that critical processes are prioritized and executed without latency, maintaining safety and responsiveness even in highly complex vehicle architectures.

Legal and Regulatory Compliance

OEMs must comply with diverse safety regulations that vary across regions. This involves maintaining detailed documentation, undergoing audits and regularly updating systems to reflect evolving standards. Continuous compliance ensures market access and also reinforces trust in vehicle safety, making it an essential part of the development and operational process.



Cost, Complexity, and Talent Shortages

Managing cost, complexity, and talent shortages is one of the most pressing challenges in the transition to SDVs. Unlike traditional automotive programs, SDV development demands substantial investment in advanced computing hardware, specialized software platforms, cybersecurity frameworks, and continuous integration tools. These costs are further amplified by the need for rigorous testing, validation, and compliance with global standards, making it difficult to balance innovation with profitability. At the same time, integrating multiple domains—such as powertrain, safety systems, infotainment, and connectivity—into a cohesive architecture adds significant technical and financial strain.

At the same time, the industry faces a pronounced shortage of skilled talent in areas like embedded systems, AI-driven development, cloud integration, and functional safety engineering. Recruiting and retaining professionals with expertise across both automotive and software domains is increasingly difficult, as competition from technology companies is intense. This talent gap slows project execution and also increases dependency on external partners and suppliers, adding further complexity to the development cycle. For many automakers, addressing these shortages requires reskilling existing teams, fostering cross-industry partnerships and leveraging global engineering hubs to meet growing demand.

Adapting Organizational Structures and Partner Ecosystems

As vehicles evolve into software-centric platforms, OEMs must fundamentally rethink their organizational structures. Traditional, rigid operating models are no longer sufficient. Companies need integrated frameworks that align governance, talent, technology, and culture, enabling a balance between agile software development and hardware-driven processes. This shift also calls for new decision-making approaches and performance metrics, particularly as the focus moves from one-time vehicle sales to ongoing digital services.

Collaboration with partners has also become more important than ever. No single Company can handle the rising complexity of software-defined vehicles alone. OEMs need to work with technology firms, startups, and other players in the ecosystem. This could mean forming joint ventures, investing in smaller companies, or creating strategic alliances. At the same time, they must clearly define and retain control over critical assets such as user data and intellectual property, while still encouraging innovation through partnerships.

By redesigning their internal structures and building strong networks with partners, companies can stay competitive in this fast-changing industry. Those who manage to combine agile internal practices with external collaboration will adapt better and also open the door to new business opportunities in the era of software-driven mobility.

Chapter 3

Role of AI in Software-Defined Vehicles

In This Chapter

- Role Of AI, ML, and GenAI across the SDV Lifecycle
- AI-Enabled Functions
- Edge vs Cloud AI Inference
- AI Model Lifecycle

AI, ML, and GenAI are at the forefront of the software-defined vehicle (SDV) revolution, transforming how vehicles are designed, tested, and operated. Together, these technologies enable real-time decision-making, adaptive learning, and advanced simulation, redefining both safety and the user experience. This chapter explores their distinct yet complementary roles across the SDV lifecycle, highlighting key applications, benefits, and emerging innovations.

Differentiating the Roles of AI, ML, and GenAI across the SDV Lifecycle

The integration of Artificial Intelligence (AI), Machine Learning (ML), and Generative AI (GenAI) is redefining the method in which SDVs are designed, developed, and operated. While these terms are often used interchangeably, each serves a distinct role in the SDV lifecycle. AI provides the overarching intelligence that enables vehicles to interpret their surroundings and make decisions in real-time. ML, as a subset of AI, equips vehicles with the ability to learn from real-world driving data and continuously refine performance. GenAI extends this transformation by enabling creativity and simulation, offering design innovation, supporting testing, optimization, and the personalization of vehicle functions. Together, these technologies are laying the foundation of next-generation intelligent mobility.

AI in SDVs functions as the 'decision engine.' It enables a vehicle to process vast amounts of data from sensors, road conditions, and driver interactions and then generate appropriate responses. For instance, AI can determine when to apply brakes in an unexpected traffic scenario or recommend energy-efficient driving patterns. ML, on the other hand, is the process through which the vehicle gains knowledge and improves accuracy over time. By analyzing millions of driving scenarios, such as recognizing pedestrians, traffic lights, or sudden lane changes, ML models continuously sharpen the vehicle's decision-making capabilities. Without ML, AI would remain static; with it, vehicles become truly adaptive and increasingly capable over time.

GenAI plays a distinct but equally vital role in the SDV ecosystem. Unlike ML, which relies on existing data, GenAI can create new scenarios and possibilities that further bolster safety and enhance user experience. For instance, it can simulate rare but high-risk events—such as a child suddenly crossing the road in heavy rain—where real-world data is limited. It also enables more natural, human-like interactions for in-car voice assistants, making infotainment systems more intuitive. This creative capability accelerates testing while deepening personalization, ultimately making vehicles smarter and more user-centric.

Across the SDV lifecycle, these technologies operate in a complementary manner. In the development stage, GenAI assists in generating test cases and virtual environments. ML is then applied in training and validation, utilizing real-world and synthetic data to build accurate models. AI governs the deployment phase, handling real-time decision-making on the road. As vehicles enter the maintenance stage, all three converge. AI manages updates, ML learns from new data, and GenAI continues to explore possibilities for future improvements. Together, they ensure that SDVs remain safe, adaptive, and continuously evolving.

AI is Reinventing the Product/Software Development Lifecycle—Accelerating Time-to-Market, Enhancing Quality and Enabling Real-Time Adaptability

AI-Augmented Design and Engineering

- Generative Engineering
- Virtual Testing and Validation
- Intelligent Powertrain and ADAS system Callibration

Software Development at Scale

- Code generation and Quality Assurance
- Continuous Integration/ Continuous Development
- Model-Based Development

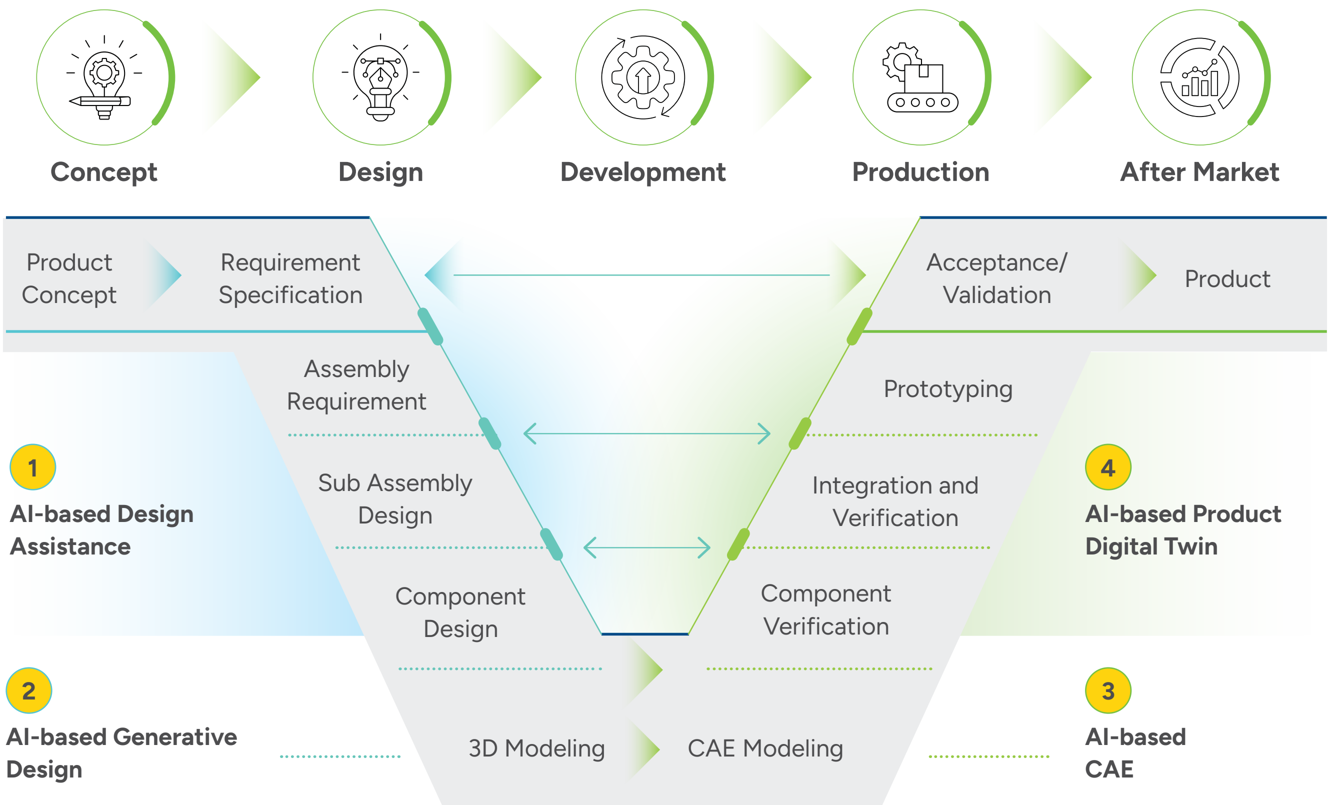
Predictive Quality and Defect Reduction

- AI in Failure Mode and Effects Analysis (FMEA)
- AI in Supplier Risk Monitoring

PLxAI: Accelerating Product Development Lifecycles with AI

PLxAI is LTTS' intelligent AI-driven platform that transforms the entire Product Development Lifecycle (PDLC) from concept to aftermarket. It integrates traditional and generative AI capabilities to accelerate design creation, optimize engineering processes, and enhance product performance. By combining AI-based design assistance, generative design, simulation (CAE), and digital twins, PLxAI enables engineers to innovate faster, reduce development costs, and ensure precision across every stage of the lifecycle.

The following diagram illustrates how PLxAI seamlessly integrates AI into each phase of the PDLC to drive efficiency, agility, and smarter engineering outcomes.



Key Features of PLxAI

PLxAI connects all stages of the Product Development Lifecycle from concept design to aftermarket support, ensuring smooth and continuous operations

It is designed by PDLC experts for PDLC engineers, built with a deep understanding of real-world engineering needs

The platform uses widget-driven architecture that allows quick and easy creation and deployment of use cases

It supports a knowledge base enriched with domain-specific constructs, improving accuracy and efficiency in engineering work

PLxAI captures tribal knowledge from past projects so that it can be reused in future designs

It is also extensible for Agentic AI workflows, enabling advanced automation and smarter decision-making.

AI-Enabled Functions Across Domains

ADAS and Autonomous Features

Next-generation ADAS systems rely on advanced ML-driven perception stacks that fuse data from cameras, radar, and LiDAR. Improvements in sensor resolution, HDR and low-light performance, along with AI embedded within the sensor pipeline, enable more accurate detection, classification, and path planning. These technologies are vital to advancing the autonomy curve, while ensuring safety and reliability.

Diagnostics and Prognostics

AI models monitor signals from ECUs, battery systems, and drivetrains to identify anomalies before they become visible to drivers. Predictive maintenance and over-the-air fixes reduce downtime and lower warranty cost. LTTS' 'Road to Connected Mobility' paper outlines how connected, AI-driven workflows allow dealerships to pre-schedule repairs, while OEMs collaborate on neural networks and specialized chips to strengthen autonomy and accelerate service innovation.

In-cabin Experiences

Within the cabin, AI is evolving from voice commands to context-aware copilots. These systems can detect driver distraction or fatigue, authenticate occupants, and dynamically adapt the human-machine interface (HMI), climate settings, and media preferences in real time. Industry developments increasingly emphasize biometrics, driver monitoring, and multimodal sensing.

Edge vs. Cloud AI Inference and Decision-Making

Edge AI runs AI algorithms locally on devices, such as sensors or IOT devices, enabling fast, real-time decisions without depending on constant internet connectivity. It is used as a combination of edge computing and AI to execute ML tasks directly on interconnected edge devices.

Cloud AI refers to the use of AI algorithms and models on cloud servers. This method offers augmented data storage and processing power capabilities, facilitating the training and deployment of more sophisticated AI models.

Benefits of Edge AI Inference and Decision Making

The advantage of Edge AI lies in its ability to provide real-time responses by processing data directly on the device, which reduces latency and allows for immediate decision-making. This is especially critical in applications, such as autonomous driving or industrial automation, where split-second reactions can make a difference.

Another key benefit is enhanced privacy and security as sensitive data does not need to travel to remote servers. It remains reliable in environments with limited or no connectivity and reduces bandwidth usage and associated costs. Additionally, by distributing processing across devices, it prevents overloading centralized systems while ensuring each device can operate independently.

Benefits of Cloud AI Inference and Decision-Making

Cloud AI enables seamless automation and intelligent decision-making by integrating powerful AI services directly into cloud platforms. It leverages these capabilities without heavy upfront investments in hardware or software, expediting deployment and maximizing efficiency.

By offering scalable, on-demand compute resources, Cloud AI handles complex inference workloads and deep analytics with ease. Businesses can process vast data volumes, adapt to changing workloads, and avoid the costs and risks of overprovisioning infrastructure.

Centralized inference in the cloud supports collaborative innovation and advanced analytics. By aggregating data across users and systems, it provides deeper insights, trend detection, and sustained model improvements, all from a unified, managed environment.

Real-World Use Case: Leveraging Edge and Cloud AI in C-V2X for Construction Vehicle Safety

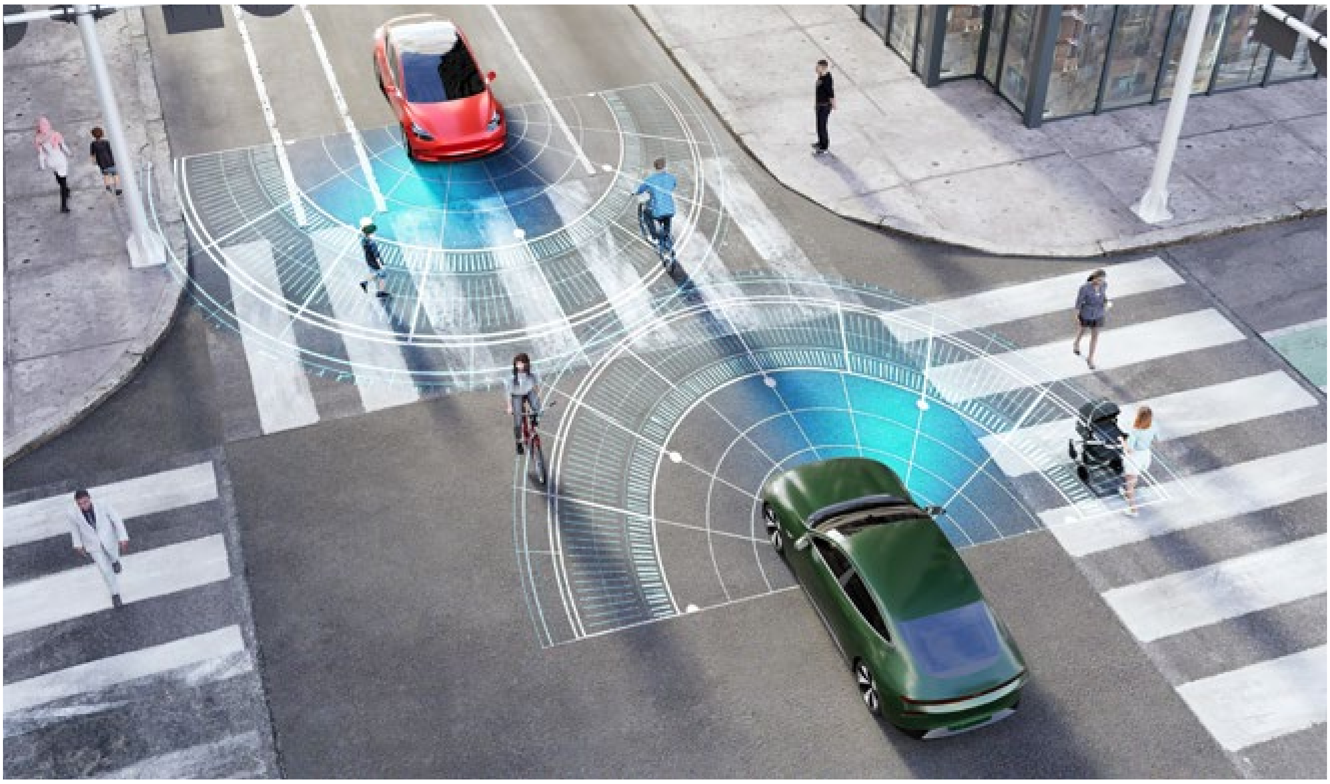
A leading North American Fortune 100 OEM in the construction equipment sector partnered with LTTS to advance the safety and autonomy of its heavy vehicles operating in mining and construction sites. The demanding conditions required low-latency, interference-free connectivity, and real-time hazard detection, which made combined Edge and Cloud AI strategy the most effective approach.

