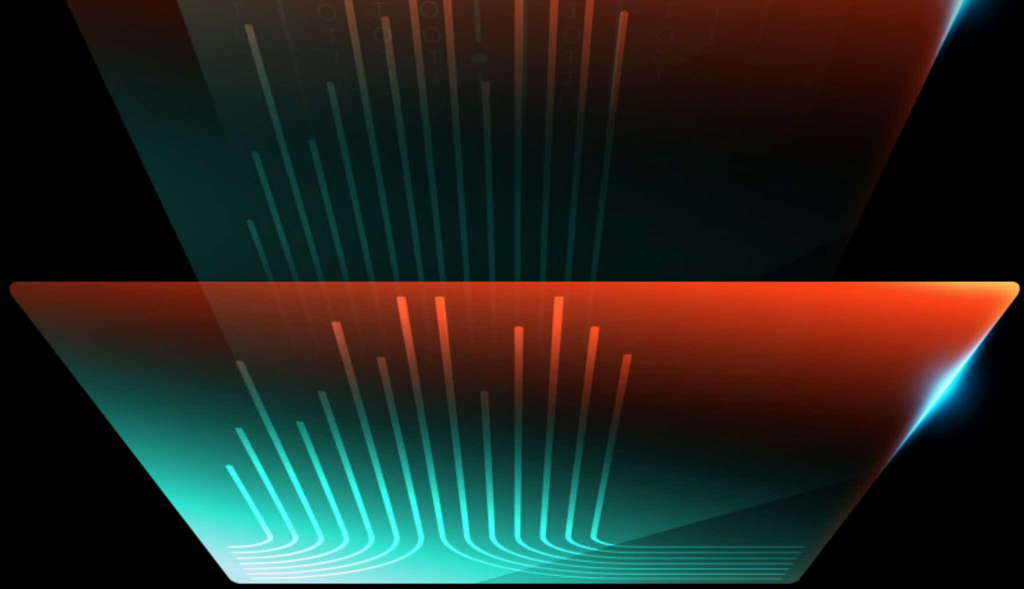

APTIV

CES 2025: What You Need to Know

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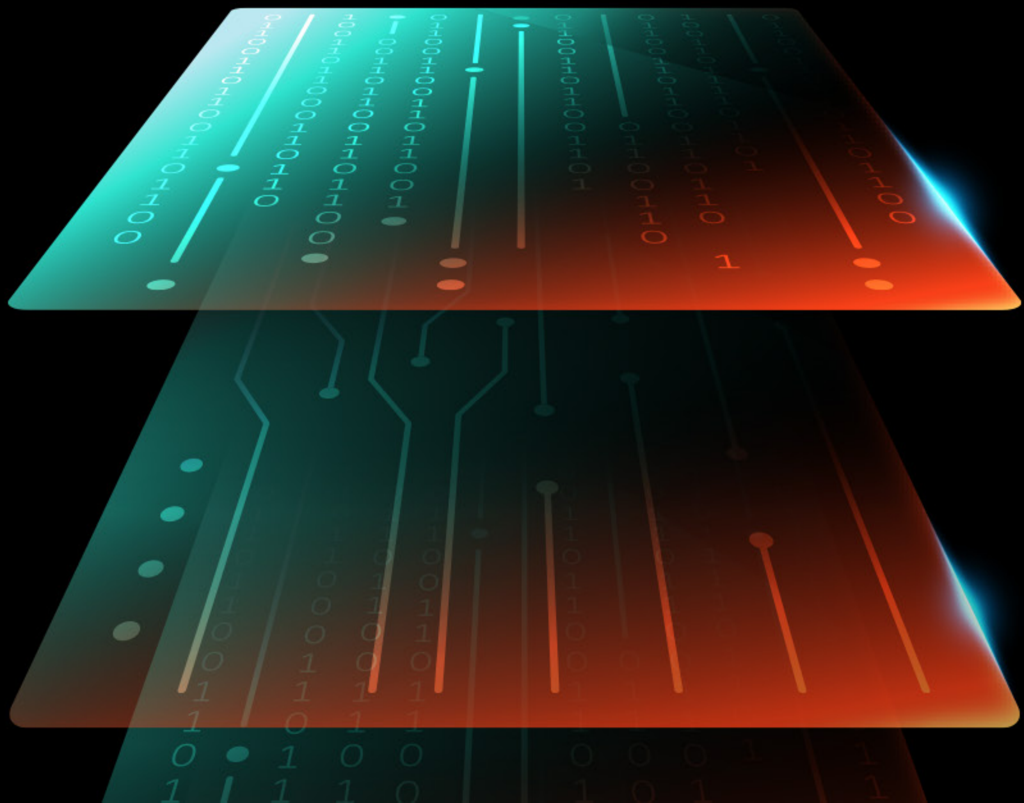
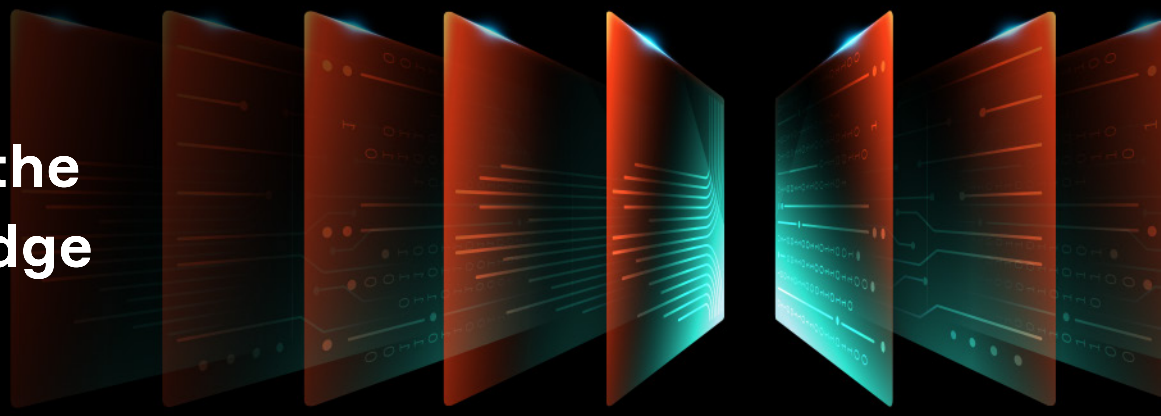


Welcome to the Intelligent Edge



There's a reason Aptiv hosts our guests across the street from the Las Vegas Convention Center, away from the noise of the vehicle technology booths of the West Hall. It's because we see the bigger picture — the places mobility intersects with the world around it — and want to make sure we have the space, the perspective and the distance from the crowd to have meaningful conversations about that picture as we collaborate with our customers and partners.

Aptiv's pavilion sits at the cutting edge of the Consumer Electronics Show — both physically and metaphorically — and it is at the edge where magic happens.

The intelligent edge is where the physical world meets the digital one. It's where connectivity enables user experiences that evolve over time and can be deeply personalized down to an individual level. It's where insights are transferred to the places where they are needed most. And it's where automated systems are able to apply machine learning technologies to elevate safety, comfort and convenience.

When you visit Aptiv's pavilion at CES 2025, you'll get a firsthand look at the possibilities of the intelligent edge fully integrated onto production vehicles, and therefore you'll also be able to see them in live driving demos under real conditions on the streets of Las Vegas.

But before you go, use this backgrounder to take a look at some of the recent technology advancements that got us to this point.

Inside the Edge

"Software-defined vehicle" was the buzzword on everyone's lips last year, but Aptiv has been laying the foundation for SDVs for years. We know you need the software architecture, the hardware architecture and the edge-to-cloud tools to build SDVs — and that the real challenge going forward will be to translate SDV capabilities into features that benefit consumers over time.

Those features start with a personalized journey, leveraging systems that adapt and learn throughout their lifecycles. We show what that means through the examples of an integrated cockpit controller and premium audio software, but we also explain why using software containers and a digital feedback loop are critical for keeping that journey going.

Safety features have just as much potential to evolve, across all vehicle levels, in a democratized advanced safety approach. Aptiv's Gen 6 ADAS platform enables that evolution, building on our Smart Vehicle Architecture™ foundation. A great example is the ML Behavior Planner, which uses machine learning to provide humanlike driving in a Level 2+ system. You'll get to experience that and our updated automated parking technologies in our CES 2025 driving demos.

All of these advances require optimized power distribution, regardless of powertrain. Aptiv has many innovations to show you across cables, busbars and connectors, but you can get a sneak peek at our unique approach to backup power, as well as modular connectors that enable automation.