LTTS' Role

- **Evaluated** customer use cases across mining and construction zones
- **Designed** and deployed Multi-Access Edge Compute (MEC) architecture for low-latency processing
- **Delivered** software-driven deployment with OTA installation for vehicles and sites
- **Provided** advisory on middleware and network requirements to ensure scalability
- **Implemented** robust SIM-based hardware security for vehicles
- **Ensured** interference-free 5G private network operations in CBRS band
- **Streamlined** handoffs across base stations to maintain seamless connectivity
- **Conducted** end-to-end testing to validate strength and reliability of the framework

Outcomes

1. Reliable collision and hazardous location alerts in real-time.
2. Enhanced vehicle autonomy and site safety through edge-enabled decision-making.
3. End-to-end design, development and implementation of connected vehicle architecture.
4. Improved operational efficiency with robust testing and continuous rollouts.
5. Scalable solution that ensures value extension to end users across construction and mining sites.
6. Enabled progressive autonomy in heavy vehicles using 5G and AI integration.



AI Model Lifecycle in Automotive Training, Deployment, Updates, and Validation

Data and Training

Training AI models for software-defined vehicles (SDVs) requires petabytes of multimodal data, including video, sensor, and telemetry inputs. To accelerate data readiness and improve ground-truth quality, LTTS leverages platforms such as AnnotAI, an AI-driven, cloud-agnostic, end-to-end annotation solution that supports 2D/3D bounding boxes, point clouds, LiDAR, semantic segmentation, and video sequence annotation with tracking. Combined with synthetic data generation and AI-assisted labelling, this approach significantly shortens annotation cycles, improves dataset accuracy, and enhances scalability, while reducing overall time and cost of model training.

Packaging and Deployment

AI models in SDVs are packaged as versioned artifacts, deployed together with firmware updates. This ensures traceability and consistency across vehicle systems.

Validation and Safety

Functional safety (ISO 26262) and rising ASIL expectations require explainable behavior, fault-tolerant runtime monitors and safe-state fallbacks. ISO-aligned practices and third-party certifications such as UL Solutions certifying an ASIL-D safety module for an AI automation platform illustrate how AI features are gated into production.

Updates and Post-Deployment Learning

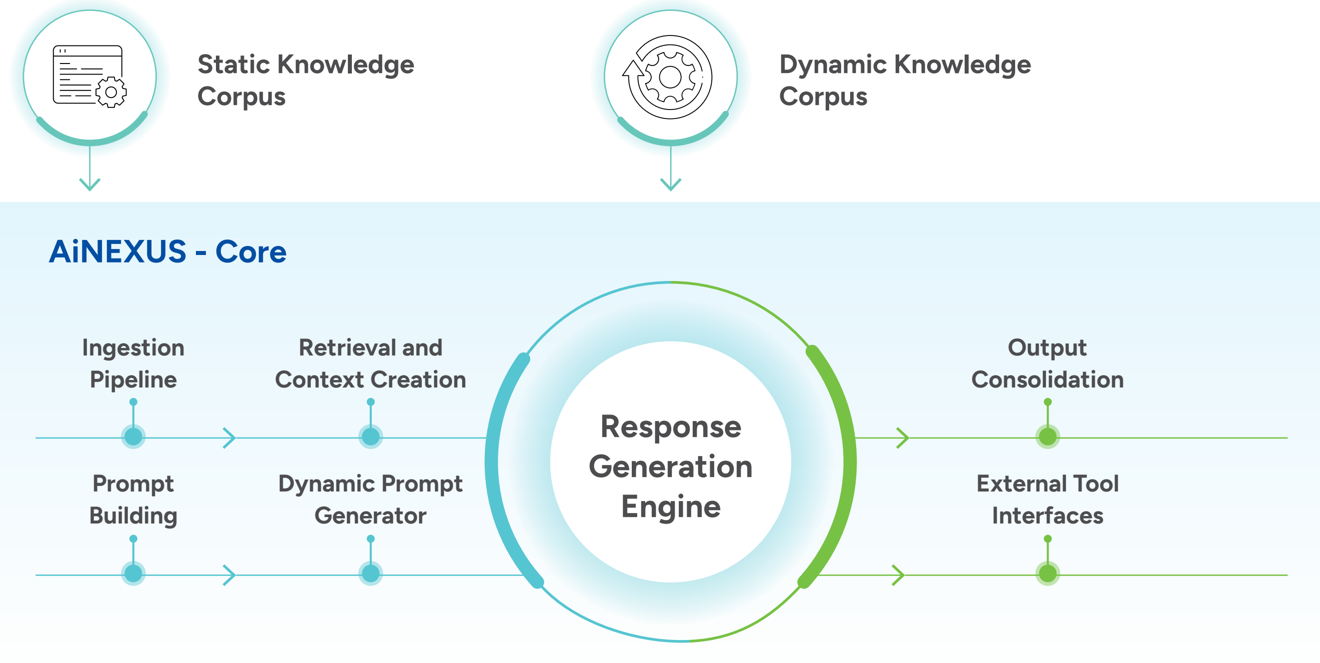
Continuous updates are essential to maintaining the accuracy of vehicle perception systems amid domain shifts, such as changing weather, new geographies, or evolving sensor inputs. Fleet-level analytics play a crucial role, feeding into re-training cycles that keep models adaptive and reliable.

To ensure safety, organizations implement staged rollouts, canary testing and rollback mechanisms. These practices ensure reliability and minimize risks during updates.

Key role of GenAI in SDV Engineering

AiNEXUS: Enabling Intelligent and Context-Aware Engineering Workflows

AiNEXUS is LTTS' unified AI-powered engineering platform designed to accelerate software development and enhance operational efficiency across industries. It integrates GenAI, machine learning, and automation within a single intelligent framework to simplify design, validation, and decision-making. The platform connects static and dynamic knowledge sources to generate context-aware insights, enabling faster responses and smarter engineering outcomes. By automating data ingestion, retrieval, and dynamic prompt generation, AiNEXUS empowers teams to seamlessly link digital and physical ecosystems, improving collaboration, accuracy, and innovation at scale.



Automated Code Generation and Optimization

AI-powered tools and platforms play a critical role in automating code generation, test creation, and validation across the SDV engineering lifecycle. This significantly shortens development cycles and accelerates time-to-market for new vehicle features. Generative AI is increasingly used to streamline the development of functions such as driver alerts, automated braking, and steering, improving both speed and engineering accuracy. In parallel, AI-driven automation enables more scalable software development, promotes the reuse of safety-compliant components, reduces duplication, and enhances overall system reliability. Advanced AI-based validation and qualification further improve software quality, strengthen compliance, and substantially reduce testing time, reinforcing robustness across next-generation vehicle platforms.

Virtual Prototyping and Digital Twins

AI-enabled simulations allow early-stage testing of software and hardware in virtual environments, leveraging integration of Things (IOT) integration. This 'shift-left' approach helps identify and resolve issues before building physical prototypes.

Within this approach, LTTSiDriVe acts as the backbone for virtual validation and testing. It brings together simulation, virtualization, and test automation in one framework. This makes it easier for teams to test early, iterate faster, and resolve issues more efficiently.

LTTS developed digital cockpit twins for automotive OEMs and Tier 1 suppliers, enabling end-to-end simulation of infotainment and zonal architectures. These twins help partners reduce costs and accelerate product launches, thereby advancing the broader SDV landscape.

Personalized In-Vehicle Experiences

AI analyzes driver behavior, preferences, and real-time conditions to personalize navigation, entertainment, and safety features, enhancing comfort, convenience, and overall user engagement.

Predictive Maintenance and Diagnostics

Machine learning processes sensor data to predict component wear and detect anomalies. By leveraging real-time data, AI driven analytics lays the foundation for predictive maintenance. This enables proactive maintenance, reducing downtime, and repair costs.

LTTSiDriVe applies AI and GenAI to automate CI/CD and DevOps pipelines in SDVs, allowing faster, safer, and compliant software releases.

Autonomous Driving and Real-Time Decision Making

GenAI improves perception, planning, and control for self-driving systems. It enhances adaptability to complex road scenarios, making autonomous features safer and more reliable.

By enabling AI-driven labeling and curation of multi-modal data such as text, images, videos, and LiDAR data, enabling high-accuracy training for autonomous driving models. This supports faster progress towards Level 5 autonomy.

Through AI-powered connectivity, LTTS delivers secure V2X communication, cloud integration, and driver-assist functions. Together, these enable smarter real-time decision-making and elevate in-vehicle experiences. Its data platform allows vehicle data to be collected and analyzed in near real time. This AI-driven feedback loop accelerates testing and helps cut product launch timelines.

By embedding GenAI into the SDV lifecycle, automakers and technology providers can create smarter, more adaptive vehicles capable of learning from their environment and continuously improving.

Chapter 4

SDV Technology Stack and Architecture

In This Chapter

- SDV Hardware
- OS and Middleware
- Application Layer and API

The SDV technology stack is built on a sophisticated, multi-layered architecture that spans hardware to user-facing services. At its foundation lies a robust software ecosystem, including board support packages, drivers, embedded operating systems such as QNX OS or Linux and virtualization layers such as Type 1 hypervisors.

This enables the consolidation of diverse vehicle functions into powerful, centralized compute platforms or domain controllers. Further complementing the foundational layer, middleware and communication layers abstract the complexity of heterogeneous hardware, harmonizing interactions between sensors, control units and applications. This layer relieves developers from hardware complexities, allowing them to focus on software functionalities. Standardized protocols and secure vehicle data exchange also facilitate Over the Air (OTA) updates and cloud integration.

The Hardware

Systems-on-Chips (SoCs)

SoCs play a critical role by integrating high-performance computing, sensor data fusion, and safety-critical functions into a single chip. This consolidation enables seamless communication across vehicle systems while optimizing hardware efficiency and software agility. Acting as the central bridge between applications, control hardware, and middleware, SoCs ensure that vehicles remain adaptable, scalable, and secure throughout their lifecycle.

High-Performance Compute Units (HPCUs)

Instead of having hundreds of small computers scattered throughout the car, SDVs use a few powerful processors. These centralized compute units and manage different areas of the vehicle, such as powertrain, infotainment, or safety systems. This reduces hardware complexity, improves efficiency, and simplifies upgrades.

Hardware Abstraction Layer (HAL)

HAL separates application software from underlying hardware components such as sensors and actuators. This decoupling allows the same software to be reused across different vehicle models and platforms with minimal modification, reducing development time and costs for OEMs.

Cloud Integration and Edge Computing

SDVs are constantly connected to the cloud, allowing real-time data sharing and decision-making. Through this integration, cars can receive over-the-air software updates, access new features, and benefit from AI capabilities such as predictive maintenance or advanced driver assistance. Edge computing ensures that critical decisions, such as braking or steering responses, are handled locally in the car for speed and safety, while the cloud supports broader functions and updates.

Microservices and Middleware

To keep the system flexible, SDVs use microservices and middleware. Microservices are small, independent software modules that perform specific tasks, while middleware acts as the connecting layer that ensures everything communicates smoothly. Together, they allow new features and updates to be deployed even after the vehicle is sold, ensuring continuous evolution over its lifecycle.

In essence, this architecture mirrors the functionality of a smartphone. SDVs are designed to remain dynamic, adaptive, and up to date long after leaving the factory.

OS and Middleware (QNX, AUTOSAR, Containers)

At the foundation of every SDV lies its operating system, which manages and orchestrates the interaction between automotive hardware components, such as sensors and actuators to computing units and higher-level software components. Similar to conventional OS platforms in smartphones or computers, vehicle OS coordinates low-level functions, such as engine control, braking systems, ADAS, and infotainment. New-age vehicle platforms often utilize real-time operating systems and embedded software to execute safety-critical applications, AI-driven experiences and OTA updates.

An embedded Operating System (OS) is specifically designed to manage the hardware and software resources of embedded systems. Unlike general-purpose operating systems, such as Windows or macOS, embedded operating systems are optimized for specific tasks and functions within the constraints of limited memory and processing power. These systems offer developers structured APIs, container-based workflows, and integrated development environments that enable efficient and reliable software development.

In SDVs, middleware acts as a bridge between the hardware and software applications, eliminating the need to write device-specific code for each chip or ECU. It abstracts hardware specifics, standardized communication protocols and facilitates modular service-based architecture across ECUs and software domains. This layer is essential in enabling seamless data exchange, accelerating testing and integration via container orchestration, and supporting OTA updates without having to reprogram each individual control unit. Middleware plays a critical role ensuring that diverse hardware and systems work in harmony within the SDV, making continuous enhancements and consumer electronics–level experiences inside the car a reality.

Middleware also supports advanced concepts, such as virtualization, containerization, and Service-Oriented Architecture (SOA), which allow multiple systems to run securely in parallel. This makes vehicles more flexible, upgradable and developer-friendly, aligning vehicle software evolution with modern digital ecosystems.

LTTS brings deep expertise in platform software and middleware, creating the crucial bridge between hardware, development tools, and applications. These offerings are especially vital in industries, such as semiconductors and embedded systems. LTTS supports full-stack middleware development starting from board bring up, OS porting (Linux, Android, RTOS) to middleware customization and application level tailoring across multiple industry domains, including automotive and IoT.

This includes driver development, pre- and post-silicon design, and system optimization with major chipsets. We enable scalable, reliable software integration, expediting the time-to-market for embedded solutions.

Our automotive middleware strategy is aligned with OTA delivery, incorporating canary and blue-green deployments and rollback mechanisms. This ensures safe, efficient, and large-scale software rollouts across global vehicle fleets.

Application Layer, Modular Deployment, Connectivity, and APIs

Application and Service Layer

Applications built on top of the middleware manage user-centric features, such as infotainment, digital cockpits, ADAS, and telematics. These are implemented using microservices that are independently deployable and scalable. LTTS enables containerized microservices by utilizing tools, such as Docker, Kubernetes, and CI/CD pipelines. This facilitates modular development and seamless connectivity across edge and cloud environments.

Service-Oriented Architecture (SOA)

The software inside an SDV is structured like an ecosystem of several independent services. Each service performs a specific function and can be updated or modified, without affecting the entire ecosystem. This means updates can be delivered quickly and seamlessly, just like updating a single app on a smartphone, instead of reinstalling the entire operating system.

Following SOA principles, the SDV stack is segmented into safety-critical (ASIL C/D), less critical and cloud-based services. This segmentation ensures clear isolation, API-driven integration, and greater lifecycle agility, enabling continuous innovation while maintaining system integrity and safety.

Advantages of SOA Architecture

- Easy access and seamless integration of third-party services
- Agile approach to technological advancements
- Modularity and Reusability driving reduced development costs
- Interoperability between components from different manufacturers leading to a personalized user experience

OTA and Data Flow

OTA updates enable vehicles to receive new features and improvements remotely, eliminating the need for service center visits. Telemetry data from sensors and systems support analytics, diagnostics, and evolving feature sets. The rise of SDVs has propelled LTTS to advance both middleware and OTA capabilities. Our solutions include adaptive AUTOSAR middleware frameworks, virtualization tools, such as Embed VIO and OTA platforms that enable secure, remote software updates.

Application Programming Interfaces (APIs)

In SDVs, APIs serve as standardized gateways through which application developers can access and control vehicle systems, ranging from sensor data like speed or battery level to actuator commands such as adjusting a mirror or opening a window. By abstracting automotive hardware and electrical or electronic architecture, these APIs enable developers to build features without needing in-depth knowledge of the underlying systems. This abstraction accelerates innovation and supports seamless integration of new services like remote diagnostics or personalized apps and also paves the way for adaptive, secure, and scalable automotive ecosystems.

AI-Driven Acceleration

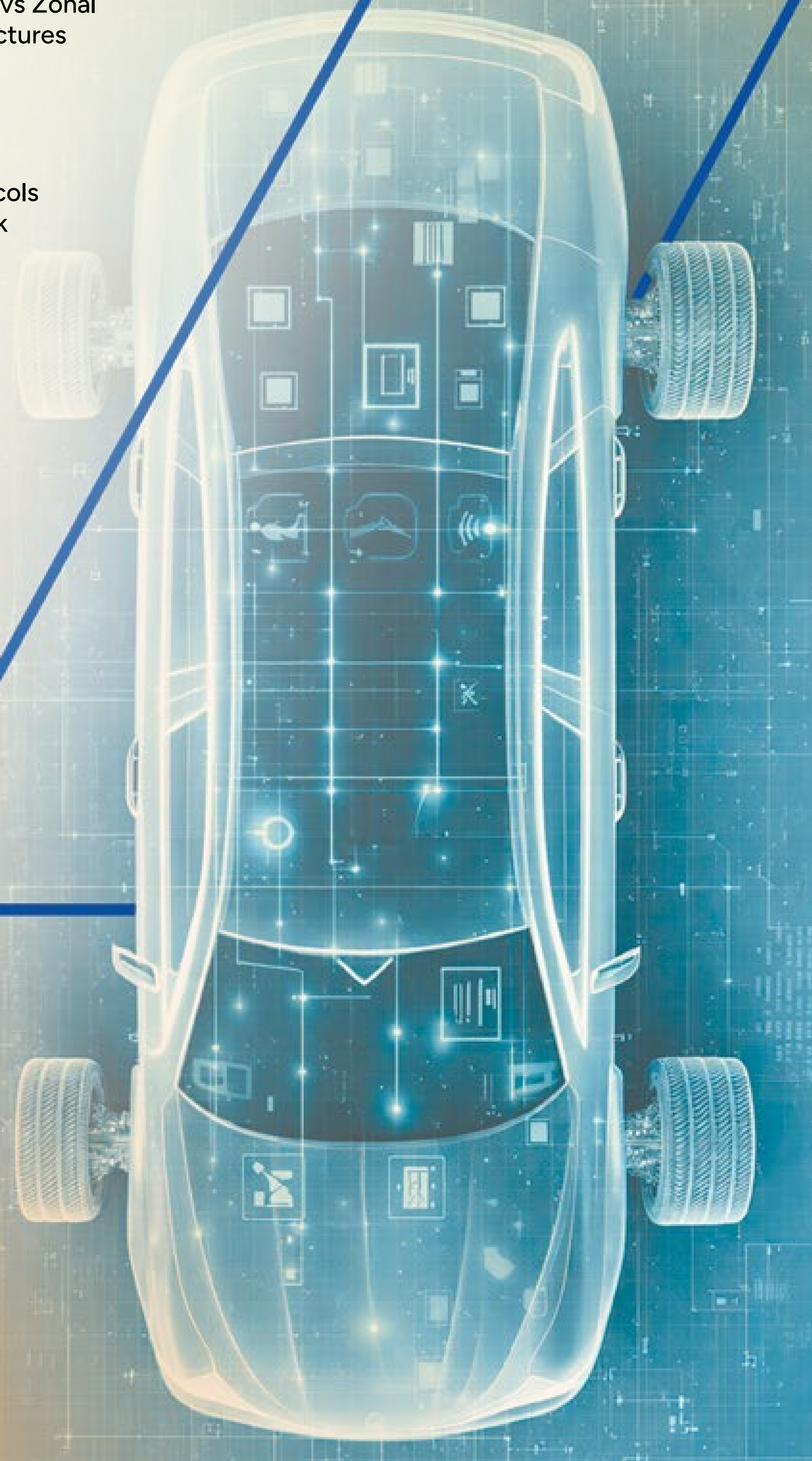
iCAF	App Studio	iGenSuite

Chapter 5

Evolving Vehicle Architectures

In This Chapter

- Distributed vs Domain vs Zonal vs Centralized Architectures
- Transition Challenges
- Zonal Controller Role
- Communication Protocols and Backbone Network
  LTTS Case Studies



The evolution of modern vehicle electronics reflects the broader transformation of the automotive industry—from mechanical precision to digital intelligence. Over the past few decades, vehicle architectures have progressed through multiple paradigms, each driven by the need to manage increasing complexity, cut costs, and unlock new possibilities.

Architectural Paradigms: Distributed vs. Domain vs. Zonal vs. Centralized

Distributed Architectures

↓

Domain Architectures

↓

Zonal Architectures

↓

Centralized Architectures

Previously, vehicles were a patchwork of independent systems, such as engine management, braking, infotainment and lighting, each managed by a dedicated ECU. While this provided clear functional segregation, it also resulted in extensive wiring, increased weight, and higher maintenance as the number of ECUs multiplied. As each ECU was tightly bound to its own hardware and software, updates or scaling across vehicle models became complex.

To overcome these challenges, the industry transitioned towards a domain-led architecture, where related functions were grouped into domains, such as powertrain, body electronics, infotainment, or ADAS. Domain controllers aggregated tasks from multiple ECUs, reducing redundancy and allowing limited software scalability. However, cross-domain communication remained complex and OTA updates were difficult to manage because each domain was typically supplied by different Tier-1 suppliers with their own proprietary platforms.

The next evolution, zonal architecture, organizes systems based on the vehicle's physical layout rather than functional domains. Sensors, actuators, and smaller ECUs connect to local zonal controllers, which aggregate data, manage power distribution, and communicate with a central computing unit. This approach significantly reduces wiring, simplifies system design, and allows for more flexible hardware reuse. Acting as intelligent gateways, zonal controllers help decouple hardware from software, making OTA updates more efficient, enabling feature rollouts without hardware redesign, and allowing components—such as in-cabin radars—to serve multiple functions.

The next frontier is a Centralized architecture, where a limited number of high-performance computers manage most of the vehicle functions. This design brings efficiency by allowing software to be reused and scaled with ease, while applications are virtualized on advanced and powerful processors. It supports the idea of the SDV, where vehicles can be continuously upgraded like smartphones. Consequently, European OEMs are investing heavily in centralized architectures and software platforms to remain competitive. However, challenges remain, especially in managing latency, ensuring real-time performance for safety-critical functions (such as suspension control and anti-pinch windows), and maintaining robust cybersecurity at high levels of system consolidation.

Overall, the progression from distributed to centralized architecture reflects a clear shift toward fewer but more powerful computing nodes with greater reliance on software modularity. Each stage addresses the limitations of the previous one while introducing new challenges related to integration, safety, and cost management.

Transition Challenges in Evolving Vehicle Architectures

One of the foremost issues is the increasing complexity of electrical and electronic (E/E) systems, particularly in rethinking wiring layouts and power distribution. Traditional vehicle designs rely on dozens—or even hundreds—of ECUs, each running application-specific firmware. These ECUs often vary across models and trims and are sourced from multiple Tier-1 suppliers, making standardization difficult. As OEMs move toward zonal or centralized computing, they must ensure compatibility with this heterogeneous legacy ecosystem while maintaining safety and real-time performance.

Cost considerations represent another barrier. Transitioning to zonal or centralized computing requires investment in high-performance processors, domain controllers, advanced communication protocols (Ethernet, CAN-FD, TSN), and an overall redesigned wiring architecture. While long-term savings arise from reduced wiring complexity and simplified updates, the up-front capital expenditure can be prohibitive, particularly in mass-market segments. Additionally, the shift demands increased software engineering effort, as functions are decoupled from hardware and rewritten to run on abstracted platforms.

OEM adoption cycles introduce another layer of complexity. Since automotive design cycles typically span five to seven years, a complete architectural overhaul cannot be implemented overnight. Incremental migration is often the only practical approach. OEMs may begin by consolidating a subset of ECUs under zonal controllers before moving towards full centralization. This gradual path requires a hybrid architecture that combines legacy and new-age systems, which in turn heightens integration and testing challenges.

Finally, regulatory and safety requirements play a defining role in the transition. Standards, such as ISO 26262 for functional safety, UNECE WP.29 for cybersecurity, and evolving data-protection frameworks impose strict compliance obligations. As more functions shift to software, regulators expect clear evidence of resilience against failures and cyberattacks. This necessitates investment in redundant communication links, secure over-the-air update mechanisms, and extensive validation campaigns across all ECUs to ensure regulatory approval.

Amid this complexity, the industry's leading engineering partners have been instrumental in smoothing the transition. Through their expertise in virtualization, Controller Design (Zonal/Domain), platform software, middleware, and communication frameworks, they help OEMs modernize architecture without losing time or safety confidence.

Zonal Controller Role in Evolving Vehicle Architectures

In zonal architecture, the zonal controller serves as the central hub for a defined physical area of the vehicle, such as front left, rear, or right. Its primary role is to aggregate sensor data, manage actuators, and enable localized decision-making.

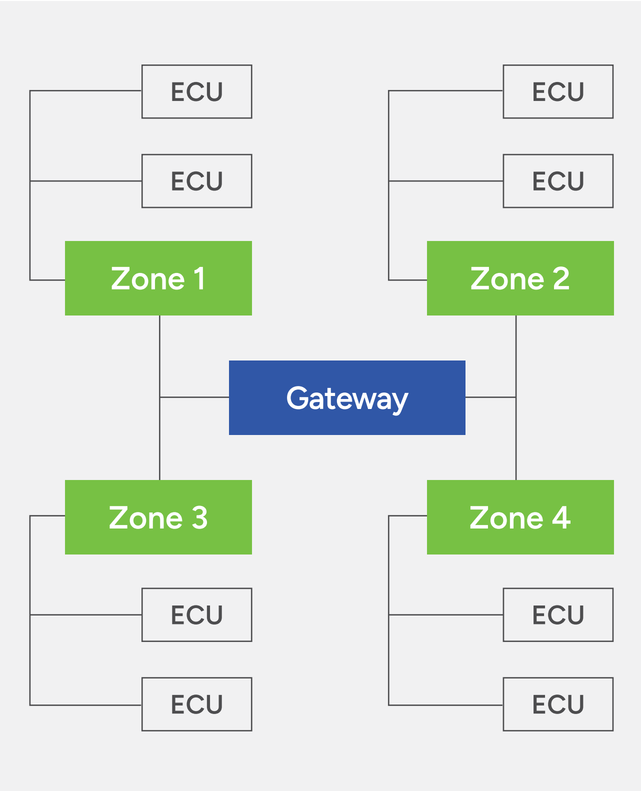
Instead of routing every signal through dozens of individual ECUs, the zonal controller streamlines the system by acting as a gateway, collecting input from multiple edge devices and relaying only processed or essential data to the central HPC. This design simplifies wiring, reduces system weight, and improves overall energy efficiency.

A key capability of zonal controllers is protocol abstraction. Contemporary vehicles use varied communication protocols, such as CAN-FD, LIN, FlexRay, and Ethernet. The zonal controller translates these protocols into a unified format for the central computer system. This ensures compatibility across legacy systems and emerging electronic components without requiring consistent redesigns. This abstraction is fundamental to decoupling hardware from software, a core principle of SDVs.

As software frameworks continue to evolve, zonal controllers are gaining more autonomy. They can execute safety-critical commands locally such as window anti-pinch or adaptive lighting—without waiting for central approval. This balance between localized intelligence and centralized decision-making defines the modern E/E architectures, delivering both efficiency and safety.

Scalability is a natural outcome of this approach. A single vehicle platform can support multiple variants, from entry-level to premium models, differentiated primarily through software. Core functionalities may be standard, while advanced features—such as adaptive lighting or noise cancellation—can be enabled through software updates. For automakers, this creates a compelling model: design once and scale across segments with flexibility and efficiency.

Illustration of Zonal Architecture in Vehicles



Communication Protocols and Backbone Network (Ethernet, CAN-FD, TSN, SOME/IP)

As vehicles transition from distributed ECU-based systems to zonal and software-defined architectures, communication protocols and backbone networks have become indispensable enablers of performance, safety, and scalability. Traditional Controller Area Network (CAN) buses, though reliable for real-time control of safety-critical functions like braking and steering, face limitations in bandwidth as sensor density rises. To address this, CAN-FD (Flexible Data-Rate) has emerged as a natural evolution, offering higher data throughput (up to 8 Mbps) while maintaining backward compatibility with legacy CAN nodes. This makes CAN-FD essential in handling ADAS and powertrain functions where low latency is vital.

Ethernet is rapidly emerging as the backbone of vehicle networks, offering scalability and the ability to consolidate disparate domains. Automotive Ethernet provides multi-gigabit bandwidth, supporting data-intensive applications, such as high-resolution cameras, LiDAR, infotainment systems, and OTA updates. By leveraging standardized protocols, Ethernet enables zonal controllers to exchange large volumes of data efficiently with central high-performance computers. When combined with Time-Sensitive Networking (TSN) extensions, Ethernet further provides deterministic communication with bounded latency and synchronization, necessary for safety-critical workloads, such as active suspension or collision avoidance. This combination of high throughput and real-time assurance positions Ethernet-TSN as the de-facto backbone of future software-defined vehicles.

Beyond transport, higher-layer protocols, such as SOME/IP (Scalable Service-Oriented Middleware over IP) are instrumental in abstracting hardware from software. SOME/IP allows distributed applications to communicate through service-oriented messaging, supporting dynamic discovery and API-based integration across domains. This aligns SOA of SDVs, where functions can be modularly deployed, updated, or scaled across zones and central computing platforms.

Synergy in a Layered Communication Ecosystem

CAN-FD

- Reliability for legacy and control systems

Ethernet

- A scalable, high speed backbone

TSN

- Deterministic reliability for critical applications

SOME/IP

- Flexible service-based communciation

This layered approach reduces wiring complexity, enhances data flow between zones, and supports sustained feature updates, which are fundamental to SDVs.

Reimagining Platforms from the Ground Up

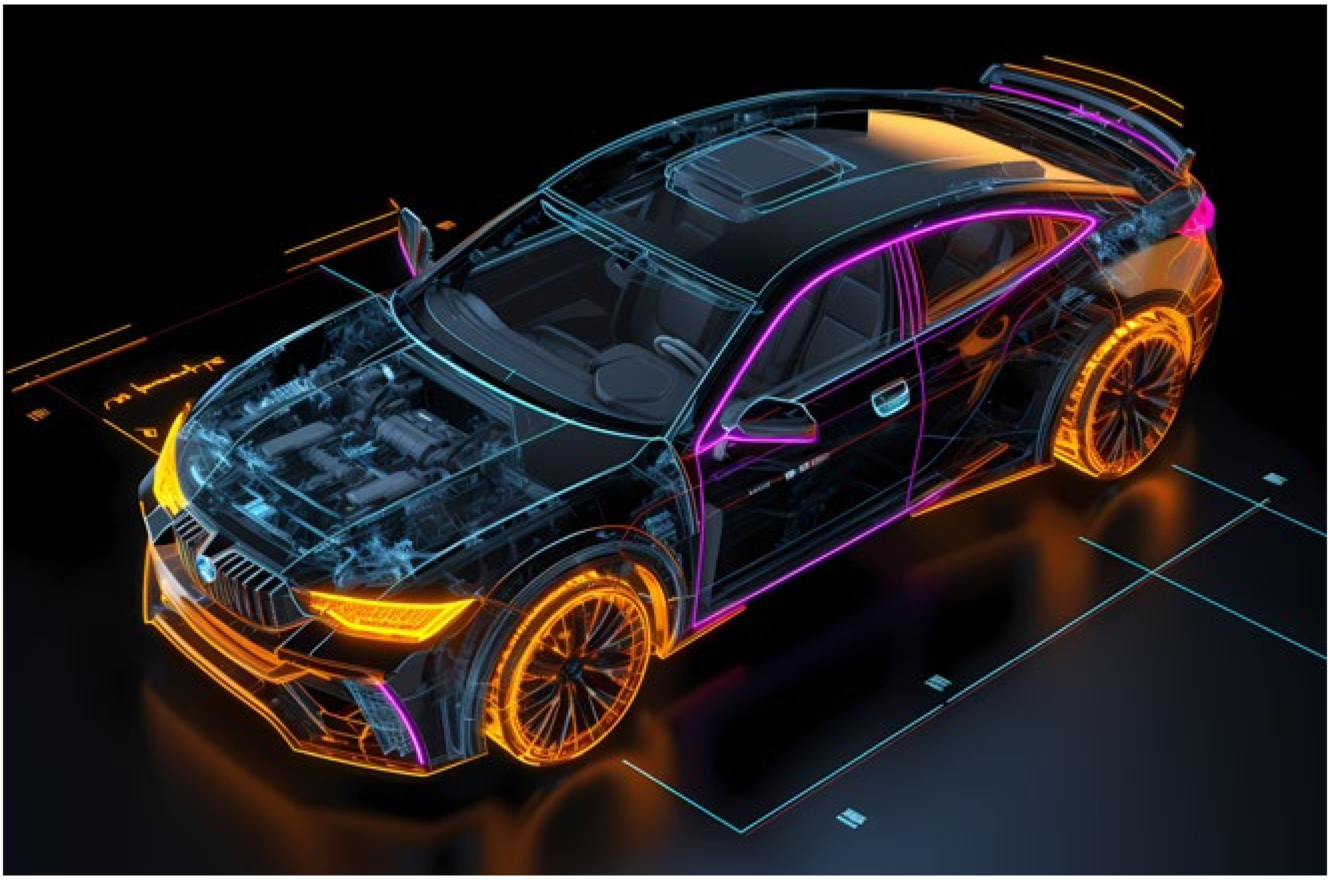
Across the global automotive landscape, manufacturers increasingly recognize that legacy architectures—no matter how refined—cannot support the transition to fully SDVs. Rather than patching existing systems, they are starting anew—designing platforms built from the ground up for electric, connected, and autonomous vehicles.