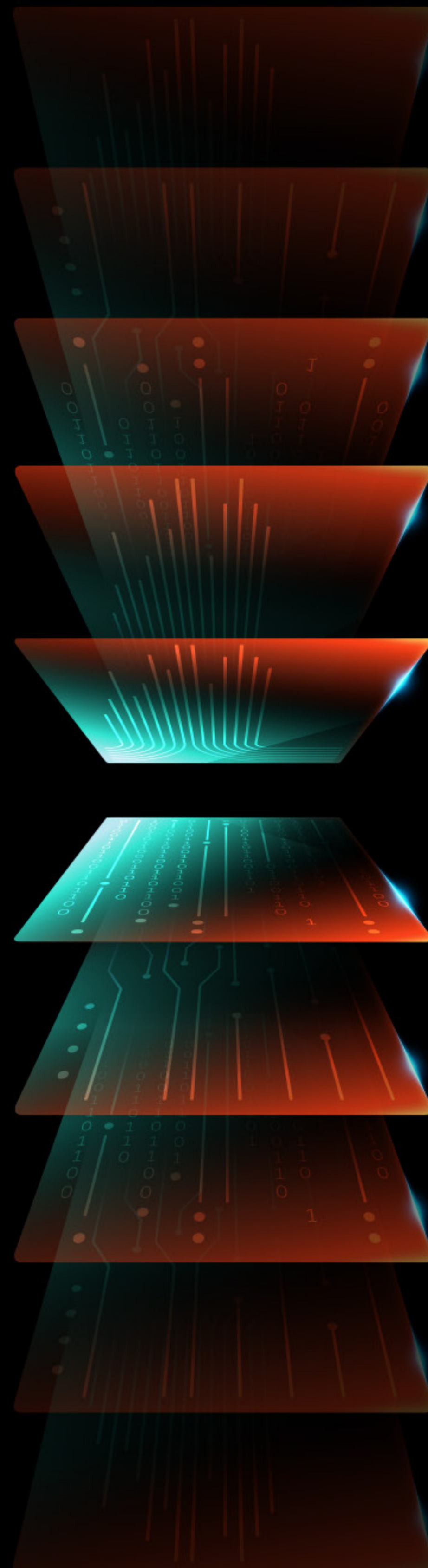
The tools that enable the development and deployment of software and AI/ML are here today. Aptiv is using Wind River Studio to achieve faster development and integration with existing toolchains — and you can, too. Wind River's and Aptiv's cloud-native technologies support the middleware and the operating systems necessary for the intelligent edge.

The last chapter of this year's edition of this guide again reflects Aptiv's approach to sustainability, with some thoughts on the future — as well as a specific example of how we can help you achieve design and manufacturing efficiencies in compute.

We're excited to discuss these topics and more with you at CES and beyond. With no shortage of tough challenges to address, we look forward to deepening our collaboration as we build a software-defined, cloud-native and electrified future.

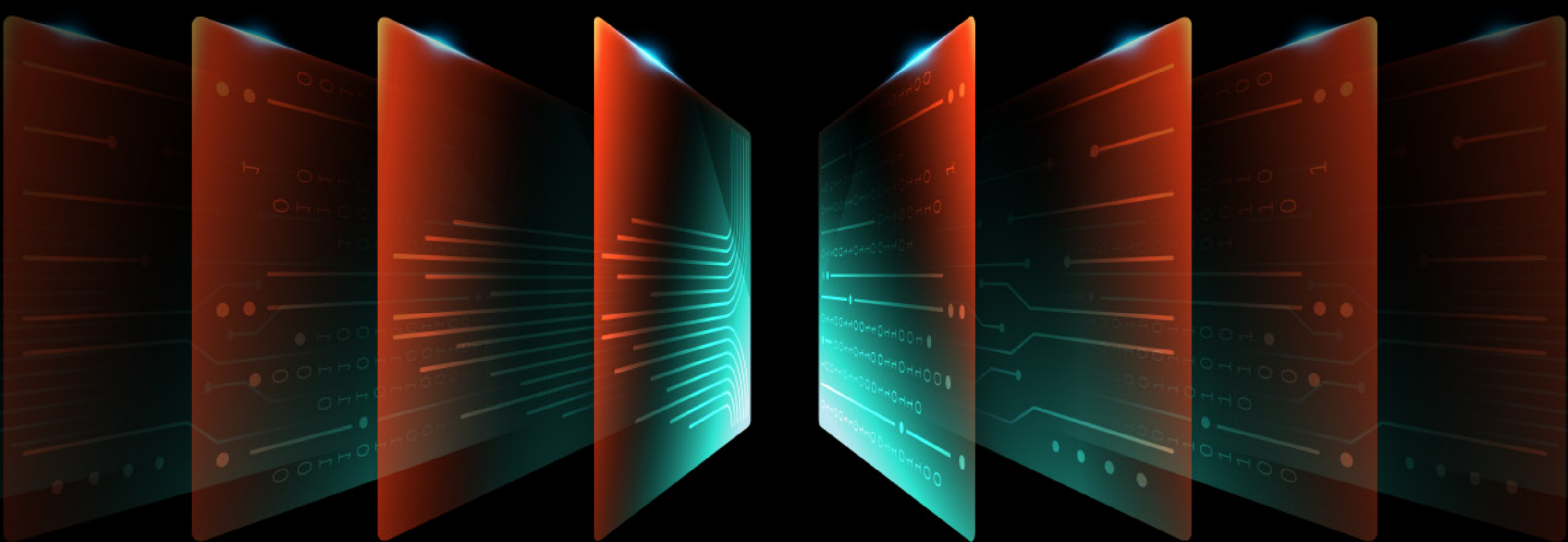
Jeff Caruso
Vice President, Thought Leadership

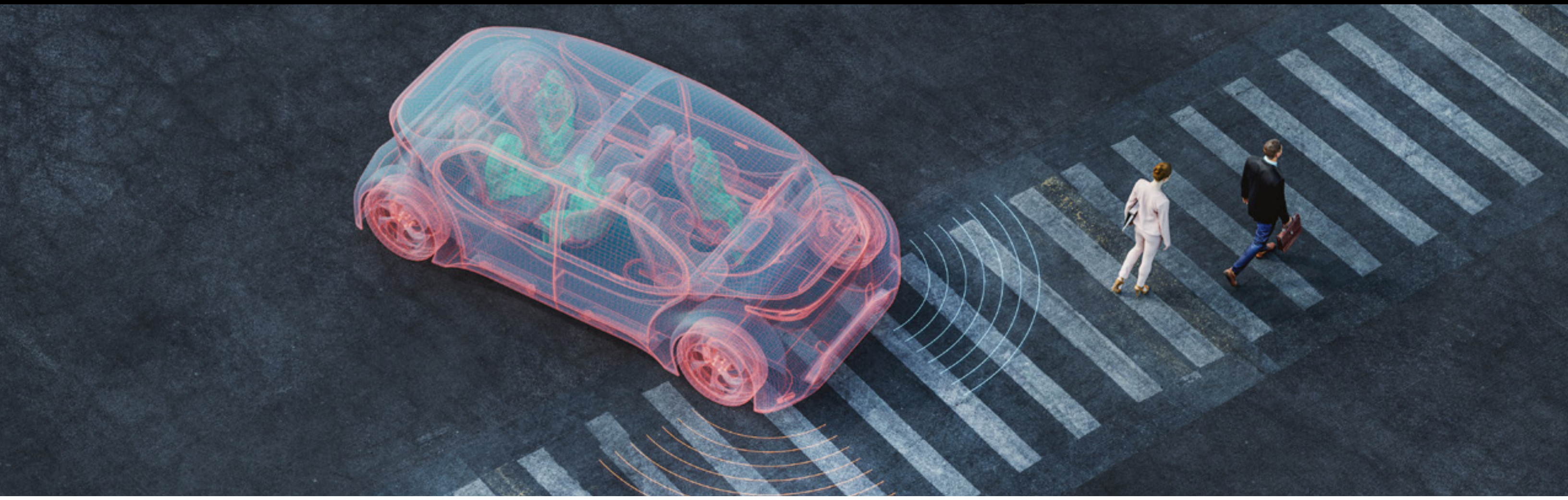
Table of Contents



The Personalized Journey

APTIV AT CES 2025





Benefits of Software Containers in Safety-Critical Environments

The transition from hardware-defined to software-defined vehicles is changing everything about the auto industry and beyond. It opens up a world of possibilities for connected, autonomous and electric vehicles, with more innovation than ever before. It also lets OEMs introduce new features quickly, both before and after sale, to meet evolving consumer tastes and needs.

To fulfill its promise, however, the software-defined vehicle requires a hardware architecture that is more optimized and designed for evolution, and a software architecture that is more open and enables a new approach to software development and management. OEMs need the flexibility to modify individual functions rather than issue updates to entire monolithic code bases, and they need a technology that ensures that any changes will not negatively affect adjacent safety-critical software in the vehicle.

Software containerization provides that flexibility. Making containers a reality in the safety-critical automotive environment will require shifts in automotive software architecture, as well as standardization across the industry.

NEW ARCHITECTURES

As software-driven functionality has increased in the automotive world, the compute hardware has evolved. Instead of electronic control units (ECUs) with dedicated hardware and software performing specific functions, high-performance compute platforms have emerged, such as central vehicle controllers (CVCs) and open server platforms (OSPs). CVCs up-integrate body control functions and networking, while OSPs consolidate functions around the specific domains of advanced driver-assistance systems (ADAS) and user experience.

The new approach to hardware saves space and cost, but it also demands a new approach to software. If software is monolithic — as it has been with ECUs — improvements will require full retesting and validation of the entire device it runs in, and any over-the-air (OTA) updates will be much larger than necessary, requiring bandwidth and time.