This transformation is not merely about technology; it is a mindset shift. By developing unified, software-centric platforms, OEMs are eliminating years of accumulated complexity. The new architectures allow over-the-air feature deployment, advanced analytics, and real-time data exchange—capabilities that are reshaping how vehicles are developed, tested, and experienced.

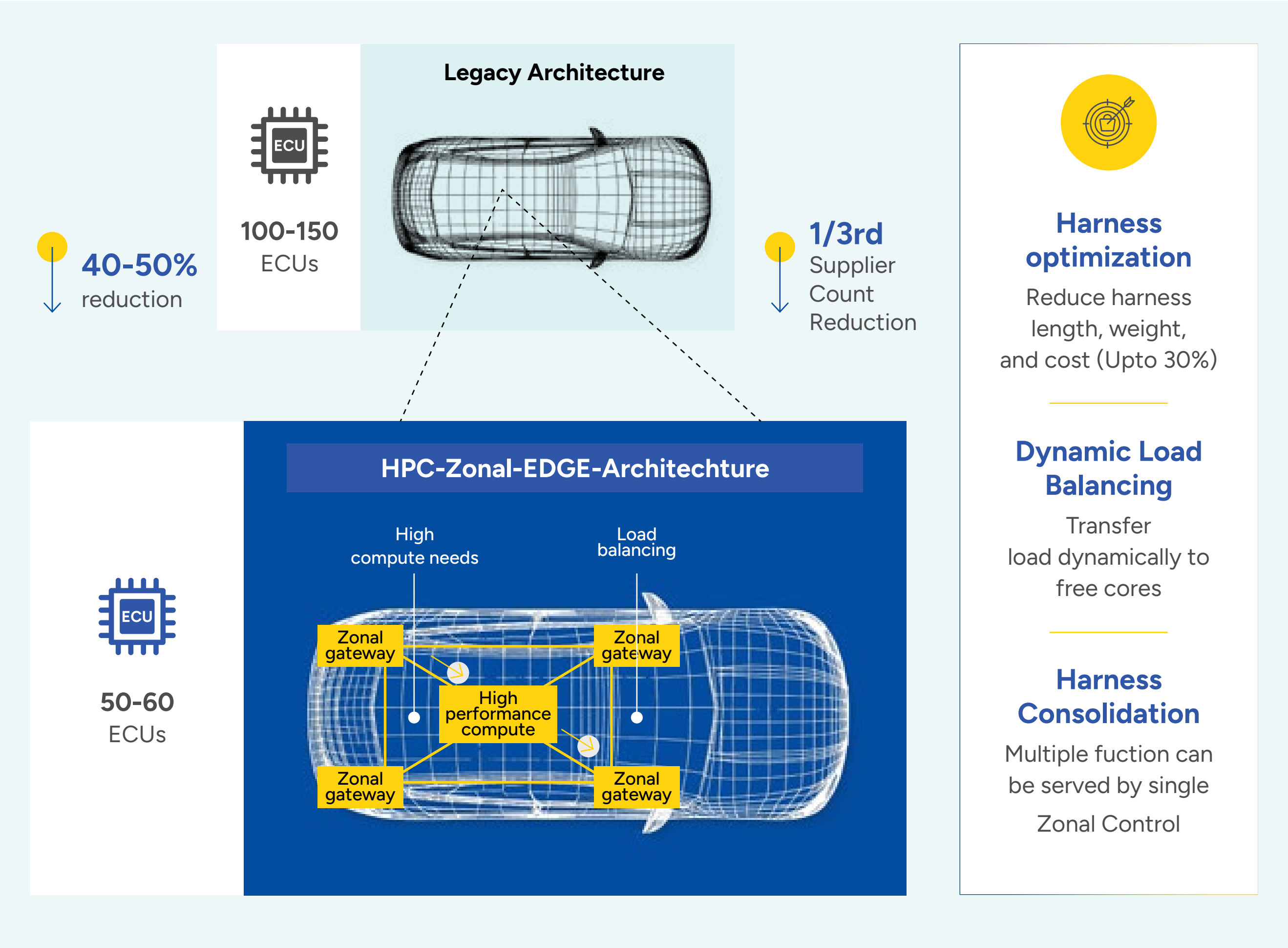
Engineering partners such as LTTS have been instrumental in helping automakers transition from fragmented legacy systems to cohesive, software-driven vehicle architectures. Their expertise spans from **electrical and electronic (E/E) framework redesign** to **ECU consolidation and virtualization**, ensuring that OEMs can confidently embrace the software-defined future. With vehicles now housing increasingly complex networks of ECUs, testing and validation have become major challenges. LTTS addresses these through advanced **ECU virtualization**, allowing engineers to test and validate both software and hardware configurations in safe, simulated environments. This virtual approach minimizes dependence on expensive prototypes, accelerates development cycles, and improves early defect detection—all while ensuring compliance with stringent safety and cybersecurity standards.

At the core of LTTS' SDV validation stack is **LTTSiDriVe**, its shift-left framework for verification, validation, and quality assurance. Within this, **EmbedVIO-VT** acts as the embedded virtualization layer for AUTOSAR environments, enabling **Software-in-the-Loop (SiL)** and **Hardware-in-the-Loop (HiL)** testing through interconnected Virtual Nodes pre-configured with simulators, agents, and virtualization libraries. This setup supports large-scale, scenario-based testing with high accuracy and efficiency.

LTTSiDriVe also integrates frameworks for next-generation zonal architectures, replacing domain-based ECUs with zonal controllers to streamline power distribution, data flow, and actuator control. Together, the platform enables a virtual-first, shift-left validation approach that reduces complexity and improving energy efficiency.



SDV Platform Success Factors: An OEM Perspective and Motivation



Through seamless middleware integration and virtualization strategies, LTTS ensures robust communication between zonal controllers and central high-performance computing platforms—supporting scalable, modular deployments across multiple OEM programs. Together, these innovations are redefining how automakers design, validate, and scale their SDVs, laying the foundation for a connected, intelligent, and future-ready mobility ecosystem.

A Journey Still in Motion

The evolution of vehicle architecture tells a story not of replacement, but of reinvention. Each generation—distributed, domain, zonal, centralized—builds upon the lessons of the one before. What began as an effort to tame wiring complexity has evolved into a complete rethinking of what a vehicle can be: intelligent, adaptable, and continuously evolving.

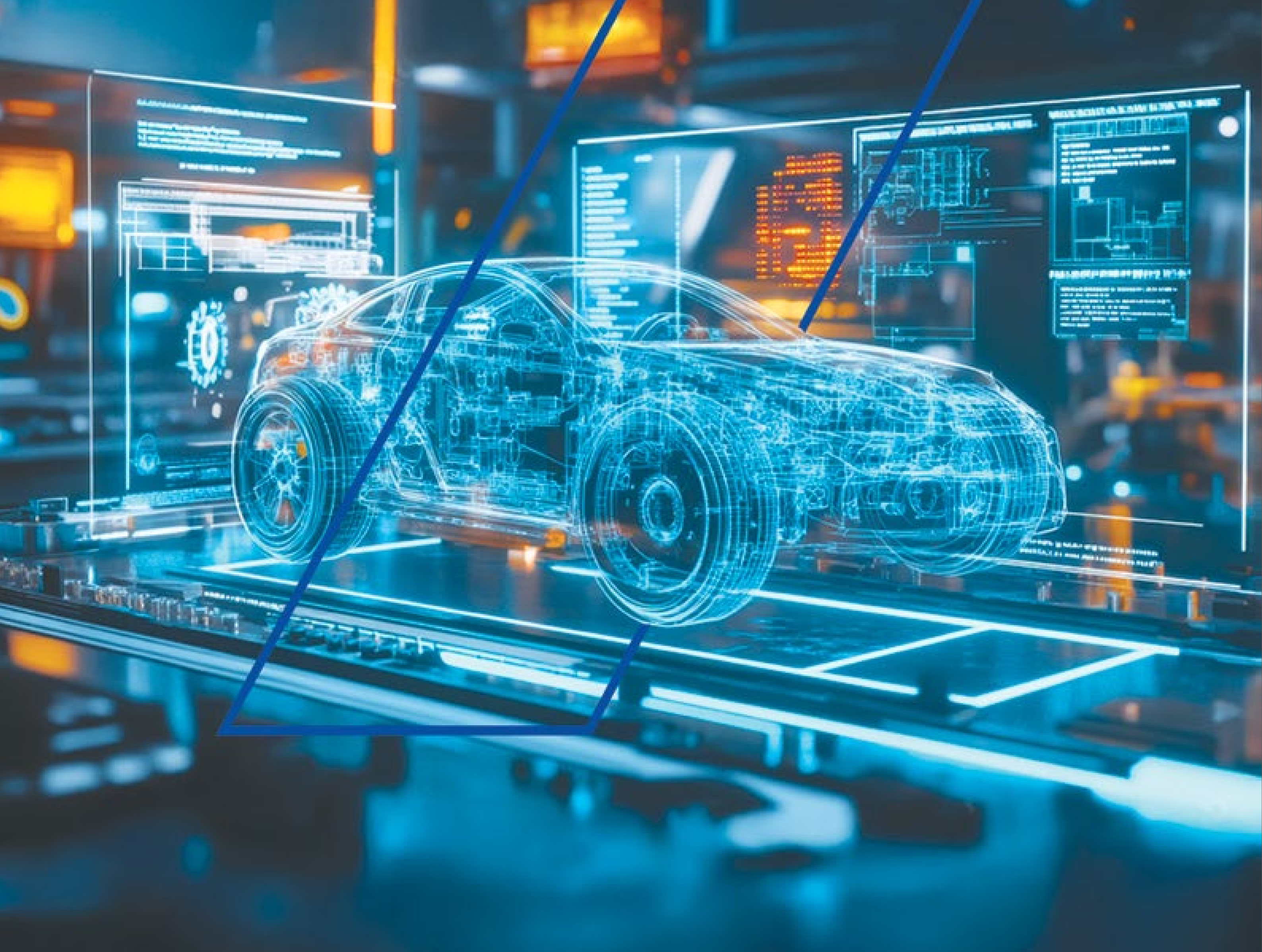
As this journey continues, the line between mechanical engineering and digital innovation blurs even further. Vehicles are no longer defined solely by their physical construction, but by the software that powers them—placing those who can effectively integrate both domains at the forefront of the future of mobility.

Chapter 6

Enablers of the SDV Transition

In This Chapter

- OTA Update Mechanisms
- Microservices and Containerization
- Connectivity and Cloud Integration
- Data and AI/ML-Driven Services
- LTTS SDV Labs and Global Delivery Model



The transition to SDVs is being propelled by technologies that transform vehicles into intelligent and upgradable platforms. HPC platforms replace multiple ECUs with centralized power for AI, connectivity, and advanced features. Advanced vehicle operating systems and middleware provide seamless integration across hardware and applications, while OTA update mechanisms ensure sustained improvements.

Microservices and containerization support modular, scalable and quicker deployment of functions. With embedded safety and cybersecurity frameworks, vehicles remain protected against emerging threats. Collectively, these enablers, supported by R&D labs and global delivery models from companies like LTTS are paving the way for secure, connected, and future-ready mobility.

OTA Update Mechanisms

One of the defining capabilities of SDVs is the ability to evolve after they leave the production line. This is enabled by Over-the-Air (OTA) update mechanisms, which allow automakers to remotely update and enhance software across the entire vehicle lifecycle, thereby reducing reliance on physical workshops and service centers. Unlike traditional cars, SDVs are not static products, they are platforms for continuous innovation. OTA updates enable dynamic improvements across functions such as infotainment, driver assistance, powertrain efficiency, and cybersecurity. This approach future-proofs vehicles and extends their lifecycle relevance.

OTA also enables a high degree of personalization. Automakers can deliver new capabilities, unlock premium features on demand, and provide customized configurations for different user segments. This transforms the business model from one-time sales to recurring subscription revenues, positioning vehicles as 'living products,' akin to smartphones. Increasingly, OEMs view OTA not just as a maintenance tool but as a strategic enabler—accelerates feature delivery, reduces operational costs, and creates new revenue opportunities through subscription and upgrade-based offerings. For consumers, it provides greater flexibility in tailoring their driving experience, which can range from varied entertainment options to advanced driver assistance packages without altering the underlying hardware.

The impact of OTA extends further into predictive maintenance and performance optimization. By integrating with real-time diagnostics and cloud analytics, vehicles can receive software corrections before issues escalate, ensuring greater safety and minimal downtime. Performance parameters—such as battery management in electric vehicles or efficiency optimization in combustion systems—can also be refined remotely, enhancing reliability and supporting sustainability by reducing unnecessary service interventions.

Microservices and Containerization

As vehicles adopt more software-led functionalities, traditional monolithic systems can no longer sustain rapid evolution. The Microservices architecture decomposes a software application into a suite of small, independently deployable services, each encapsulating a discrete function and communicating via lightweight APIs. This modular approach improves scalability, resilience, and agility, allowing teams to develop, deploy, and scale services independently without impacting the entire system. Unlike monolithic systems, where changes may require redeploying the whole application, microservices enable targeted updates and continuous delivery, expediting development cycles and reducing risk.

Containerization complements this approach by providing a lightweight, portable, and consistent runtime environment for each service. Containers package applications along with their dependencies and runtime libraries, ensuring consistent behavior across development, testing, and production environments. Compared to traditional virtual machines, containers are more resource-efficient, start faster, and share the host operating system kernel, making them well-suited for microservices-based architectures. Combined, microservices and containers enable fine-grained scaling, improved fault isolation, and streamlined deployment practices, especially when orchestrated through tools like Kubernetes or Docker.

Connectivity and Cloud Integration

The transition to SDVs represents a decisive shift in automotive design, shifting the emphasis from hardware centric systems towards vehicles defined and organized by software. Two critical enablers accelerating this transformation are connectivity and cloud integration, which together unlock new functionality, enhanced efficiency operational efficiency, and enable innovative business models for the future of mobility.

Connectivity: The Lifeline of SDVs

In the world of SDVs, connectivity acts as the thread that binds vehicles to external systems, the internet and broader mobility ecosystems. By enabling real-time data exchange, it allows automakers to collect sensor data, monitor vehicle health, and continuously enhance performance. Insights derived from this data power features such as predictive maintenance, adaptive in-cabin personalization, and optimized safety functions—key characteristics of next-generation SDVs.

Moreover, a strong connectivity architecture serves as the bedrock of the entire SDV software stack, supporting the onboard middleware and hypervisors to AI-enabled chipsets and cloud services. This framework enables the deployment of digital twins, which are virtual models of vehicles used for remote simulation, testing, and management. These digital twins remain synchronized with their physical counterparts through continuous data exchange, enabling proactive diagnostics and accelerated development cycles.

Connectivity is also redefining in-vehicle system design. Traditional subsystem-based hardware nodes like fuse boxes and wiring harnesses are giving way to centralized computers and zonal architecture. This evolution simplifies physical complexity, while consolidating and streamlining function control. The greater integration of electronics and data transfer among vehicle modules heightens reliance on secure, reliable data connectivity frameworks. In this way, connectivity is becoming both a technological enabler and a strategic differentiator for the mobility of tomorrow.

Cloud Integration: Scaling, Updating, and Enabling Services

Cloud integration equips SDVs with the scalability, flexibility, and advanced functionality needed to go beyond the limitations of onboard systems. By offloading compute and storage to the cloud, automakers are no longer constrained by in-vehicle hardware. Instead, they can process massive datasets at speed, enabling real-time services such as advanced navigation, remote diagnostics, and OTA updates.

Software versions can be centrally managed, whittled down to specific vehicle targets and securely deployed to vehicle fleets, eliminating the need for physical intervention. This capability accelerates iterative development and ensures that vehicles evolve continuously throughout their lifecycle.

The SDV transition rests on two interdependent pillars: connectivity, which ensures seamless, secure data flow between vehicles and external systems and cloud integration, which enables scalable computing, continuous updates, and rich digital services.

Data and AI/ML-Driven Services

The SDV transition is anchored in advanced data infrastructure and machine learning capabilities. Supported by high-performance in-vehicle compute systems and networking, zonal Ethernet architectures, and OTA update mechanisms, vehicles are evolving from static machines into adaptable platforms capable of continuous improvement. This data-centric foundation enables real-time processing, modular upgrades, and seamless integration of new functionalities, reducing dependence on rigid hardware systems. As a result, manufacturers can deploy enhancements faster, tailor services to user needs, and improve safety through predictive diagnostics based on vehicle performance data.

Integral to this transformation is the integration of **AI and ML-driven services**, ranging from predictive maintenance and anomaly detection to adaptive driver assistance and personalization. By continuously learning from vast streams of real world vehicle data, these algorithms anticipate component failures, optimize performance, and tailor user experiences over time. Additionally, the rise of **edge AI**, where advanced models operate directly on the vehicle's hardware rather than relying on the cloud is further accelerating this shift. This allows for faster, safer autonomous features, such as hands off driving, while managing bandwidth and latency more effectively. Collectively, these advancements are making vehicles increasingly intelligent, adaptive, and aligned with both driver expectations and operational efficiency.

LTTS Enablers for SDV Transition

Strategic Approach

LTTS plays a critical role in enabling the transition to SDV by combining its deep automotive engineering expertise with advanced digital platforms. A key enabler is its comprehensive SDV transformation framework, which spans consulting, design, development, and validation.

LTTS supports OEMs in migrating from legacy architectures to zonal and service-oriented designs, while offering advisory on long-term SDV strategy, cybersecurity compliance, monetisation models, and operational transformation. This consulting-led approach ensures that automakers can align technology adoption with business goals and regulatory needs.

Proprietary Tools and Accelerators

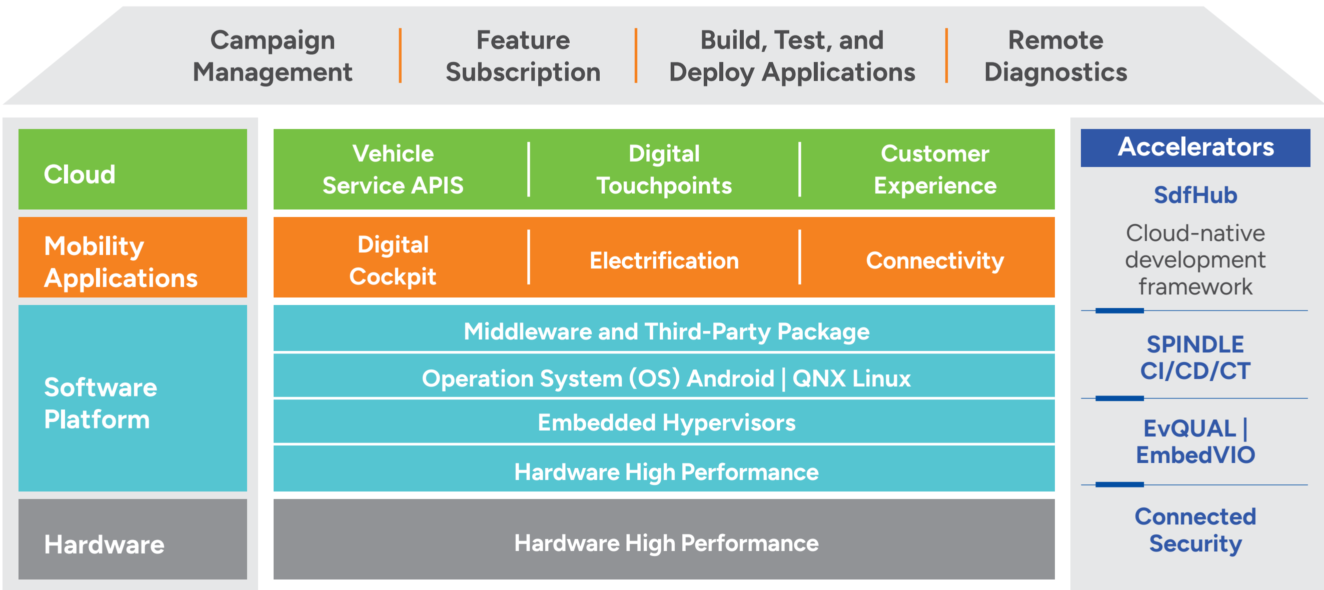
Another important enabler is LTTSiDriVe, an integrated SDV platform developed by LTTS to help automotive companies build, test, and deploy next-generation vehicle software faster and with greater flexibility. As vehicles continue to shift from hardware-driven systems to software-led architectures, the platform supports the migration of critical vehicle functions into software, making it easier to add new features, improve performance, and deliver continuous updates.

Built for this new automotive era, LTTSiDriVe reduces complexity by abstracting underlying hardware and system layers while providing ready-to-use development and testing environments. It allows engineers to work across multiple semiconductor platforms and operating systems, use virtual testing environments, and apply AI-driven automation to accelerate development and improve quality. This helps teams focus more on innovation and software robustness, while lowering manual effort and shortening time-to-market.

Key Features and Capabilities

- Ready-to-use development environments with pre-configured tools and toolchains, enabling faster project initiation and reduced setup effort.
- Virtual nodes, simulators and agents that support early 'shift-left' testing, allowing software validation even before hardware is available.
- GenAI-enabled automation and AI-assisted capabilities to generate test scenarios, models, while improving test quality and reusing knowledge from past projects.
- Support for multiple operating systems and multi-core architectures, along with digital twins and simulation capabilities for realistic system validation across mixed-critical workloads.
- Interoperability with third-party tools, cloud-based workflows, reducing hardware dependency, and improving scalability.

LTTSiDriVe Architecture



Ecosystem Partnerships and Global Presence

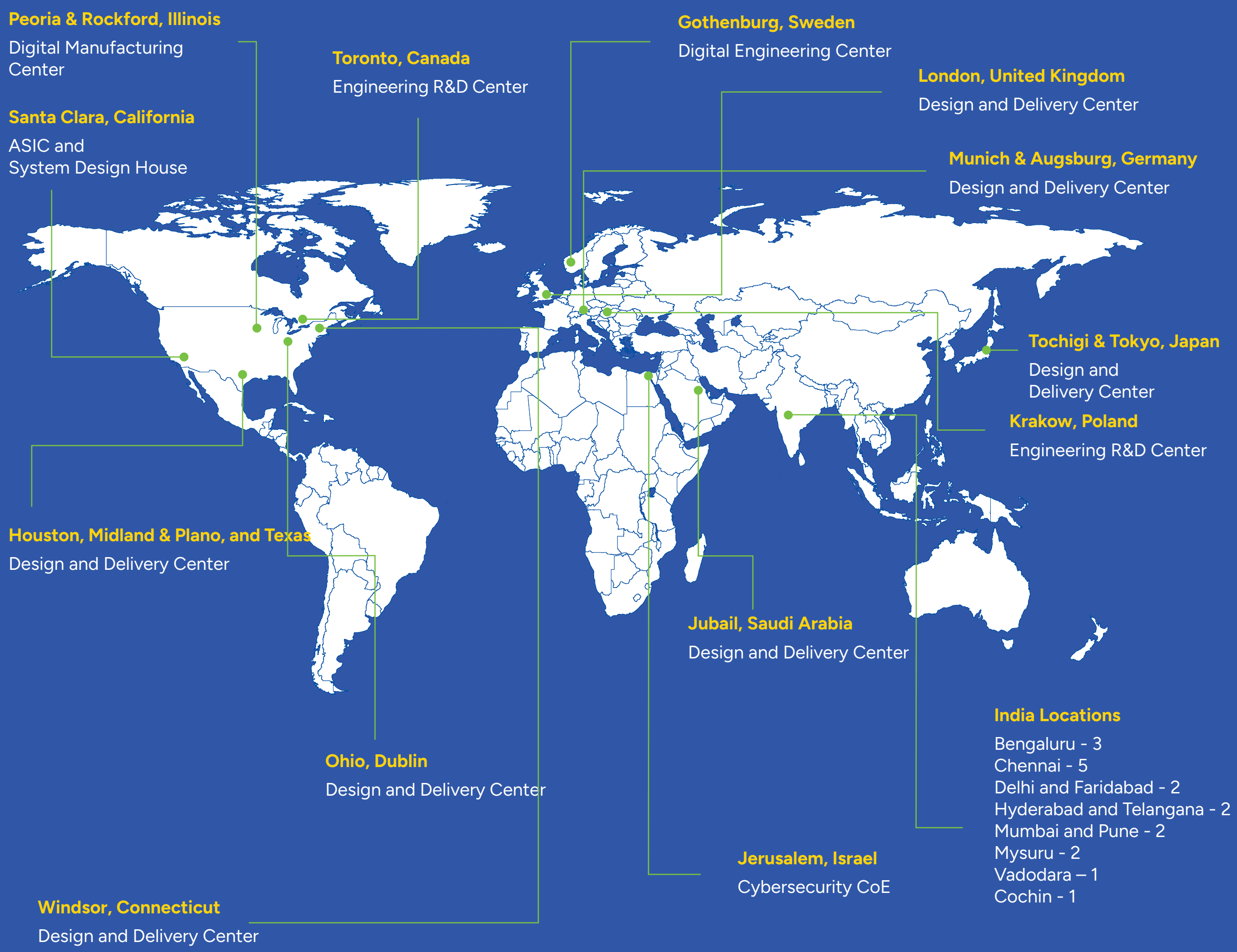
LTTS further strengthens the SDV journey through a robust ecosystem of partnerships and global delivery capabilities. By collaborating with semiconductor manufacturers, hyperscalers, and automotive consortia, it ensures access to the latest technologies, platforms, and industry standards.

Its global R&D network provides scalable support across hardware abstraction, middleware, connectivity, data analytics, and cybersecurity.

With proven frameworks for FOTA (Firmware Over-the-Air) and CYSAF (cybersecurity for ECU and component assessment), LTTS addresses both innovation and risk management.

This integrated ecosystem approach positions LTTS as a trusted partner for automakers navigating the complex shift toward software-driven mobility.

LTTS' SDV Labs and Global Delivery Model



With its specialized design centers labs, global delivery capabilities, and deep domain expertise, LTTS is playing a critical role in advancing the industry's transition to SDVs. LTTS provides the foundation for transforming conventional vehicles into intelligent, software-driven platforms.

At the core of this transformation are LTTS' state-of-the-art SDV labs and proprietary tools. The semiconductor-agnostic LTTSiDriVe platform offers preconfigured toolchains, virtualization frameworks, and ready-to-use development environments that simplify software deployment across diverse hardware ecosystems. These capabilities are further enhanced by advanced solutions such as hardware-in-the-loop testers, virtual development environments, and CI and functional safety orchestration tools like SPINDLE—all designed to accelerate development, validation, and compliance.

LTTS' delivery framework extends across global design centers and innovation hubs, enabling customers to benefit from allowing clients to access both scale and strong local engineering expertise. These centers support end-to-end SDV engineering covering embedded software, middleware, platform integration, system validation, and lifecycle management. The Company's SDV centers provide a strong environment for developing and testing software-defined vehicle architectures, with capabilities in areas such as real-time diagnostics, cybersecurity, and OTA frameworks. This integrated ecosystem of centers, delivery hubs, and domain expertise enables seamless engineering across geographies and time zones. As a result, OEMs gain the scale, flexibility, responsiveness, and accelerated pathways needed to successfully transition to next-generation SDVs.

Chapter 7

Software Development and Testing in SDVs

In This Chapter

- Shift-Left Strategy
- Model Based Approach
- Hardware-in-the-Loop and Software-in-the-Loop Testing
- Virtual Validation
- GenAI

As the industry moves toward an interoperable, software-driven future, automakers face mounting pressure to innovate in order to remain competitive. On the supply side, this competitive intensity is driving the need to accelerate time-to-market while carefully managing development costs. On the demand side, customers have already demonstrated a strong preference for upgradable and continuously evolving vehicle experiences—making software-driven adaptability a critical expectation in the era of SDVs.

To fulfil this dual mandate, OEMs have transitioned to systems where software takes the center stage in automotives. To understand how software-centric approach is supporting the need for newer development strategies, it is essential to first examine the limitations of legacy systems.

Traditional methods require validation of systems in sequential silos, i.e., a target controller for every dedicated feature is independently tested leading to slow and cumbersome rollout of updates. This approach results in slow and cumbersome update cycles, making validation resource-intensive, difficult to scale, and inefficient for system-wide integration. These challenges are further compounded by limited access to real-world data and constrained computational capabilities.

In order to keep up with the fast-evolving technological advancements, modern systems incorporate a generic platform on top of which multiple units can function. This change in system architecture now allows for increased investigations thereby enhancing the functional and safety capabilities. This integrated approach has given rise to the shift-left strategy in software testing.

What is Shift-left Strategy?

Shift-left as a strategy aims to integrate testing and quality assurance in the early stages of the product development lifecycle. The aim is to proactively address or prevent issues rather than in the later stages, allowing for iterative quality control. Aligned with Agile methodologies, this approach creates tighter feedback loops, supports progressive refinement, and significantly reduces time-to-market.

The practical implementation of Shift-left strategy is evident in LTTS' pioneering work in developing error-free infotainment systems through automated test utilities. For a leading global automotive manufacturer headquartered in Germany, our team of experts developed an adaptable utility to 1000+ screens for 20+ variants of the vehicle across multiple OS platforms. This solution transformed infotainment display testing from manual processes to automated validation, using defect-based analysis to identify inconsistencies in language, translation, and HMI elements. Even minor UI changes—often missed in manual testing—were detected automatically. This resulted in 25% improvement in defect detection ratio over previous monthly defect data and 85% defect acceptance rate by development team for further processing. Early detection of UI defects saved time and effort, demonstrating the real world effectiveness of Shift-left strategy.

Complementing the Shift-left strategy's focus on early testing integration, DevSecOps (Development, Security and Operations) is another framework that aims to integrate security earlier into all the phases of the software development lifecycle. Rather than treating security as a post-development step, DevSecOps embeds it from the outset, minimizing vulnerabilities, and reducing the risk of oversight. DevSecOps builds on the earlier DevOps framework which was based on collaboration between development and operations team to integrate testing and integration throughout the lifecycle. However, in the contemporary era, the need for continuous security is vital to safeguard the organization's assets and data. In DevSecOps, threat modeling starts early and is automated throughout the lifecycle for continuous testing. This helps organizations identify and fix issues early and monitor systems effectively, minimizing potentially costly and reputation-damaging risks. A key objective of DevSecOps is to detect vulnerabilities at the code level before integration into shared repositories. High-quality code is then committed in small, frequent increments, ensuring smoother integration and faster feedback. This model relies on strong communication, cross-functional collaboration, and robust automation to maintain speed without compromising security.