Key to moving away from the monolithic approach is modularization and abstraction of functions into manageable software blocks, a practice common in the IT world. Controlling a device within the vehicle, for example, is performed by specialized software that handles all signaling to and from the device while presenting a standard, simplified service interface to higher levels of software. This way, the higher-level software does not have to be concerned with the details of how the device is managed, and developers – who are sometimes far removed from the specifics of a vehicle – can focus on just the higher-level logic.

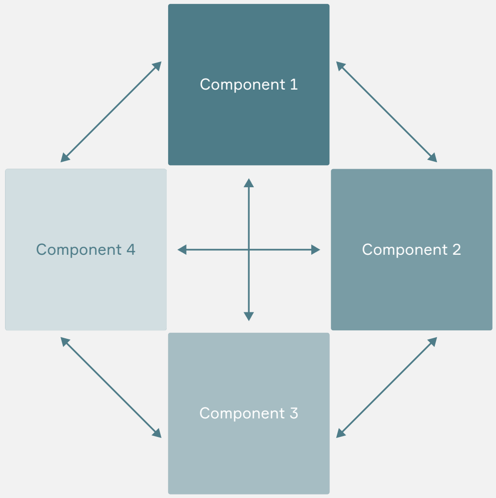
In fact, all vehicle functions can be abstracted and presented as services to other software, creating what is known as a service-based architecture. Software containers fit neatly into this approach.

Leaving Monolithic Architectures Behind

Containerization eliminates interdependencies on common software libraries, allowing each function to be updated independently.

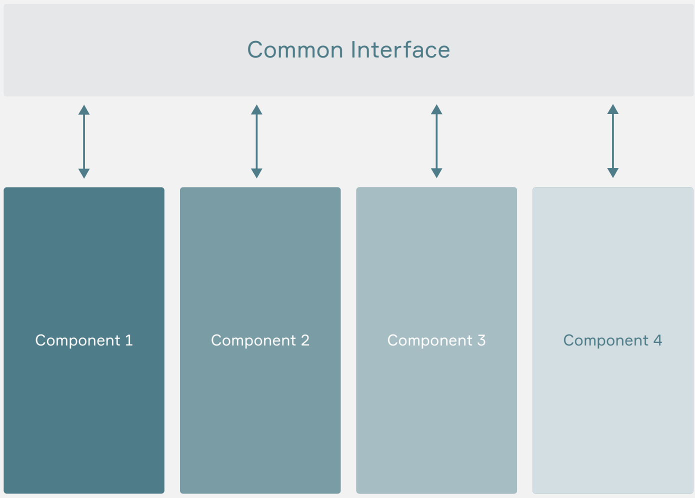
MONOLITHIC

Single, Complex, Intertwined



MICROSERVICES ARCHITECTURE

Standard APIs



Containerization, developed for use in cloud computing, places applications in standard structures that ensure that the dependencies — in the form of service interfaces — among applications are known and controlled. This helps drive stability and consistency in the code base, simplifying isolation of services, and effectively reducing the chances of interfering with other software. It also improves security by keeping attacks that target one application from spreading to others.

By using containers, OEMs and suppliers can adopt modern, agile software methodologies: small teams continually improving individual functions throughout the life of a vehicle with OTA updates, with such changes integrated quickly and automatically. By aligning with open specifications such as that of the Cloud Native Computing Foundation, an OEM and its suppliers can easily update vehicle platforms and even port functions from one platform to another, saving time and money while reducing the risk of errors and systemwide failures.

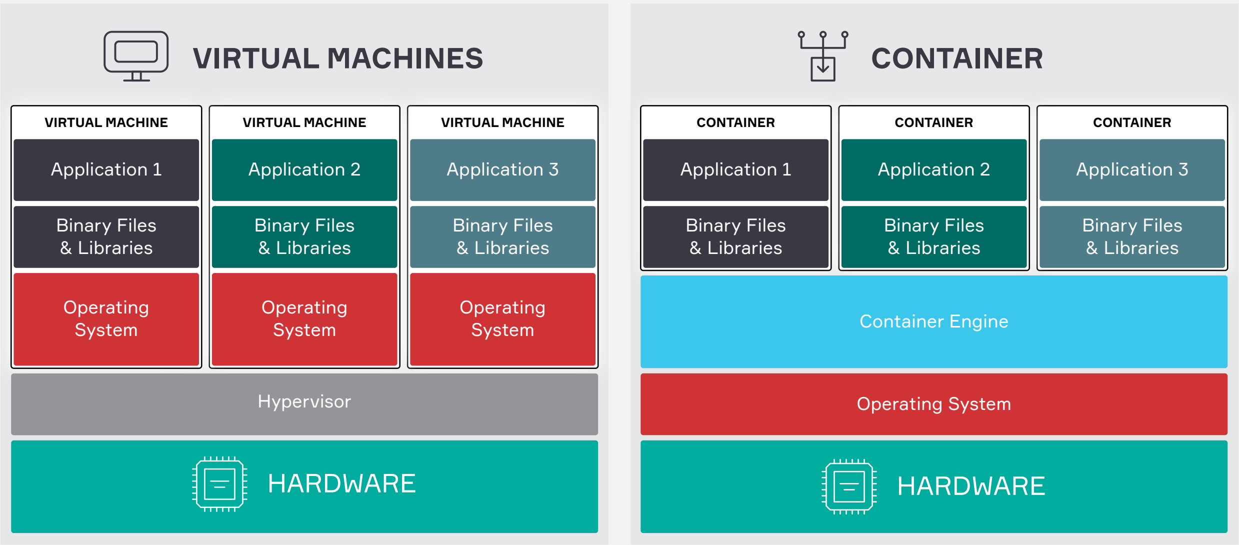
As one piece of the multifaceted transition to software-defined vehicles, containerization is gaining traction across the industry for non-safety-related functions. Because their use in automotive is still new, containers have not yet been certified for use with safety-critical automotive applications such as ADAS, but they are ideally suited to safety features in several ways. Solutions leveraging containers have proven performance in other mission-critical industries, including aerospace, defense, telecom and medical, which helps validate their viability. Key industry players are collaborating to make containers based on the specifications developed by the Open Container Initiative (OCI) that are compliant with industry-standard safety certifications.

CONTAINERS' ROLE IN AUTOMOTIVE COMPUTING

A container is a lightweight packaging format for software. It often includes the application for

Virtual Machines vs. Containers

Hypervisors support virtual machines, each with their own operating system and applications, while containers sit on top of an operating system and container engine, making them lighter.



one function and the specific components that the application requires to run, such as libraries or a programming language runtime. Multiple applications residing in containers can run on one system-on-a-chip or CPU and share processor cycles, memory, storage and networking resources at the operating system level.

Containers were first developed so that cloud-based applications could easily be distributed and scaled up and down. Like virtual machines (VMs), they allow diverse workloads to run concurrently in a shared computing environment. However, VMs are virtualized at the hardware level and incorporate a complete computing environment for the guest application, including an OS. Containers are virtualized at the OS level and are typically smaller. An automotive software architecture might include both VMs and containers: VMs that allow more than one OS on shared hardware, and containers to separate functions under each OS.

Vehicle platforms require three main elements for containerization: a runtime environment that supports containers, a container orchestration system such as Kubernetes, and an OTA network connection for dynamically exchanging containers to and from the cloud in a safe and reliable way. The runtime environment provides standardization among containers and visibility for monitoring the health of each container. A container orchestration system adds another layer for overseeing all containers in a given vehicle.

Containerization turns each function into a standard module that can be added or removed like a Lego® block, making it easier to install, update and manage software. For scalability, the OS can temporarily add more instances of a function at particular times, such as when the vehicle starts up. For portability, a container that performs one function in a comprehensive way can likely be reused in different domains, models and platforms. Containers also ease the integration of legacy software to next-generation vehicles.

In contrast, adding a feature to a traditional automotive code base might require the whole code base to be retested with up to 100,000 miles of driving due to the unpredictable ways in which that feature might interact with others. This approach is growing more costly in terms of time and money as vehicle platforms become more complex.

There are several potential benefits to using containers in automotive environments, including easier OTA updates, increased portability, the ability to adopt modern software methodologies, and coordination across development environments.

OTA updates

The most important way containerization can benefit OEMs is by making OTA updates faster, easier and more frequent. This is becoming essential as more consumers expect — and in many cases are willing to pay for — new features throughout the life of the product. OTA updates offer new ways to increase owner satisfaction and brand loyalty and potentially generate additional revenue.

In traditional, monolithic software environments, after-sale updates tend to be major, infrequent and difficult to distribute over the air. With containerization, they can be smaller and more targeted, both in the number of functions they address and the number of vehicles to which they are distributed. Code verification is standardized and routine, while lower bandwidth requirements mean that most updates can be sent over cellular networks.

Just how much faster and more frequent the updates will be will depend on many factors, not the least of which is how the containers are structured and how lightweight their design is. This is an important area of focus architecturally as developers determine the optimal way to divide applications into smaller pieces, each in its own container.