While DevSecOps addresses security integration challenges, the automotive industry faces additional complexities in validation methodologies. Given the limitations of traditional simulation techniques in accurately simulating complex real-world conditions, the abundance of real world data and evolving EE architecture has led to the increasing adoption of model-based approaches for more effective validation.

Model Based Approach Enabling Shift-Left

A model-based approach involves creating digital representations of entire systems, enabling comprehensive analysis of design, validation, and compliance requirements throughout the product lifecycle. This method supports earlier and more accurate forecasting, allowing organizations to adapt quickly while reducing costs. Compared to traditional document-based approaches, model-based design enables continuous integration, improves validation outcomes, and enhances reusability—unlocking long-term efficiencies.

To optimize performance while minimizing reliance on physical prototypes, engineers incorporate hardware-in-the-loop and software-in-the-loop in the validation process.

HIL/SIL testing in Automotives

HIL testing involves connecting the actual control hardware to the simulated system of vehicle dynamics to validate electrical and mechanical outputs. By replicating real-world driving scenarios under controlled conditions, HIL ensures hardware reliability even in demanding situations. Real-time feedback allows engineers to identify and resolve issues quickly, streamlining development processes and reducing the need for frequent physical prototypes.

SIL testing, on the other hand, substitutes physical controllers in testing with a virtual platform. Software functionality is tested across a wide range of simulated operating scenarios. In this controlled setup, identifying coding errors, algorithmic inaccuracies, compatibility issues, and resource allocation problems becomes easier with more time to rectification strategies.

Both HIL and SIL can work parallelly to identify issues earlier and enhance the robustness of the validation process while reducing overheads and time to market. By creating a cycle of continuous and rigorous checks, they mitigate the risk of emergence of risks in the later stages and delayed timelines.

Building on these methodologies, the industry is advancing toward comprehensive virtual validation frameworks. There is a growing need for interoperability across tools and open architectures to accelerate feature deployment. As a result, manufacturers are pivoting to adoption of digital twins and IoT integration across the lifecycle. These virtual validation approaches, powered by real-world data, enhance the safety, reliability, and efficiency of next-generation vehicle systems.

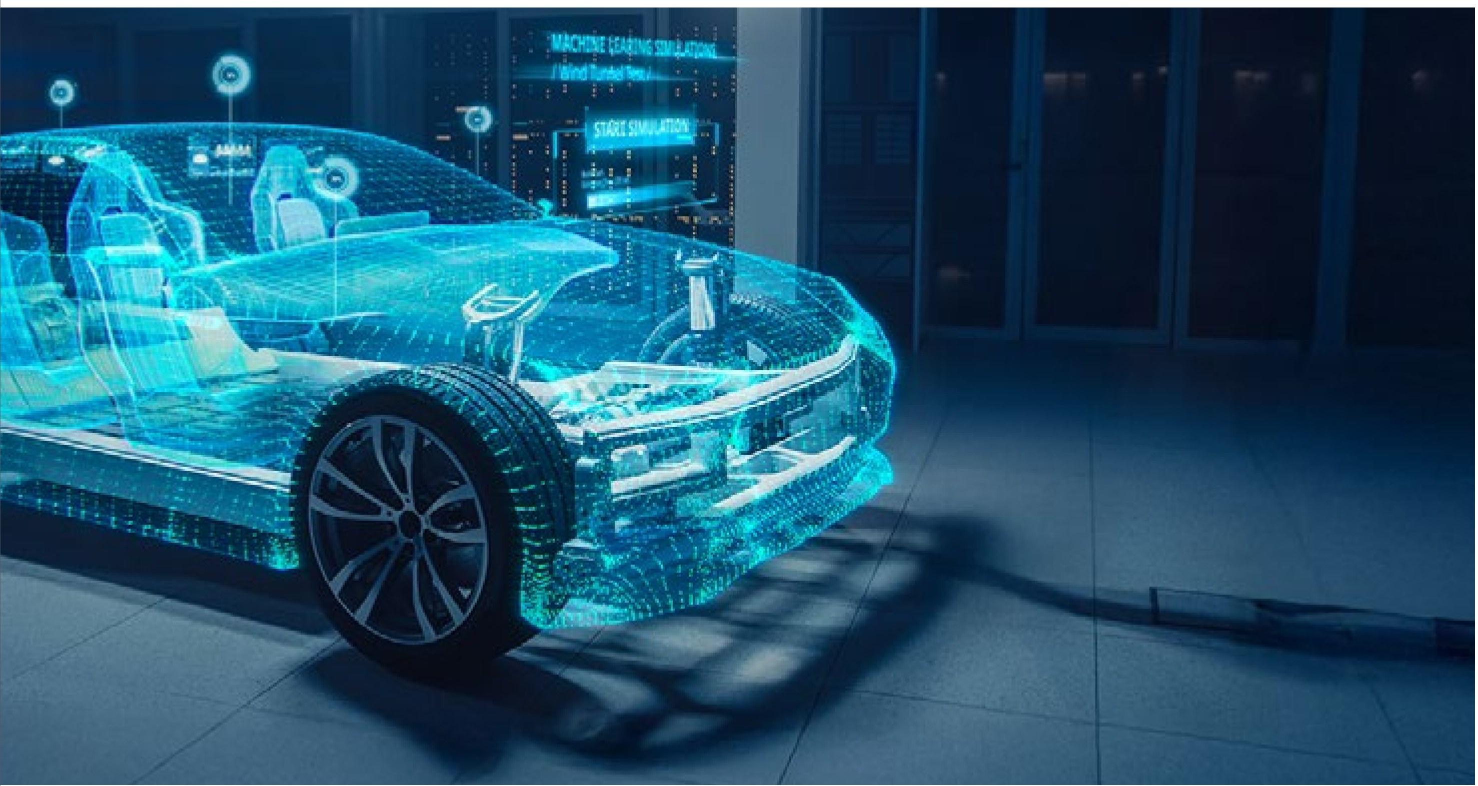
Virtual Validation Transformation in Testing

Virtual Validation uses digital models of hardware and software to emulate real-world driving conditions and system interactions. This approach enables early identification and resolution of potential issues, ensuring stable, reliable performance while minimizing the risk of costly changes later in the development lifecycle. This approach emboldens the manufacturers to take risks with new designs and materials before issuing physical prototypes, thereby encouraging innovation.

AI models and cloud-based platforms have significantly enhanced virtual validation by supporting large sets of data and facilitating real-time changes. With the help of GenAI, organizations can greatly enhance productivity while managing costs and enhancing safety features. GenAI can generate test cases to validate software against requirements, identifying potential issues facilitating automation and integration ensuring that system modules work together.

The success of virtual validation platforms like LTTS' digital twin solution has been further amplified by the integration of AI capabilities. LTTS supported automotive EU Tier 1 manufacturer in transforming the digital cockpit of contemporary automotives with its sophisticated Digital twin solution. We developed an advanced virtual replica of the real-world digital cockpit system including instrument cluster, infotainment system, navigation, connectivity, and user interface controls for extensive validation and optimization. Our digital twin supports accelerated time-to-market by reducing software development time by 70% and lowering prototype costs by 30%, by leveraging advanced virtualization and cloud- based simulation technologies.

Digital twins are advanced virtual models of real-world assets that constantly receive live data to simulate, monitor, and improve performance. LTTS is using its strength in AI and machine learning, especially through methods like physics informed neural networks and reduced order models, to make digital twin deployment faster and more cost effective. What sets LTTS apart is its deep mix of engineering knowledge and strong software expertise, allowing it to deliver a full spectrum of digital twin solutions across industries.



How Our Digital Twin Delivers Value

Our cloud-based Digital twin platform with IoT core MQTT (Message Queuing Telemetry Transport) connectivity, enables sharing of parameters between actual DCU (Domain Control Unit) and its digital replica, helping teams test, validate, and fine-tune software in a SDV environment.

Over the air device management and updates, making it easier to roll out improvements, fixes and new features without physical intervention.

Designed to work across different vehicle variants and electronic architectures, supporting reuse of software and faster rollout across platforms.

Cost savings by reducing the need for physical prototyping, thereby lowering development time and cost by shifting more testing and validation to the virtual stage.

Reduces development cost and time by limiting the need for physical prototypes and shifting more testing and validation to the virtual stage. Enables real-time monitoring of system performance, helping with early issue detection, remote diagnostics and continuous optimisation.

Improves safety and reliability by allowing software-driven features like autonomous emergency braking, lane-keeping assist, and parking assist to be tested and refined faster in a virtual environment before real-world deployment.

The Digital Twin Advantage

Vehicle Design and Development

Digital twins enable engineers to simulate, test, and optimize vehicles before building physical prototype.

Predictive Maintenance

Automotive manufacturers use digital twins to track vehicles in real time, predict maintenance needs, identify issues remotely, and plan repairs in advance, improving overall reliability.

Driver Assistance Systems

Digital twins are used to virtually test advanced driver assistance and autonomous driving systems, ensuring their performance and safety before they are implemented in real vehicles.

Vehicle Lifecycle Management

Digital twins oversee the entire vehicle lifecycle, from design and production to maintenance, improving operational efficiency and customer satisfaction.

Enhanced Customer Experience

Digital twins enable manufacturers to study data from connected vehicles, gain insights into customer preferences, and customize their products to better meet user needs.

Supply Chain Optimization

Digital twins improve collaboration across the supply chain by providing real-time visibility into production, inventory, and logistics, resulting in better inventory control and stronger supplier partnerships.

Regulatory Compliance

Digital twins help maintain regulatory compliance by keeping detailed records that make reporting, audits, and certifications easier and more accurate.

GenAI and Business Strategy

GenAI plays a significant role not just in validation but along several other facets in the development lifecycle. In the design phase, it analyzes real-time performance and safety requirements to generate actionable insights, enabling the creation of scalable platforms with improved hardware integration and reduced time-to-market. During development, GenAI enables code optimization while ensuring optimal hardware interfacing. It also improves the capabilities of ADAS by generating a wide variety of test cases in virtual simulations. In autonomous systems, this capability is extended further through continuous analysis of real-world driving data, improving safety, reliability, and system performance over time.

LTTS leverages GenAI and Large Language Models through its AiNEXUS platform to streamline test generation and maintenance. Within this framework, the AiTEST capability enables automated conversion of use cases into test cases and further into executable test scripts, supported by AI-driven workflows, log analysis, and self-healing mechanisms, helping reduce manual effort, improve coverage, and accelerate validation cycles.

In one instance, a leading European commercial vehicle manufacturer with operations in over 100 countries partnered with LTTS to standardize in-vehicle connectivity and infotainment systems across its product portfolio using a centralized platform. LTTS developed an integrated digital cockpit solution based on a next-generation modular architecture, encompassing infotainment systems, telematics control units, gateway units, platform software, and application layers. The team created a library of 12 reusable software components that could be deployed across more than 25 vehicle variants. This resulted in a 15% reduction in development time and costs, while the automation-driven, scalable, and reusable approach accelerated time-to-market by 70%. Additionally, the solution significantly reduced future validation efforts, delivering long-term efficiency gains.

Chapter 8

Cybersecurity and Compliance

In This Chapter

- Overview of the Key Regulatory Frameworks
- Automotive Software Process Improvement and Capability dEtermination (ASPICE)
- AUTOSAR
- V2X Security

Overview of the Key Regulatory Frameworks

ISO 26262:2018

The ISO 26262:2018 is a series of standards that adapts IEC 61508 series of standards for E/E safety within road vehicles. It provides a risk-based reference framework for the safety measures to be maintained across lifecycle of the automotive. Central to this framework are ASILs, which classify risk and define the required rigor of safety mechanisms.

The standard follows a V-model approach to product development, emphasizing strong alignment between development and validation phases. The interconnected "V" structure highlights traceability and consistency across ISO 26262 Parts 3 through 7, ensuring that safety is systematically addressed from concept through production.

Part 6 of ISO 26262, which focuses on software development, outlines key requirements under Clause 5.4.1. It mandates that software development processes and environments must.

"When developing the software of an item, software development processes and software development environments shall be used which:

- **a** are suitable for developing safety-related embedded software, including methods, guidelines, languages and tools;
- **b** support consistency across the sub-phases of the software development lifecycle and the respective work products; and
- **c** are compatible with the system and hardware development phases regarding required interaction and consistency of exchange of information."

Overall, the standard ensures that safety is embedded at the software architecture level and seamlessly integrated with hardware systems. Compliance requires rigorous validation, supported by test-based evidence, to confirm that embedded software meets all functional safety requirements within the target operating environment.

1. Vocabulary

2. Management of functional safety

- 2-5 Overall safety management
- 2-6 Project dependent safety management
- 2-7 Safety management regarding production, operation, service and decommissioning

3. Concept phase

- 3-5 Item definition
- 3-6 Hazard analysis and risk assessment
- 3-7 Functional safety concept

4. Product development at the system level

- 4-5 General topics for the product development at the system level
- 4-7 System and item integration and testing
- 4-6 Technical safety concept
- 4-8 Safety validation

7. Production, operation, service and decommissioning

- 7-5 Planning for production, operation, service and decommissioning
- 7-6 Production
- 7-7 Operation, service and decommissioning

12. Adaptation of ISO 26262 for motorcycles

- 12-5 General topics for adaptation for motorcycles
- 12-6 Safety culture
- 12-7 Confirmation measures
- 12-8 Hazard analysis and risk assessment
- 12-9 Vehicle integration and testing
- 12-10 Safety validation

5. Product development at the hardware level

- 5-5 General topics for the product development at the hardware level
- 5-6 Specification of the hardware safety requirments
- 5-7 Hardware Design
- 5-8 Evulation of the hardware architectural metrics
- 5-9 Evulation of safety goal violations due to random hardware faliures
- 5-10 Hardware intergation and veryfication

6. Product development at the software level

- 6-5 General topics for the product development at the software level
- 6-6 Specification of the software safety requirments
- 6-7 Hardware architectural Design
- 6-8 Software unit design and implementation
- 6-9 Software unit verification
- 6-10 Softwareintegration and verification
- 6-11 Testing of the embedded software

8. Supporting processes

- 8-5 Interfaces within distributed developments
- 8-6 Specification and management of safety requirements
- 8-7 Configuration management
- 8-8 Change management
- 8-9 Verification
- 8-10 Documentation management
- 8-11 Confidence in the use of software tools
- 8-12 Qualification of software components
- 8-13 Evaluation of hardware elements
- 8-14 Proven in use argument
- 8-15 Interfacing an application that is out of scope of ISO 26262
- 8-16 Integration of safety-related systems not developed according to ISO 26262

9. Automotive safety integrity level (ASIL)-oriented and safety-oriented analyses

- 9-5 Requirements decomposition with respect to ASIL tailoring
- 9-6 Criteria for coexistence of elements
- 9-7 Analysis of dependent failures
- 9-8 Safety analyses

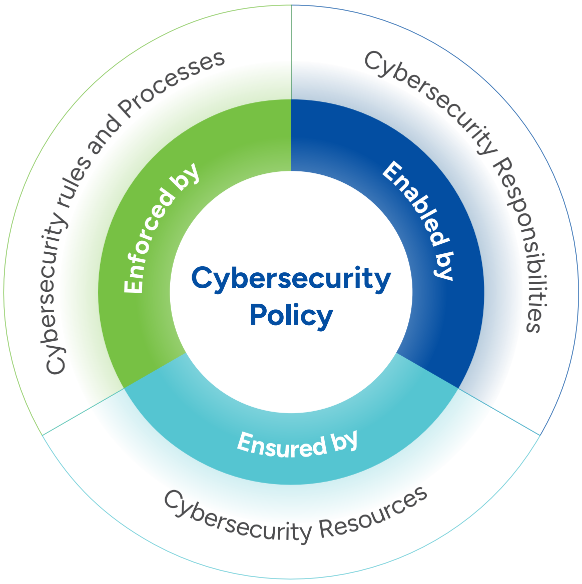
10. Guidelines on ISO 26262

11. Guidelines on application of ISO 26262 to semiconductors

ISO series of standards based on the ‘V’ model

ISO/SAE 21314:2021

ISO/SAE 21434:2021 requires organizations to establish a comprehensive cybersecurity policy that identifies road vehicle cybersecurity risks and reflects management's commitment to addressing them. It emphasizes the need to foster a strong cybersecurity culture by integrating security practices into existing processes and clearly defining, assigning, and communicating cybersecurity roles and responsibilities across the organization.