By ensuring the container structure is optimized, OEMs can more easily perform updates for new features, subscriptions, third-party apps and personalization of individual vehicles. As consumers show interest in new features, dedicated teams can deliver them quickly, which creates an efficient feedback loop.

Portability

Containers also make automotive functions portable across vehicle platforms, models and even vendors. A feature developed for one platform can be deployed throughout an OEM's product lineup with less integration effort. Legacy applications, when placed within standard containers, can easily be integrated into new, containerized vehicle platforms. Portability also prevents vendor lock-in: OEMs can switch to a new supplier more easily, swapping the previous vendor's software for another supplier's containerized application providing identical services.

The portability of containers means the requirements of hardware platforms no longer dictate software development. OEMs can reuse applications as their vehicle platforms evolve from specialized ECUs to domain controllers, to full serverization on central computing engines. Manufacturers can even change the hardware in current models or vehicles already on the road with much lower software update costs.

Modern methodologies

The auto industry has been late to adopt software methodologies that have made other sectors more agile and fast-moving, including DevOps and continuous integration/continuous deployment. OEMs using a traditional waterfall software development process in three-to-five-year development cycles can no longer keep up with technology or consumer tastes.

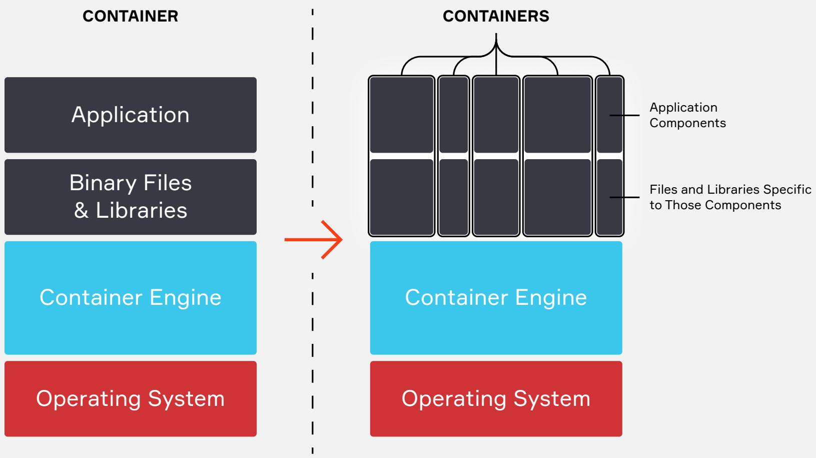
Containers provide the modular architecture needed to quickly accommodate changes in requirements and design. Teams devoted to specific functions can develop and update the software in independent release cycles, owning that code throughout the life cycle of each product or even multiple platforms. Automotive companies that use these methodologies will also have a larger pool of software developers from which to hire.

Coordination

The more that OEMs and their suppliers standardize on the same container specifications, the more they will be able to streamline software rollouts. Most automotive applications go through

Optimized Containers

Containerization and microservices open up new possibilities, and applications themselves don't have to be monolithic. Where it makes sense, they can be divided into smaller modules, each in its own container, making updates more targeted and lightweight.



several environments in the course of simulation, development, testing, verification and production, with separate teams managing each environment. Without containers, the teams need to carefully coordinate any changes to their environment that might affect how those applications run.

Reusing a common container format means that each function has the same context in all environments and that developers can use standard tests to verify whether the code in the container is running correctly. This removes bottlenecks to development in the cloud or any other environment. In addition, once a vehicle is on the road, containerized applications might be able to use the cloud for extra processing power. For example, some automation or infotainment functions could run partly in the cloud, in identical containers.

THE SAFETY CHALLENGE

Traditionally, safety-critical automotive software has been static, isolated in specialized ECUs and limited in size to minimize the overhead of certifying code. In the future, OEMs want to be able to run these functions on shared hardware and update them more frequently.

Co-locating safety-critical functions with other applications creates a need for logical boundaries between applications with different safety and security requirements. Containerization offers a way to implement a modularized architecture via lightweight, easily managed components that can encapsulate safety-critical functions and form those boundaries, so that one container image can be modified without having unpredictable effects on others running in the same environment. This protects safety-critical applications from unexpected failures in noncritical functions that might otherwise spread and violate safety requirements.

The role of VMs

On some vehicle platforms today, such logical boundaries are created by VMs managed by hypervisors with automotive safety certifications.

While VMs will continue to play an important role in safety-critical environments, containers present certain advantages. Because more containers than VMs can share a given amount of computing resources, containers can be lighter and require less overhead for verifying safety. In addition, containers are easier to standardize across environments and update over the air.

VMs and containers could be used together in a safety-critical scenario. For example, a VM could run a real-time operating system such as Wind River VxWorks®, and software containers could run on top of that RTOS.

The value in dependability

The well-defined boundaries of containers lend themselves well to applications in situations where it is important to know exactly what to expect.

For example, without containers, developers might not know for sure whether a particular update will overcommit hardware resources until they attempt to load it — and, if it works, they will be hesitant to make any changes for fear of causing it to stop working. In contrast, the defined boundaries of the container mean that developers always know precisely the amount of resources it will use.

Containers also are not persistent — that is, they are loaded from a master image every time the vehicle starts. They do not change over time, and the data they use is stored in a different location. This aspect is attractive from a security perspective because it means that containers can always be counted on to behave the same way, and the services they provide can be considered immutable. It also means that unused applications can be dismissed, freeing up system resources.

A STANDARD IS VITAL

Having a safety-certified runtime environment for containers would ensure that all containers had the resources needed to guarantee safety. No runtime for containers has yet been certified for automotive safety, but efforts are underway.

There is much work to be done to create the processes and documentation required for all of the different development phases.

Standardization can bring the benefits of containerization to more automotive vendors, expanding the market opportunity for next-generation software and the availability of easily integrated applications. In addition, the broad adoption of one container format will create momentum for safety certification.

There is growing industry support for the idea of container standardization, and the OCI container specification offers a proven approach. OCI offers benefits to automotive software development that are similar to what it already provides in cloud computing: Rather than having to adapt applications to each OEM's environment and perform time-consuming integration work, developers could expect to find an OCI-compliant runtime environment on any vehicle platform and write code that could be added to the platform with only minor modifications.

This would go far toward realizing the vision of software-defined vehicles as platforms for applications from a broad ecosystem of suppliers. OCI could play a role like that of the Android OS in smartphones. OEMs could tap into a much larger universe of features, from which customers could choose when purchasing a vehicle or download (or subscribe to) later.

Hurdles to standardization

Containerization is a widely accepted approach to computing but has been used mostly in environments with unconstrained resources. Due to critical safety requirements and tight constraints on space, weight and power consumption, vehicles pose a different set of problems.

Despite this, the challenges of using containers in automotive are less technical than cultural. Several vendors are already working on automotive runtime environments that would support containers and are making efforts to attain safety certifications. To realize the benefits of containerization, OEMs and suppliers also need to change long-standing development practices and shift some resources from integration and testing to innovation and ongoing updates. While all players could eventually benefit, some need to take the initiative to begin the transition.

The first OEM that introduces containerization across its supplier ecosystem might need three or more years to achieve it. But if the industry coalesces around a single standard, such as OCI, others could soon follow in order to derive the same benefits of increased agility, innovation, cost savings, upgradability and time to market. The next step will be for OEMs to implement a container management layer on vehicle platforms, which might take several more years.

SEEDING INDUSTRY EVOLUTION

Aptiv is cooperating with other vendors to accelerate container adoption and standardization across the automotive industry. We demonstrated OTA deployment of OCI-compliant containers to vehicles, using our container orchestration system, at CES 2023. Wind River, the edge software provider Aptiv acquired in 2022, offers an embedded runtime OS that supports OCI containers, and we are working with Wind River to update its automotive safety certification for its newest technology offerings in 2024.

The costs and limitations of using traditional, monolithic software have not become major barriers to OEMs' business models or competitiveness. But as vehicle platforms become steadily more complex and consumers expect safety, comfort and convenience features to evolve more quickly, the pain will increase with each model release. With strong industry cooperation, soon standardized containers that support safety-critical functions will provide an ideal path to more agile development and continuous improvement.

ABOUT THE AUTHOR

Michel Chabroux
Vice President, Product Management, Wind River

Michel Chabroux drives technology and business strategies for Wind River's Intelligent Edge portfolio. He has more than 20 years of industry experience, including roles in technical sales, support, training and product management.e.

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Integrated Cockpit Controller Streamlines In-Cabin UX Design

Many global OEMs are prioritizing the redesign of the in-cabin user experience — by moving away from traditional head units, introducing immersive audio features or offering consumers seamless integration between a vehicle's infotainment system and their smartphones, for example.

The latest-generation integrated cockpit controllers (ICCs) can meet these requirements and more as capable and agile platforms that support rich functionality while realizing significant efficiencies in automotive design and production.

Transforming the in-cabin user experience

The in-cabin user experience is evolving rapidly. Cabin environments reflect the 24/7 connected world that now dominates so much of modern life. Consequently, infotainment systems have migrated to familiar, intuitive interfaces and have incorporated ubiquitous connectivity protocols such as Bluetooth, CarPlay and Android Auto while offering smart navigation capabilities.

Emerging regulations are also driving changes. The latest initiatives in the European Union, such as Euro NCAP (European New Car Assessment Programme) protocols and GSR2 (General Safety Regulation 2), are set to compel all new vehicles to incorporate a series of active safety systems, with implications that include the need for cameras in the cabin for driver monitoring.

Until recently, introducing new features on this scale almost invariably required an increase in the number of disparate systems — each with its own processing and software architecture — that would have to be integrated. That led to higher design and manufacturing costs, with more components, greater design complexity and more potential for errors during development, validation and the production and assembly process. Further, future system hardware and software upgrades required full system testing and support, a challenging process to complete with vehicles already in the hands of consumers.

The ICC is a single, powerful platform

The ICC represents a compelling alternative, replacing multiple electronic control units (ECUs) with a single, powerful compute platform capable of supporting audio, infotainment, connectivity, navigation, interior sensing and real-time vision.

The ICC not only consolidates ECUs but also enables higher levels of performance and scalability to meet expanding requirements for memory, graphics and computational speed. For example, ICCs can support multiple tuner module variations to meet the specific requirements and expectations of individual countries and regions, reducing complexity and cost in the main computing platform while still supporting all geographies in which an OEM operates.

By implementing an ICC design that is SoC-agnostic, upgradeable and flexible in both hardware and software, OEMs can cater to the future needs of their consumers over a vehicle's full life cycle through over-the-air updates.

Since the underlying ICC hardware for both safety-related (e.g., instrument cluster) and non-safety-related (e.g., Android infotainment) systems is the same, mixed-criticality processing becomes a crucial element in the design. Employing various building blocks, such as a hypervisor, a real-time operating system, containers and middleware can help efficiently prioritize critical applications while delivering a feature-rich user experience.

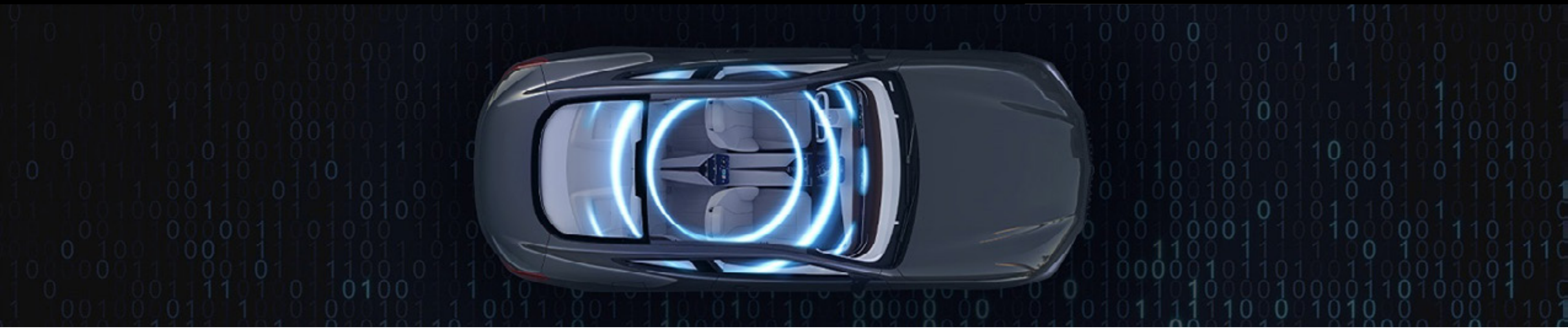
By employing a single computing platform rather than multiple dedicated ECUs, the ICC streamlines updates, simplifies overall design and saves cost, space and weight. Having a common, highly scalable, future-proof solution in the heart of the vehicle facilitates evolution without the need for significant, costly and time-consuming design changes.

Embracing change

The ICC offers OEMs and consumers a genuine win-win proposition. Enhanced in-cabin experiences can be combined with significant manufacturing efficiencies.

Aptiv offers a comprehensive portfolio of high-performance ICCs. Crucially, we bring our expertise in all of the key technologies currently transforming the in-cabin user experience to the ICC, including active and advanced safety systems; infotainment systems supporting Android Automotive, CarPlay and Google Automotive Services; and interior sensing systems for detecting driver drowsiness and distraction to support regulatory requirements.

These solutions reflect the very latest expectations of OEMs and consumers for a far more sophisticated user experience, as well as the ongoing need for products that can be easily and cost-effectively upgraded at the pace of innovation.



Premium Audio Software Enables OEM-Branded User Experience

Software-defined vehicles open the door for innovation in all areas of user experience. However, to get the best performance from their vehicles' audio systems, OEMs need to be able to address the unique acoustics of a specific vehicle with minimal integration and adapt to different cabin settings and car configurations. Many system-on-chip (SoC) suppliers today originate from the smartphone ecosystem and do not fully leverage digital signal processing (DSP) capabilities for scalable automotive audio algorithms, frameworks and applications.

In 2016, a leading global OEM began leveraging Aptiv's DSP expertise, earned through decades of experience with vehicle infotainment, to co-develop an end-to-end software framework that could deliver premium audio. While the solution spans the entire audio software stack — including DSP, audio management, control logic, and tuning and calibration — the OEM owned the tooling to build a differentiated user experience on top of that core software. By centralizing the audio processing in a cockpit domain controller instead of in audio nodes, Aptiv was able to fully integrate the embedded real-time software and eliminate the need for an external unit for audio processing, leading to a 20 percent cost reduction.

By building on top of core software, up-integrating hardware and taking advantage of Aptiv's flexible business model to support co-development, the OEM was able to accelerate time to market and reduce the total cost of ownership across generations.

Scalable

Aptiv created the solution to be highly scalable, from base to premium sound systems. Because the core software is the same for all variants, it is not dependent on any specific hardware or amplifier, and it supports multiple SoCs and digital signal processors. The OEM was able to transition to a new SoC faster and more cost-efficiently and could use the core software across several programs, generations and head units.

Future-proof

By abstracting the core software — now called Aptiv Sound Framework — from the hardware, we have made it possible to continue building on it. Aptiv can offer OEMs a variety of options, including supplying core software to operate on existing hardware, providing hardware and software together, or supporting the OEM through premium consultancy services ranging from identifying and fixing audio issues to testing and implementing improved solutions.

We welcome collaboration and have the capability to provide hardware solutions that can flexibly integrate any third-party DSP software audio libraries.

Aptiv's decades of experience with audio architecture and our strong focus on reuse enables us to reduce time to market, development costs, the total cost of production and the cost of sustaining engineering — all while delivering better sound quality and performance.

CHALLENGE

- **Deliver premium audio and a unique user experience**
- **Reduce development costs**
- **Decouple development and tuning to accelerate speed to market**

SOLUTION

- **Codeveloped an end-to-end audio stack**
- **Delivered a core software framework to enable an OEM to develop a differentiated user experience**
- **Developed audio software that works across OEMs, platforms and configurations, and supports third-party algorithms**

RESULTS

- **Increased scalability and eliminated redundancy by reducing the number of software variants from 40 to one**
- **Reduced time to market from four years to as little as one year by decoupling hardware and software dependency**
- **Increased flexibility via a fully configurable development framework**
- **Reduced costs 20% by up-integrating audio processing into the domain controller**
- **Reduced labor requirements for supplier coordination by 80%**

What Is a Digital Feedback Loop in Automotive?

A digital feedback loop is a process of data collection and analysis used in the automotive industry to inform continuous improvements to vehicles via over-the-air software updates.

For most of the automotive industry's history, vehicle features typically have not evolved beyond the point of sale. However, with technology evolving so rapidly in other areas of their lives, consumers now expect OEMs to incorporate new features continuously.

Two-way communication between the vehicle itself and software developers is essential for such ongoing innovation. That is where the digital feedback loop comes in. Feedback is collected from vehicles, analyzed, and used by developers to create software updates. The updates, in turn, are downloaded to vehicles to complete the loop, and the cycle begins again.

Understanding vehicle behavior

To accelerate innovation, developers need to know how well their features are meeting consumer expectations — how the features are performing, how frequently they are being used and if anything unexpected is occurring. Many customer-facing businesses solicit feedback on their products and services through social media platforms, emails, surveys, online reviews and customer-support interactions. Of course, user-generated feedback is subjective, and it is not always easy to extract a clear or consistent message from it — especially when it concerns something as complex as a vehicle.

As vehicles increasingly become more software-defined and connected to the cloud, OEMs have an opportunity to collect objective data on how a vehicle's software and hardware systems are functioning in the field, through quantifiable measures like CPU performance, memory performance, event-driven data, and diagnostic and usability metrics.

Collecting that data and transmitting it back to OEMs is no easy feat. The amount of data produced when using a smartphone is a fraction of the data produced by a vehicle. Fortunately, 5G connectivity is making it easier than ever for a vehicle to connect with the cloud. And intelligent preprocessing on the vehicle can ensure that only essential data is transmitted, conserving bandwidth usage.