The ISO/SAE 21314 includes the performance of a Threat Analysis and Risk Assessment (TARA) which is critical in the detection of potential threats and development of mitigation measures. The two components of TARA are

Threat Analysis

This involves analyzing potential attack vectors, security vulnerabilities, and plausible attack scenarios to develop a comprehensive understanding and prepare for the eventualities of security issues. This enables organizations to anticipate security challenges and implement effective countermeasures, thereby strengthening the overall security posture.

Risk Assessment

Once threats are identified, their severity is evaluated which leads to prioritization of protective measures. The aim is to manage risk impacts to an acceptable level and warrant vehicle safety.

Benefits of TARA Approach in Cybersecurity

A sound TARA framework ensures-

- A forward-looking approach to cybersecurity by identifying threats early
- Development of customized protective measures catering to specific risks
- Continuous monitoring and upgrade of security initiatives to keep pace with the evolving cybersecurity threats
- Collaboration between stakeholders in the automotive industry by standardizing cybersecurity frameworks.

LTTS demonstrated a robust TARA-based cybersecurity framework to support source code review and security feature validation for a global Tier-1 client. As part of the client's first hardware security module (HSM) implementation, LTTS enabled end-to-end cybersecurity design, development, and validation across all variants of the collision avoidance decision module. Our optimized security features included-

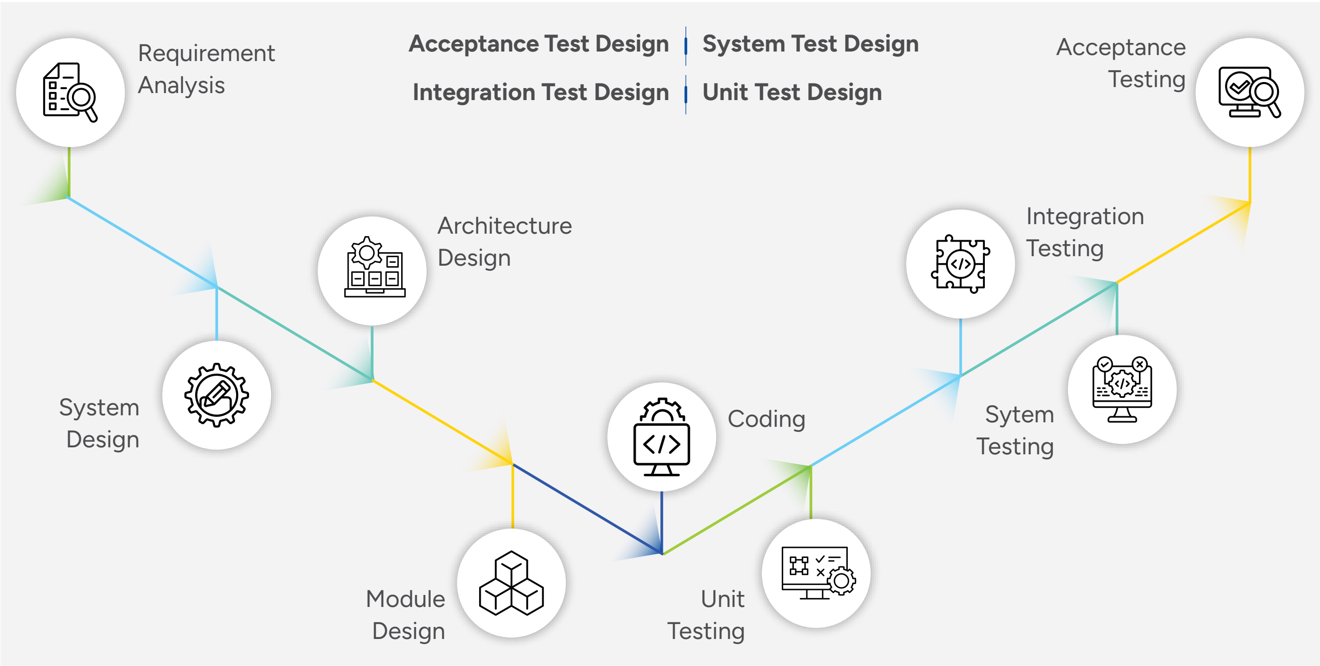
- Secure and quick boot (with less than 250 ms boot time to meet specifications)
- Secure Hardware Security Module (HSM) based root of trust
- Authenticated diagnostic access and firmware update for ECU and HSM
- Firmware Over the Air (FOTA) update and ECU ID

As a result, the client was successful in developing a secure ADAS ECU in compliance with the SAE standards.

Automotive Software Process Improvement and Capability dEtermination (ASPICE)

While ISO 26262 deals with the functional safety of automotives across the lifecycle, there are other best practices for automotive software development beyond safety concerns which are prescribed by the ASPICE standard. To ensure effective security, contemporary automakers should adhere to both ASPICE and ISO 26262 standards.

Using the V-model, let us understand the ASPICE framework-



Requirement Analysis	Module Design	System Testing
Collection and organization of the client's needs along with clear documentation so that everyone understands the goals.	Detailed designs for each module so they match the system design and preparation of unit-level plans	Testing the entire system to see if it works as expected and meets the stated requirements.
System Design	**Coding**	**Integration Testing**
Designing the entire system and planning the needed hardware and communication setup based on those needs	Writing and building the units according to the designs at the bottom point of the V.	Integration of units and testing to check if modules work together and if interfaces and architecture still function well
Architecture Design	**Acceptance Testing**	**Unit Design**
Breakdown of the system into modules and definition of how parts connect and talk to each other	Client or users perform final tests to confirm the system meets their needs in a real or close-to-real environment	Verification of each unit's code match with its design and basic standards.

UNECE WP.29

The United Nations World Forum for Harmonization of Vehicle Regulations (WP.29) was developed to govern the introduction of innovative automotive technologies and enhance global vehicle safety. Along with security capabilities, the framework also incorporates environmental considerations in vehicle approval procedures. Its mandate is supported by three multilateral agreements adopted in 1958, 1997, and 1998, which provide the legal foundation for WP.29 activities.

WP.29 aims to strengthen cybersecurity in an era defined by increasing automation, connectivity, and data exchange. It harmonizes UN regulations, rules, and guidelines related to vehicle construction, road safety, and environmental protection, while also bringing connected vehicles under a unified governance framework.

Cybersecurity Architectures

As next-generation vehicles become more connected, they are increasingly exposed to diverse attack vectors. This necessitates the evolution of cybersecurity architectures toward multi-layered, defense-in-depth models that ensure resilience across all system layers and eliminate potential vulnerabilities.

Secure Interfaces

The user interface serves as the primary point of interaction between the vehicle and its users, effectively acting as a gateway to the external environment. As the vanguard of security, these channels need to protected to safeguard user privacy and vehicle safety. Strong encryption and authentication standards are required to establish trust with the user/s and their personal data.

Secure In-Vehicle Communication

Between in-vehicle nodes in an SDV, communication must be protected from manipulation, misinterpretation and data theft. This layer of security prevents the vehicle form malfunctioning on the road and ensures data security.

Secure Gateway

To ensure protection from attacks from external interfaces such as the internet, a strong safeguard needs to be implemented between the vehicle's internal networks and external communication.

ECUs and HPC Security

The processing units of the contemporary SDVs deal with large amounts of personal data. Every data processing activity and OTA update must be secured with robust protection measures against attacks and exploitations. A compromise at this level can impact core vehicle functions and lead to costly, resource-intensive remediation for automakers. To mitigate these risks, proactive security measures based on the AUTOSAR framework are essential, enabling a resilient and trustworthy system architecture.

AUTOSAR

The AUTOSAR (Automotive Open System Architecture) is a global collaboration between leading automotive and software companies to develop a standardized software framework and open E/E architecture. The standardized API enables applications to communicate with each other across vehicle variants and manufacturers. AUTOSAR supports a modular and scalable approach to embedded software development, while its services and interfaces also address the needs of high-performance ECUs. The foundational standards ensure interoperability across platforms, including compatibility with non-AUTOSAR environments.

LTTS was onboarded by a leading European OEM to develop a customized Body Control Module (BCM) to cut down software development costs and streamline design processes along with development and testing of ASIL-A safety features and fixing of software component bugs. In modern vehicles, BCMs manage critical functions such as lighting, power windows, security, and comfort systems. Our Unified Modelling Language (UML)-based architecture design and model-based approach enabled speed and clarity with UML diagrams to map behavior and AUTOSAR deployment to facilitate the compatibility of the software with diverse hardware.

By automating tests and using standardized software building blocks, we were able to cut down the overall costs by up to half, increasing productivity due to test automation by 40%, and improving the test system throughput by 20%. We were able to enhance safety and productivity while reducing the man hours required per module from 8 to 2 hours.

Threat Modelling

Threat modeling is a critical practice that shifts risk assessment to earlier stages of the automotive lifecycle, enabling the development of robust mitigation strategies and minimizing the likelihood of costly, unforeseen remediation. Common threat modeling techniques used in the automotive domain include:

STRIDE (Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service, Elevation of Privilege)

Originally developed by Microsoft for IT security, the STRIDE framework is widely adopted in software-intensive automotive threat modeling due to its structured approach. It categorizes threats into six classes—spoofing, tampering, repudiation, information disclosure, denial of service, and elevation of privilege—enabling systematic identification and early-stage mitigation of potential risks.

HEAVENS (Hardware Security Evaluation and Risk Assessment)

Developed by the automaker Volvo in collaboration with other partners, the HEAVENS and its successor HEAVENS 2.0 frameworks align risk assessment with ISO 26262 and ISO/SAE 21314 using factors such as attack feasibility and impact. The functional safety assessments are tailored to the automotive domain while using TARA analysis in many cases.

PASTA (Process for Attack Simulation and Threat Analysis)

A risk-based approach that simulates potential attack scenarios to evaluate their impact. By aligning identified risks with business objectives, it enables more informed and streamlined decision-making on mitigation strategies.

V2X Security

V2X technology enables seamless communication between vehicles, infrastructure, and connected devices, facilitating the exchange of safety alerts, weather updates, traffic conditions, and route information over wireless and cellular networks. This connectivity underpins advanced use cases such as autonomous driving, platooning, and remote vehicle operation, while also enabling services like in-vehicle payments, smart parking, and automated charging through integrated infrastructure systems.

Given the real-time nature of these interactions, low latency and continuous security updates are critical to safeguarding connected vehicles in motion. Secure V2X communication ensures that data exchanged across networks remains trustworthy and protected from tampering or unauthorized access. At a broader level, traffic management systems can leverage this shared data to optimize signal control, manage traffic flow, and reduce congestion, thereby improving overall efficiency.

Let us dive into the features which play a key role in an evolving Internet of Vehicle environment-

Vehicular Public Key Infrastructure (VPKI) for Authentication

A Public Key Infrastructure (PKI) is a combination of hardware, software, policies, procedures, and people used to create, manage, distribute, store, and revoke digital certificates. It is the widely accepted framework in V2X communication which uses public-key cryptography to bind public keys to users through digital certificates. VPKI plays a vital role in establishing trust and identity in vehicle to everything communications by preventing malicious interceptions, legitimizing authentication and preserving user privacy.

Data Storage and Encryption

The widespread adoption of V2X will result in connected vehicles and infrastructure generating and transmitting large volumes of data, some of which may be highly sensitive. If compromised, such data can lead to serious privacy and security risks. Therefore, robust mechanisms must be implemented to ensure the secure and confidential collection, transmission, and storage of this information.

Strong encryption techniques play a critical role in protecting data from leakage and unauthorized access. At the same time, these mechanisms must be optimized to avoid excessive computational overhead, ensuring they meet the real-time, low-latency communication requirements essential for effective V2X operation.

Secure Cloud Infrastructure

The vast volumes of data generated by connected infrastructure are often stored on cloud platforms for monitoring and large-scale computation. However, a failure or compromise of cloud infrastructure can impact the entire network, making cloud security a critical foundation for connected systems.

Common threats to cloud environments include malicious service impersonation, data leakage during transmission, data loss, phishing attacks, botnets, and vulnerabilities within the platform itself. To address these risks, robust data management and security frameworks are essential. One such approach is the implementation of a Product Data Management (PDM) system, which provides a centralized platform to manage product and process-related data, including CAD models, part information, manufacturing instructions, and documentation.

In one instance, a global automotive OEM sought to enable real-time data collection and standardize data management across its operations. LTTS was engaged to implement PDM support across eight locations and 20 business units. The team defined a comprehensive PDM roadmap and successfully digitized and migrated over 900,000 records, including CAD data, to Teamcenter, establishing a single source of truth.

The implementation included 24/5 server monitoring and technical support for over 1,500 users across multiple geographies, enabling real-time data sharing and collaboration. As a result, the standardized PDM system delivered a 10% reduction in costs through design automation and reduced manual effort for content management by 50%. Additionally, data accessibility improved significantly, with access times reduced from two days to approximately 30 minutes.

In-Vehicle Security

A Controller Area Network (CAN) is a communication protocol that enables various vehicle components to exchange data efficiently. Operating on a broadcast-based architecture, it allows individual ECUs to access and interpret messages shared across the network. Since CAN supports critical vehicle functions, securing it against external threats is essential to prevent potential system failures and safety risks.

LTTS strengthens vehicle security through advanced penetration testing of next-generation connected systems, identifying and mitigating vulnerabilities before deployment. For a leading European OEM, LTTS conducted comprehensive black-box testing across key components, including in-vehicle infotainment, key fob systems, telematics, connected car platforms, and mobile applications. The assessment also involved source code reviews and the development of customized security test cases and scripts to evaluate network interfaces.

By simulating real-world attack scenarios on fully assembled vehicles, LTTS identified 48 vulnerabilities, including one critical and 16 high-severity issues, prior to launch. This proactive approach enabled timely and cost-effective remediation, significantly enhancing the vehicle's overall security posture.

Network Security

Connectivity to the Internet of Vehicles (IoV) increases exposure to potential attacks, including threats targeting the CAN bus and other communication interfaces. As vehicle networks become more complex and integrate multiple platforms, the risk of large-scale attacks—such as malware intrusions and data manipulation—intensifies. To address this evolving threat landscape, network security awareness and protection mechanisms must continuously advance. Security frameworks need to scale and adapt to safeguard multiple nodes and interconnected networks, ensuring robust protection across the expanding IoV ecosystem.

Chapter 9

End-User Features and Functional Use Cases

In This Chapter

- Personalization and Remote Vonfiguration
- Features-as-a-Service
- Energy Management and Real-Time Monitoring
- Fleet Management
- Predictive Maintenance and Diagnostics
- Mobile and Ecosystem Integration (Smartphones, Home IoT)

While the adoption of SDVs has exponentially improved several existing features and added new use cases, this chapter explores some of the most notable functional applications.

Designing a Personalized Drive

A vehicle is often a deliberate expression of identity and aspiration, with careful consideration given to every detail—from the model and paint to the interiors and finishes. With the evolution of digital cockpits, this sense of personalization has expanded beyond physical elements to the vehicle's digital experience. Users can now customize infotainment interfaces, voice assistants, and even aspects of the in-cabin environment to suit their preferences. The integration of Generative AI further enhances this experience, making digital cockpits more intuitive, immersive, and engaging.

LTTS has demonstrated strong capabilities in enabling advanced personalization features across in-vehicle infotainment systems, enhancing both safety and the overall driving experience. Its next-generation digital cockpit solutions support customized user experiences through CI/CD integration, digital clusters, V2X connectivity, and seamless system interoperability. For a leading OEM, we developed and implemented virtualization of android components on a Linux based infotainment platform. Our end-to-end software development and validation support in delivery of an enhanced platform enabled greater flexibility for the customer with customization and 3rd party application support along with a user-friendly interface.

Remote Configuration

Unlike conventional software architectures, SDVs centralize computing platforms and modular architectures. This facilitates OTA updates, allowing automakers to remotely deliver new features, performance enhancements, and safety improvements through software. Similar to smartphones, SDVs have now evolved to extend the scope of upgradability beyond the sales of the vehicle. A simple OTA software update can enhance navigation, security, energy efficiency, or even the driving capabilities, eliminating the need for frequent visits to service centers. These capabilities enable drivers to subscribe to on-demand features further personalizing their vehicles.