Once data has been collected, developers can use analytics tools to identify any problems that need fixing, as well as opportunities for enhancement or even entirely new features. Eventually, AI and machine learning could be used to analyze patterns in the data to generate insights that are harder for developers to derive.

In the future, cabin monitoring systems could also provide OEMs with near-real-time feedback on driver satisfaction by monitoring reactions and emotions — such as facial expressions that convey joy or frustration during a certain use case.

Instead of representing isolated events, data will be anonymized and aggregated at the fleet level to reveal meaningful trends. So instead of seeing just one driver's experience with a certain feature, developers could observe tens of thousands of drivers consistently experiencing the same feature, prompting them to make improvements.

Leveraging cloud connectivity for processing power

The processing of large amounts of vehicle-generated data occurs in the cloud, where algorithms analyze data on a specific vehicle over time and aggregated data on fleets of vehicles.

For example, as battery management software evolves, a data-driven DevOps toolchain enables the creation of a cloud-based digital twin of the vehicle, using data collected from the digital feedback loop. Algorithms leverage the experiences of other vehicles all over the world in a variety of driving scenarios to learn about and help extend the life of EV batteries and the vehicles they power.

Cloud connectivity enables vehicles to utilize offboard processing power to run powerful algorithms, including those training AI and machine learning modules. Developers can see the interaction between different sensors and datasets so that potential issues, improvements and innovations become apparent.

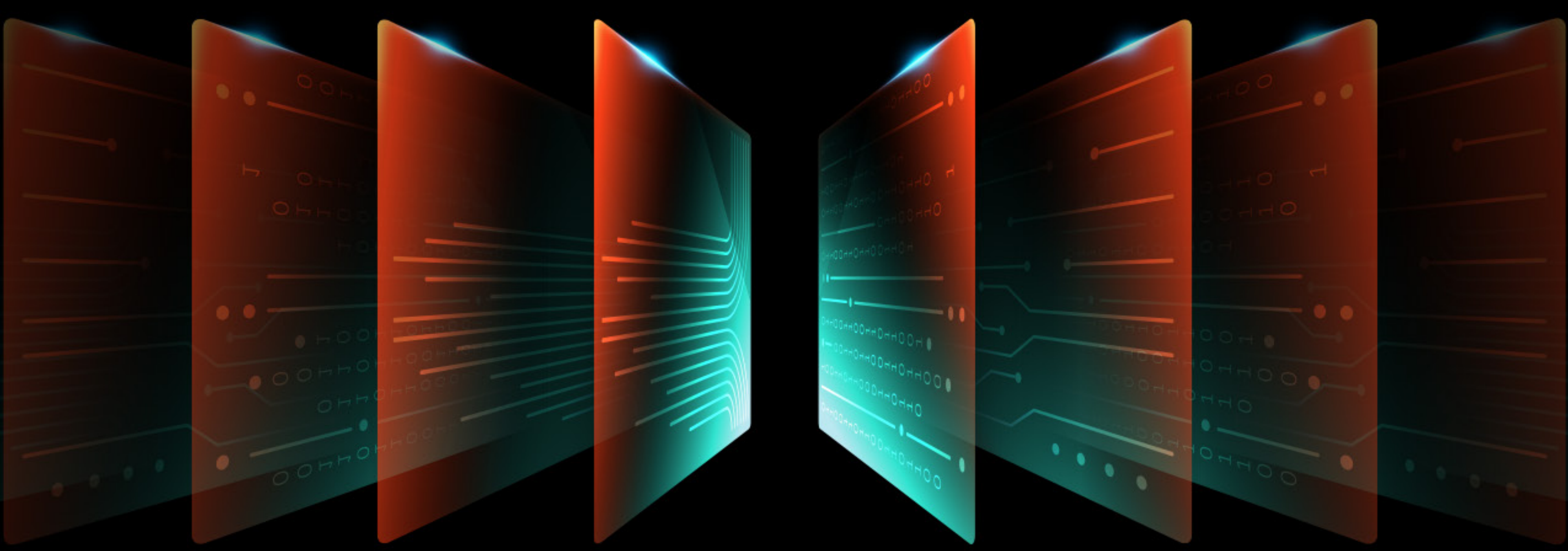
Digital feedback loops help OEMs shorten development cycles by providing developers with immediate feedback from the field. This enables updates to be delivered in a timely and ongoing manner that aligns with the CI/CD methodology.

Wind River and Aptiv

Aptiv's expertise in high-performance sensing and compute, application software development, edge analytics and vehicle architecture, combined with Wind River's edge-to-cloud software portfolio, helps OEMs reduce costs and complexity, increase flexibility and unlock new business models through the digital feedback loop.

Democratized Advanced Safety

APTIV AT CES 2025



Aptiv's Gen 6 ADAS Platform for Software-Defined Vehicles

Advanced driver-assistance systems are not simply a line item to be added to a vehicle window sticker, a checkbox on a list of options. ADAS is a strategy, a vision. It is a path to a better future, a safer future – for everyone.

Achieving this vision requires the proper infrastructure to support it every step along the way, from the sensors and compute hardware that perceive the environment around a vehicle to the software and intelligence that make sense of the signals and decide on actions to take.

Just as importantly, an ADAS platform has to adapt as the technology evolves at both an industry and OEM level, from basic safety compliance functions to advanced levels of automation. It has to be designed today for the electrical and electronic architectures of tomorrow, such as in Aptiv's Smart Vehicle Architecture™. And it has to be flexible, truly open to innovation, recognizing that innovation can come from anyone in an ecosystem – and that some of the most useful features to come are the ones that have not yet been developed.

*Updated June 2024

A COMMON GOAL

In the automotive industry, we share a common goal: a world with zero traffic accidents and zero traffic fatalities. It is an ambitious goal, and it will take close collaboration across the entire industry to make it a reality.

According to the World Health Organization, the lives of about 1.3 million people are cut short as a result of road traffic accidents every year. More than half of those deaths involve vulnerable road users: pedestrians, cyclists and motorcyclists. Another 20 million to 50 million others suffer non-fatal but nonetheless life-changing injuries. And road traffic crashes cost most countries an estimated 3 percent of their gross domestic product.

However, the good news is that most accidents are preventable. According to NHTSA, 94 percent of accidents involve human error.

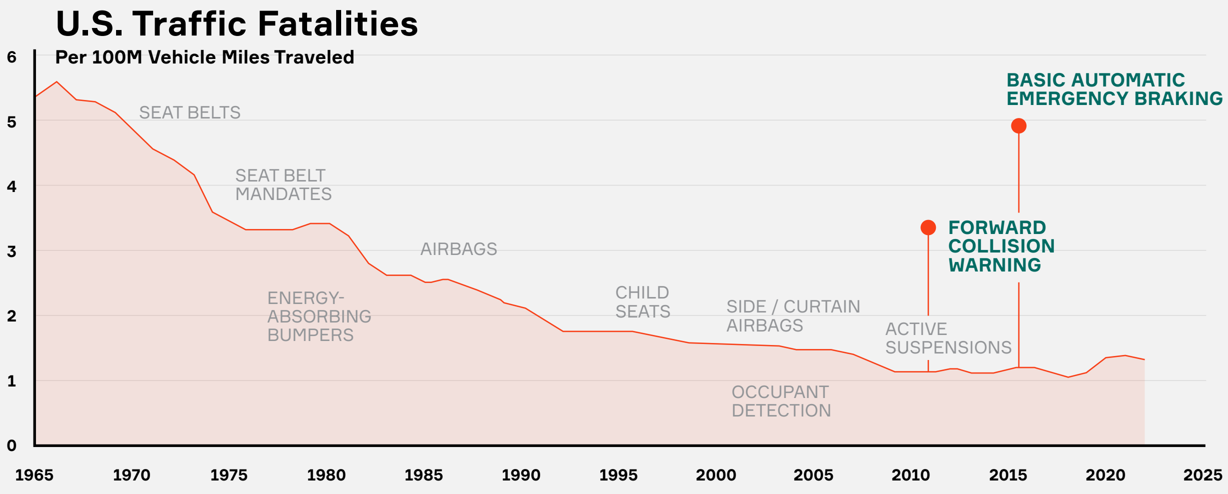
We can reduce the effects of human error through active and advanced safety.

We have already seen tremendous gains from passive safety systems such as seat belts and airbags. Largely taken for granted today, these features were instrumental in bringing the number of traffic fatalities per million miles traveled from 5.5 in the mid-1960s to a little over 1 today. But that number has plateaued, and challenges like distracted driving are adding to the headwinds.

Active safety has the potential to take the industry even closer to its goals of zero traffic accidents and fatalities. This requires embracing technologies that are flexible and scalable, that help protect vulnerable road users, and that democratize safety technology so that it can be deployed on high-volume vehicles. It means giving auto manufacturers the tools they need to collaborate so that we can more quickly reach our common goals.

PASSIVE SAFETY REACHING LIMITS

The automotive industry has reduced vehicle fatalities through passive safety advances, but active safety is critical for further progress.



SOURCE: NHTSA

APTIV'S GEN 6 ADAS PLATFORM

To address these needs, Aptiv has developed the sixth generation of its ADAS platform to leverage AI/ML for enhanced performance. It provides OEMs with several key elements:

- **A sustainable platform.** Any ADAS platform built for the future has to enable the features that run on it to evolve and scale over time. OEMs want to avoid having to port features from one platform to another, which can be costly. They also want to ensure that they can enhance ADAS features throughout a vehicle's lifetime, which means taking advantage of over-the-air updates to upload software to vehicles in the field.

- **Cost effectiveness.** To bring lifesaving technologies to every part of the world, OEMs are looking to leverage their investment over the largest possible volume. For that, they need a platform that can scale from lower-cost vehicles up to premium models, one that can provide compliance with regulations at the lowest cost while still accommodating advanced differentiating features related to higher levels of automation.

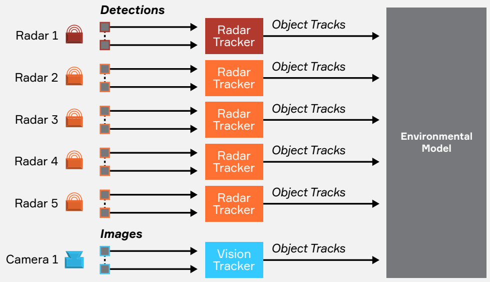
- **Flexibility.** Active safety systems are complex and require high levels of integration. Some OEMs are looking for a full-system solution that provides that integration out of the box. Others want to be able to specify providers for individual features or to better integrate with a particular development environment or ecosystem, which requires an open, developer-friendly platform that encourages innovation. Aptiv's Gen 6 ADAS platform has the flexibility to support either approach, and everything in between.

APTIV'S APPROACH TO SENSOR FUSION

Aptiv's sensor fusion software centrally fuses input from radars, cameras and other sensors to intelligently deliver 360° perception.

TRADITIONAL SMART SENSOR SYSTEMS

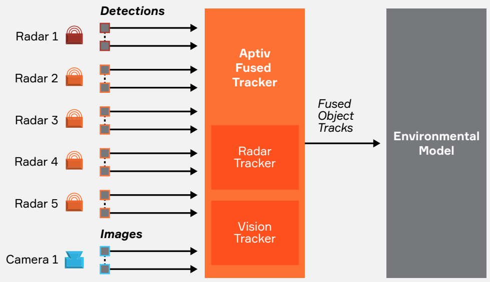
Smart sensors process environmental inputs independently, but because data is processed at each sensor, decision making is only as good as what that individual sensor can see.



example

APTIV'S APPROACH

Centralizing the intelligence means reduced latency, while combining unprocessed sensor data provides increased confidence in detections, particularly for low-level returns.



example

ELEMENTS OF THE PLATFORM

These principles inform Aptiv's approach to every aspect of our ADAS platform, starting with the software and hardware that form its fundamental building blocks:

AI/ML-ENHANCED SENSOR FUSION

The heart of the platform is in software, running either in sensors or in the domain controller. Sensor fusion software takes the inputs from multiple sensors – radars, cameras and lidars – and integrates them to better identify objects around a vehicle, distinguishing between pedestrians, cyclists, vehicles and other objects. Aptiv's approach to sensor fusion takes advantage of centralization in the domain controller to fuse the data in one step, reducing latency. Our real-time embedded neural network can classify dozens of objects within milliseconds. By fusing low-level detections centrally, the software can identify objects that would normally not be visible. This improves the reliability of detecting small, obscured or static targets. It also helps the system accurately identify and track multiple targets, such as those typically encountered in dense urban environments.

ENVIRONMENTAL MODEL

With Aptiv's approach to sensor fusion and machine learning, the platform creates a powerful, software-based environmental model. Each object is identified and tracked, and the system anticipates how those objects might behave. Machine learning allows the system to improve radar range by 50 percent, enabling the tracking of small objects that are more than 200 meters away, which is critical at high speeds. The system is better able to figure out whether an object is something that the vehicle can drive over or under. Machine learning enables the ADAS platform to account for a wide range of these kinds of corner cases (see related white paper).

SENSORS

Every active safety system requires reliable, high-resolution sensors to collect data on the environment around the vehicle. Aptiv pioneered this area with the industry's first vehicle-mounted radar in 1999, and has been innovating ever since. Our next-generation forward-facing radars use imaging radar technology to detect objects 300 meters away and determine how tall those objects are. Our latest corner/side radars double the detection range from the previous generation to 200 meters, while also doubling range resolution. The vertical field of view is three times as high, and angular resolution is tripled.

Radar helps build a solid foundation in sensing, as it can reliably detect objects and their speeds in all kinds of weather and lighting conditions. And with machine learning, the platform is less dependent on other sensing modalities that cost more and require more power, such as lidar.

HIGH-PERFORMANCE COMPUTE

Signals collected by radars, cameras and lidars feed back to an active safety domain controller – or, in an SVA™ implementation, the open server platform – a centralized compute platform dedicated to interpreting those signals and executing decisions based on what the vehicle sees. Aptiv anticipated this shift to centralization more than 10 years ago and was the first in the industry to introduce a domain controller to perform those tasks.

With these elements in place, vehicle manufacturers can equip advanced features at lower cost. For example, coupling sensor fusion with the wide field of view and long range of Aptiv's corner radars allows OEMs to eliminate the need for a frontal radar in hands-free driving applications. In another example, sensor fusion can work with Aptiv's short-range high-resolution radars to cost-effectively enable automated valet parking.

ADDITIVE SCALABILITY

Aptiv's two decades of experience in active safety have given us valuable insights, not just in the requirements for advanced features, but also in the requirements for scaling safety technology across all vehicle platforms. Many of those insights came from the development of the fifth generation of our platform, called Satellite Architecture, the precursor to Aptiv's Gen 6 ADAS platform.

Satellite Architecture took the first steps toward next-generation safety by removing intelligence from the sensors and centralizing it in a domain controller. This leaves in place lighter and smaller sensors that contain only the hardware necessary to operate them. The approach reduces mass in the vehicle and simplifies packaging. As a result, it is easier and less expensive to add satellite sensors as the level of automation increases.

Satellite Architecture's centralization yields significant benefits at Level 1 and increase at Level 2 and Level 3. At Level 0, it can be more cost-effective to keep the intelligence with the small number of sensors required, depending on the desired performance.

To address these differences, Aptiv used the concept of additive scalability to specify multiple software and hardware configurations ranging from entry-level safety compliance features, to comfort and convenience features, to premium or luxury performance. With additive scalability, each configuration builds on the previous one, which has a number of benefits, including reducing design and engineering costs, simplifying the interface into the vehicle electrical architecture, and improving lifecycle management – all while increasing performance.

SATELLITE ARCHITECTURE

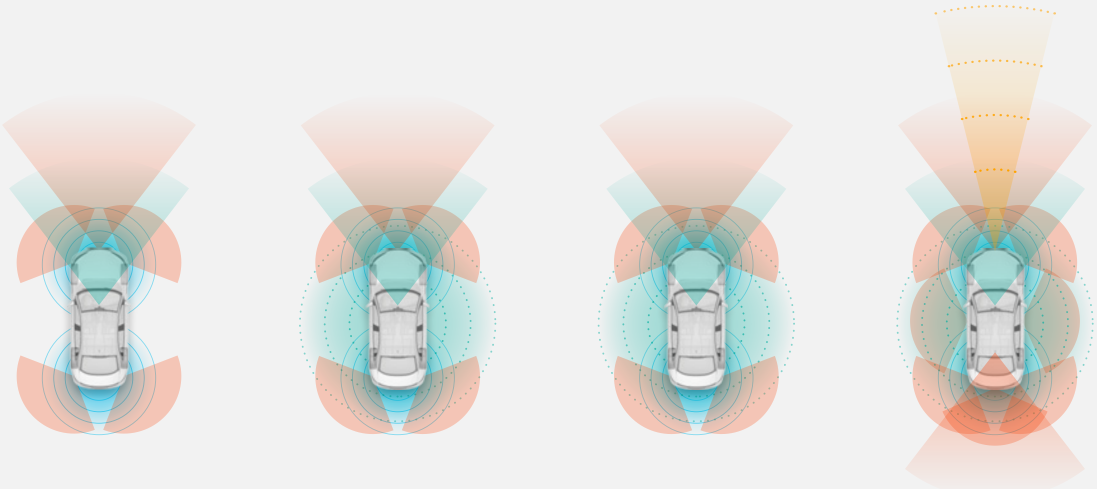
Satellite Architecture is being deployed now by multiple OEMs in every region of the world across multiple vehicle platforms, and is expected to be installed on more than 10 million vehicles over the next few years.