By shifting value from hardware to updatable software, SDVs remain relevant for longer through continuous enhancements. For a leading European automotive manufacturer, LTTS helped to develop remote ECU software update framework for charging inlets across Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). Our flash concept architecture enabled software update of non-AUTOSAR ECU.

Feature-as-a-Service

The paradigm shift to upgradable software incentivizes OEMs to switch to Feature-as-a-Service. The FAAS strategy monetizes comfort and performance features unlocking a new revenue stream for the OEMs. Through subscription-based upgrades, OEMs can generate recurring income while also improving customer loyalty and extending the functional lifespan of FaaS-enabled vehicles.

A common example is heated seating in newer vehicle models, which can be activated on demand through a subscription, allowing users to access features only when needed. Similar models are emerging for performance enhancements, such as improved acceleration capabilities, as well as value-added entertainment features. In parallel, real-world data collected from connected vehicles enables manufacturers to personalize offerings and monitor system performance in real time, further enhancing user experience and operational efficiency.

Energy Management and Real-Time Monitoring

With real-time data, software algorithms are enabling users to enhance fuel efficiency and improve power output of their vehicles. These algorithms can analyze real-time driving conditions and optimize fuel consumption, thereby reducing costs and improving the longevity of the engines.

LTTS' iDrive LTTSiDriVe tool exemplifies real-time vehicle monitoring, leveraging real-time diagnostics and performance monitoring to facilitate proactive maintenance and enhance vehicle performance. This innovative approach finds diverse applications including facilitating software updates, integrating advanced AI-driven features, and managing fuel and battery systems of the vehicle.

To deliver a sustainable solution, we helped a leading automotive OEM leverage by improving fuel management and maintaining reduced level of emissions. By leveraging advanced control algorithms and real time signal processing, we were able to optimize fuel quantity and reduce fuel injection timing by 20%. Additionally, we created a library of Failure Mode and Effects Analysis/ Failure Modes, Effects and Diagnostics Analysis (FMEA/ FMEDA) which reduced time required for potential future development efforts by 50%.

In another instance, we streamlined the engine control system for a leading OEM to optimize performance and engine efficiency while meeting global legislative requirements and reducing carbon emissions. By supporting the development of Diesel particulate Filters (DPF) after treatment control strategies and tailpipe emission management system.

Fleet Management

Automotive fleet management software centralizes operations for fleets by using GPS and telematics to track vehicle location, monitor driver behavior, manage maintenance schedules, and control fuel consumption in real-time.

LTTS' telematics application on cloud provides comprehensive fleet management and predictive analysis solution for automotives, enabling remote monitoring and control of vehicles. Our next generation telemetry system facilitated cost savings for a leading US based automotive OEM by optimizing fleet operation after application deployment. Our flexible engagement model and cross platform compatibility ensured ease of deployment for the client.

Predictive and Preventive Maintenance

The shift-left mentality in fault repair and prevention of in-field failures is supporting a paradigm shift from descriptive and diagnostic maintenance towards predictive and preventive maintenance. While OTA fixes has considerably improved maintenance, predictive repair advances it further enabling just-in-time repair call-ins or planning ahead for component replacements or recalls. This reduces the operational costs and time involved in analyzing and fixing the issue.

PPM can also mitigate the risk of minor issues developing into in-field failures leading to costly recalls. Traditional diagnostic approaches typically identify and address problems only after they become visible, which can result in significant downstream impact. In contrast, PPM continuously analyzes usage and performance data to detect early warning signals, enabling timely alerts and allowing users to take preventive action before failures occur.

Troubleshooting

In order to understand how SDVs improve the diagnostic processes, let us first understand how the conventional diagnostic system functions. Conventionally, Diagnostic Trouble Codes (DTCs) are logged when fault is detected by the diagnostic software in the ECU of the car. The logs are then analyzed to identify the issue, making the solution costly and time-consuming.

SDV technologies improve the current diagnostic process by

- Enhanced metrics for analysis with data points which are more connected to the performance of the device
- More data points allowing for broader coverage
- Continuous data monitoring to identify potential points of failure
- Analysis of big data with cloud integration to identify discrepancies in performance and safety

Ecosystem Integration

We have seen how software-defined vehicles redefine the automobile as an adaptive personal ecosystem, shifting it from static configuration to continuously calibrated experiences that, in real time, respond to every driver, journey, and context through modular, updatable software services. Biometric feedback, learned behaviors, and health signals can be used to fine-tune seating, climate, lighting and drive modes within a digital cockpit that maximizes comfort and safety on the fly. Current multi-profile capabilities from major OEMs are heading in this direction, establishing the foundation for predictive, cloud-synchronized profiles across vehicles and sessions. As the paradigm matures, personalization will evolve to include emotion-aware UX, contextually relevant media and health-integrated environments wherein mood, fatigue or health alerts determine vehicle behavior and interface design in the moment. We shall dive into detail on the evolving prospects of a mature SDV later in the book.

In the current landscape, service-oriented architectures are enabling the transformation by encapsulating features as independent, modular services that may be developed, deployed, and revised separately—supporting OTA delivery, cross-domain personalization and seamless integration with third-party systems. The same architectural abstraction allows OEMs to consolidate overlapping functions distributed across ECUs into unified software services spanning AD/ADAS, digital cockpit, and body domains—improving reuse, reducing complexity, and accelerating feature deployment. OTA pipelines ensure these services remain continuously updated and aligned with evolving user expectations and ecosystem partnerships.

SDVs are becoming complete with end-to-end ecosystems, over-the-air updates, and seamless integration within the digital life of users. This convergence emphasizes the significance of automobiles within the expansive IoT ecosystem, enabling communication with smart infrastructure, other connected devices and cloud services to forge cohesive, intelligent experiences that transcend mere transportation.

Chapter 10

SDV-EV Convergence

In This Chapter

- An Electrically Driven Future
- The Role of 5G
- AI as a Catalyst

People's driving experience today is being reshaped by the convergence of Software-Defined Vehicles (SDVs) and the accelerating shift toward electric mobility. With climate consciousness increasingly influencing decision-making across governments and corporations, electric vehicles (EVs) have emerged as a strong alternative to traditional internal combustion engine (ICE) vehicles. Beyond their environmental benefits, EVs are also becoming a more cost-effective option for consumers.

While upfront acquisition costs for EVs may still be higher, the Total Cost of Ownership (TCO)—factoring in lower energy costs compared to petrol, diesel, or gasoline—is already at parity with, or in some cases lower than, that of ICE vehicles. As battery technologies continue to mature and scale, ongoing improvements in energy density, charging efficiency, and manufacturing economics are expected to further reduce costs. This trajectory positions EVs as an increasingly compelling and economically rational choice for the future of mobility.

> The imperative to act is clear, as policies across the world are being redefined to accelerate SDV-EV integration.

Another challenge faced by EVs of today is range anxiety. Users are accustomed to the flexibility of driving without having to plan around refueling stops, whereas contemporary EVs typically offer a range of around 200–300 miles (300–500 km) on a single charge. This makes it impractical for long journeys and commercial transport which would need multiple charging stops and planning ahead to locate the next charging station owing to limited charging infrastructure. Charging times also vary significantly depending on the available infrastructure, adding another constraint for users accustomed to the speed of conventional refueling. On most days however, the current range is more than capable to handle the journey on a single charge allowing users to increasingly gravitate toward the technology. Automakers are responding with expanded model options and continuous improvements in battery performance. The Battery as a Service (BaaS) model introduced by some automakers further provides flexibility in EV transition by lowering the upfront cost. Charging technologies are also advancing steadily, while governments and industry players are investing heavily in expanding charging infrastructure. As these barriers continue to diminish, the integration of smart EVs into a broader vehicle-to-everything ecosystem is expected to accelerate significantly.

5G in SDV

The 5G revolution in SDVs unlocks the next gear in propulsion toward a reliable, connected network of vehicle to everything. These next-gen LTE networks possess higher throughput and low latency capabilities, facilitating real-time communication between V2X to improve road safety and minimize traffic congestions. In this connected future, everyday inefficiencies—such as driving multiple blocks to find parking—can be significantly reduced through intelligent location and navigation services. Enhanced connectivity also enables precise vehicle tracking, including locating a vehicle within large or crowded parking areas. Beyond navigation, 5G adoption strengthens predictive maintenance and optimizes energy consumption through real-time data analytics. Infotainment systems will also capitalize on enhanced connectivity to deliver high fidelity content and data-intensive applications. As 5G becomes widely standardized across mobility and digital ecosystems, it will unify communication between smartphones, vehicles, and connected infrastructure, creating a more seamless and interoperable IoT environment for users.

AI-Driven Acceleration

We have already seen the role of GenAI in transforming today's SDVs to 'vehicles of tomorrow,' but in terms of its full potential, we may have only begun to scratch the surface. In real-world conditions, AI needs to replicate and improve upon human ability to anticipate, react, and make decisions instantly on the basis of a large string of unpredictable inputs. With software embedded in nearly every function of contemporary vehicles, AI integration is the injection of fuel to fire needed to catapult automotives into smart vehicles. Automakers are integrating AI in ADAS, predictive maintenance, and accelerating the development of safer and more reliable autonomous vehicles.

As dependency on AI in automotive systems grows, safety considerations become critical. It is essential to ensure that AI systems make correct decisions across diverse real-world scenarios, particularly at high speeds and under edge conditions. Current-generation AI still faces challenges such as hallucinations and limitations arising from siloed data. Additionally, the introduction of moral decision-making in extreme driving scenarios raises important questions about accountability and reliability. Like any transformative technology, however, continued maturation and normalization of AI will drive meaningful progress toward robust real-world deployment in transportation.

True cultural change in our era will ultimately be defined by the acceptance of these technologies that enable an intelligent, connected, and clean future. Until then, Enzo Ferrari's words—"What's behind you doesn't matter" perfectly encapsulate the list of innovation at the cusp of real-world adoption to make going to someplace just a little bit better.

Chapter 11

The Road Ahead

In This Chapter

- Trends in SDV Evolution
- SDVs as Foundations for Future Mobility
- LTTS' SDV Roadmap and Ecosystem Collaborations

Trends in SDV Evolution

The coming decade will see SDVs evolve from experimental platforms to the central paradigm of automotive design. With modular architectures becoming ubiquitous in mobility, independent upgrades of software and hardware more readily changeable, making vehicles more adaptable to rapid technological change. AI will become integral, enabling predictive maintenance, real-time decision-making and advanced driver assistance and autonomous drive that continuously improves through machine learning. At the same time, high-bandwidth connectivity powered by 5G and eventually 6G will integrate vehicles into broader mobility and smart-city networks. This convergence of modular platforms, AI, and always-on connectivity will transform vehicles into continuously upgradable digital assets, rather than static machines.

The long-term impact of this shift will redefine the very concept of mobility. SDVs will not only raise safety standards through autonomous features and advanced sensing but also enhance sustainability by optimizing energy consumption and enabling large-scale electrification. Cars will evolve into personalized digital environments, offering tailored services and immersive experiences that adapt to the preferences of individual users. More broadly, SDVs will underpin the growth of shared, connected and sustainable transport ecosystems, making vehicles an integral part of digital lifestyles and green urban infrastructures. In this sense, the SDV revolution will extend beyond the automotive industry, shaping the future of how societies move, interact, and consume mobility services.

SDVs as Foundation for Future Mobility

SDVs are fast becoming the structural backbone of modern mobility. They deliver adaptability that supports seamless digital integration, personalized in-vehicle experiences, and advanced safety in passenger cars. In commercial fleets, SDVs enable predictive diagnostics, intelligent telematics, and operational efficiencies that reduce downtime and cost. Even in rugged off-highway domains such as mining and construction, their software-first architecture powers autonomous functions, optimized energy management, and enhanced safety systems. Across these diverse applications, the software-defined approach has emerged as the unifying architecture capable of meeting evolving regulatory demands, environmental goals, and user expectations. This transition marks a clear shift from hardware-centric design to software-driven capability, laying the foundation for a future where vehicles are adaptable, intelligent, and resilient.

Looking ahead, SDVs will evolve into dynamic, cloud-connected nodes within expansive intelligent transport networks. With deeper integration of cloud and edge computing, these vehicles will participate in real-time data exchanges, supporting V2X communication, traffic coordination, and shared mobility services, while critical decisions such as braking or collision avoidance will continue to be executed locally with minimal latency. This hybrid edge-cloud model will define the next generation of mobility by combining safety and responsiveness with scalability and continuous learning. In essence, SDVs will not only transport passengers and goods but will also function as digital infrastructure, enabling smarter, safer, and more sustainable transport ecosystems.

LTTS' SDV Roadmap and Ecosystem Collaborations

LTTS' roadmap for SDV is set to become a catalyst for reimagining automotive engineering. The Company's approach integrates modular platforms, service-oriented architectures, and virtualized development environments that separate software from hardware dependencies. By embedding AI into core functions, SDVs will gain predictive and adaptive capabilities, from real-time diagnostics to enhanced driver assistance systems that learn continuously. High-speed connectivity through 5G and eventually 6G will make these vehicles nodes in a larger digital ecosystem, ensuring that updates, security patches, and new features can be deployed seamlessly. LTTS' collaborations across semiconductor firms, industry consortium, cloud providers, and automotive OEMs will further strengthen this roadmap, building interoperable platforms that accelerate industry-wide adoption of next-generation SDVs.

Looking ahead, the impact of these initiatives will extend beyond technological advancement into the transformation of mobility itself. Vehicles will evolve from mere modes of transport into intelligent, personalized digital companions integrated within urban and social ecosystems. Safety will be elevated through autonomous functions powered by AI and edge computing, while sustainability will benefit from over-the-air optimization of energy consumption, fleet electrification, and reduced lifecycle emissions. For users, the driving and riding experience will evolve into a tailored environment shaped by adaptive interfaces, immersive connectivity, and seamless integration with smart city infrastructure. By aligning its roadmap with global collaborations, LTTS positions SDVs as the foundation of a safer, greener and more connected future of mobility.

Glossary

Abbreviations

ECU - Electronic Control Unit

HPCUs - High-Performance Computing Units

SDVs - Software-Defined Vehicles

OTA - over-the-air

SOA - Service-Oriented Architecture

LTTS - L&T Technology Services

FaaS -Features-as-a-Service

EVs - Electric Vehicles

ADAS - Advanced Driver Assistance Systems

AI - Artificial Intelligence

ML- Machine Learning

GenAI- Generative AI

MEC - Multi-Access Edge Compute

SoCs - Systems-on-Chips

HAL - Hardware Abstraction Layer

OEMs - Original Equipment Manufacturers

OS - Operating System

APIs - Application Programming Interfaces

E/E - Electrical/Electronic

CAN - Controller Area Network

Flexible Data-Rate - CAN-FD

TSN - Time-Sensitive Networking

SOME/IP - Scalable Service-Oriented Middleware over IP

SiL - Software-in-the-Loop

HiL- Hardware-in-the-Loop

DevSecOps - Development, Security and Operations

MQTT - Message Queuing Telemetry Transport

DCU - Domain Control Unit

LLMs - Large Language Models

TARA - Threat Analysis and Risk Assessment

HSM - Hardware Security Module

FOTA - Firmware Over the Air

ASPICE - Automotive Software Process Improvement and Capability dEtermination

AUTOSAR - Automotive Open System Architecture

BCM - Body Control Module

UML - Unified Modelling Language

STRIDE - Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service, Elevation of Privilege

HEAVENS - Hardware Security Evaluation and Risk Assessment

PASTA -S for Attack Simulation and Threat Analysis

VPKI - Vehicular Public Key Infrastructure

PKI - Public Key Infrastructure

PDM - Product Data Management

BEVs - Battery Electric Vehicles

PHEVs - Plug-in Hybrid Electric Vehicles

FMEA/FMEDA - Failure Mode and Effects Analysis/ Failure Modes, Effects and Diagnostics Analysis

DPF - Diesel particulate Filters

DTCs - Diagnostic Trouble Codes

PDLC - Product Development Lifecycle

Notes

Notes

L&T Technology Services

Purposeful.
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