The benefits of Aptiv's Satellite Architecture are evidenced by the Gen 6 ADAS platform. They include:

- Improved sensing and perception performance
- Sensor scalability
- Flexible radar and camera packaging
- Reduced vehicle mass
- Heat dissipation
- Simplified electrical architecture
- Reduced warranty and repair cost
- Simplified lifecycle management

A RANGE OF CAPABILITIES

With Aptiv's Gen 6 ADAS platform, the configurations are grouped into four categories, though each can be modified to meet the needs of specific OEMs:



	CORE	PLUS	PRO	ULTRA
EURO NCAP	**1-4 STAR**	**4-5 STAR**	**4-5 STAR**	**5 STAR**
DRIVER ENGAGEMENT	Up to L0-L2 **(Hands-On)**	Up to L2+ **(Hands-Off)**	Up to L2++ **(Hands-Off)**	Up to L3 **(Eyes-Off)**
SOFTWARE FEATURES	**Safety and Base Convenience Features** **Containerized** **OTA Updatable**	Safety and Base Convenience Features Containerized OTA Updatable **L2+ Hands-Off Highway Policy** **Automatic Lane Change**	Safety and Base Convenience Features Containerized OTA Updatable L2+ Hands-Off All Roads Policy Automatic Lane Change **ML-Assisted Driving Policy**	Safety and Base Convenience Features Containerized OTA Updatable L2+ Hands-Off All-Roads Policy Automatic Lane Change ML-Assisted Driving Policy **L3 Eyes-Off Highway Policy**
SOFTWARE PERCEPTION	**Radar + Vision + Fusion**	Radar + Vision + Fusion **HD/ADAS Map** **Radar AI/ML**	Radar + Vision + Fusion HD/ADAS Map Radar AI/ML **Multi-Modal Localization**	Radar + Vision + Fusion HD/ADAS Map Radar AI/ML Multi-Modal Localization **+ Lidar**
ADAS HARDWARE	1x Smart Camera (Compute) 0-4x Corner Radar(s) 1x Front Radar (Optional) Surround View Camera(s) (Optional) 8-12x Ultrasonic Sensors	1x ADAS ECU (Compute) 1x Smart Camera (Compute) 4x Corner Radars 1x Front Radar 4x Surround View Cameras 8-12x Ultrasonic Sensors GNSS/IMU	1x ADAS ECU (Compute) 1x Smart Camera (Compute) 4x Corner Radars 1x Front Radar 4x Surround View Cameras 8-12x Ultrasonic Sensors GNSS/IMU	2x ADAS ECU (Compute) 1x Lidar 2x Satellite Cameras 2x Side Radars 1x Rear Radar 4x Corner Radars 1x Front Radar 4x Surround View Cameras 8-12x Ultrasonic Sensors GNSS/IMU

As OEMs enhance their ADAS offerings over time, this additive scalability approach has several attributes that facilitate those improvements:

- The features run on a common, standards-based software framework, regardless of the configuration. This allows continuity of software from one level to the next.
- Transitions from a smart-sensor architecture to a centralized domain controller architecture are seamless.
- Radars can be added easily, and the type of radar can be changed. This allows platforms to move from three-radar to five-radar configurations, for example, or incorporate imaging radars to further bolster the environmental model.
- Cameras can maintain a consistent optical path, with the same field of view and the same configuration between the lens and the imager, helping avoid revalidation costs as the equipment is upgraded.
- The configurations provide compliance functionality up to Euro NCAP 2023 five-star at a highly competitive price, while anticipating future standards. Because these compliance features are common to all configurations, Aptiv can distribute development costs over the largest possible volume on these non-differentiating features and free up OEMs to focus on differentiating features.

A KEY PART OF SVA™

The Gen 6 ADAS platform enables vehicle manufacturers to build the software- defined vehicles envisioned by Smart Vehicle Architecture™. SVA™ is Aptiv's approach to simplifying the electrical and electronic architecture in vehicles to simplify complexity, reduce costs and enable the advanced features and high degrees of automation consumers increasingly are demanding. (Learn more about the SVA™ approach in this white paper.)

INSIGHTS FROM AUTOMATED DRIVING

With more than a decade of automated driving experience, Aptiv knows what it takes to support affordable, fail-operational performance for power distribution, network stability and compute availability and performance. In addition to Aptiv's experience in electric vehicles and ADAS, our Smart Vehicle Architecture™ approach was born out of our experiences developing autonomous solutions, including:

- Development of self-driving technology for the DARPA challenges in 2007
- The first coast-to-coast automated drive in 2015 – when we covered nearly 3,400 miles with more than 99 percent of the drive in fully automated mode
- A first-of-its-kind partnership with Lyft, which has completed more than 100,000 automated ride-hailing experiences in Las Vegas since 2018
- The Motional joint venture with Hyundai Motor Group, which launched in 2020 to quickly become a leader in Autonomous Mobility on Demand solutions and has continued the partnership with Lyft

These experiences mean Aptiv truly understands the software architecture and system performance requirements needed to deliver ADAS systems on the path to fully autonomous driving, having already encountered and solved many challenges along the way.

Aptiv's Gen 6 ADAS platform supports several SVA™ design principles.

First, the platform abstracts hardware from software. It establishes standardized interfaces for sensors and feature functions. This gives OEMs the flexibility to specify these elements in the way that best aligns to their individual strategies and adjusts over time as their needs change.

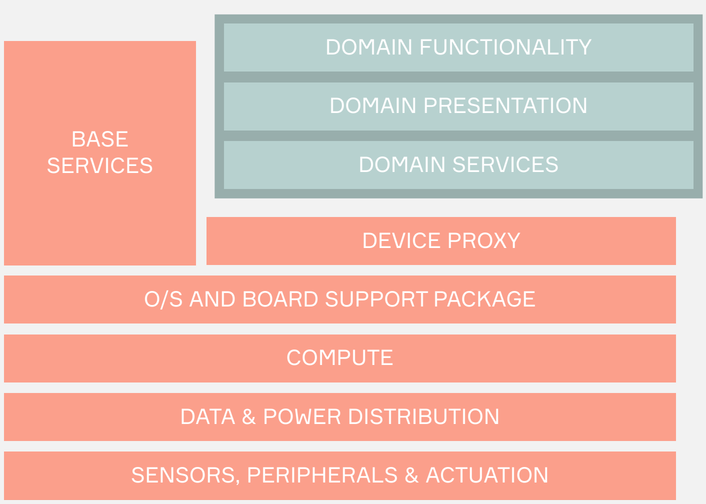
Second, the platform establishes a common software integration platform capable of supporting significant development reuse, leveraging both classic AUTOSAR and AUTOSAR Adaptive standards. By standardizing elements such as communication protocols and diagnostic services, the platform allows significant reuse of base software components, reducing development costs. And because ADAS features are pre-integrated with the architectures that support them, reuse can be as high as 90 percent for OEMs selecting from a core set of functionality.

Third, the platform is fully compatible with a zonal architecture, where I/O is separated from compute. In a zonal architecture, each sensor connects to a local zone controller, which then aggregates the data from the sensors onto a single high-speed interface that connects to the compute. That is, software in the zone controller handles the communication with the end devices, and software in the compute focuses on processing information. (Learn more about zone controllers in this white paper.)

The Gen 6 ADAS platform stretches across both the "Machine" and "Domain" aspects of the SVA™ framework. The SVA Machine provides known hardware capabilities with standardized software interfaces that are easily ported as components are added or changed. With the ADAS platform, the Machine is a dedicated ADAS domain controller, or – further in the evolution of up-integration – a serverized compute platform such as Aptiv's open server platform. Machine functionality is not directly visible to the consumer, so OEMs will want to strike the right

ADAS Integral to SVA™

TWO LAYERS: MACHINE AND DOMAIN PLATFORMS



GEN 6 ADAS PLATFORM

- Encapsulates essential capabilities in vertical stacks owned by domain specialists
- E.g., ADAS software platform, interior sensing software

SVA™ MACHINE PLATFORM

- Provides known capabilities with standardized interfaces that are easily ported to new hardware
- The machine can be a dedicated ADAS controller or a more comprehensive computer

LEGEND MACHINE DOMAIN

balance of power, performance and price. The SVA Domain encapsulates essential capabilities in vertical stacks owned by domain specialists. The consumer experiences many of these domain features every day, and therefore an open and flexible approach empowers OEMs to define that experience.

OPEN DEVELOPMENT

Aptiv's Gen 6 ADAS platform provides a foundation upon which OEMs can innovate and cost-effectively deliver features that exceed consumer expectations over the lifetime of the vehicle. For many OEMs, Aptiv's ADAS platform is a proven solution that lowers total cost of ownership and reduces development risk. For OEMs with feature development capabilities, Aptiv can act as a collaboration partner, offering them the tooling and services they need in addition to the pre-integrated features provided by the platform.

The platform's development tool chain gives OEMs the flexibility to drive further innovation on top of Aptiv's proven solutions and accelerate the development of safe, green and connected features consumers want with the automotive-grade systems they can trust. OEMs can easily add features and scale them up or down for different vehicle models.

This approach facilitates up-integration as well, as features can be consolidated onto the platform. In this way, one can imagine more interior and exterior sensing functions up-integrating onto a common platform and creating a greater level of situational awareness around the vehicle.

CONSIDERING THE WHOLE VEHICLE

In developing the Gen 6 ADAS platform, Aptiv drew on our full systems insights, combined with our domain expertise in areas such as user experience and high voltage electrification. This allows us to include features designed to support the highly electrified and connected vehicles of the future while balancing performance and cost. Here are some examples:

- Driver state sensing functions, which allow OEMs to account for driver distraction and availability, can easily be up-integrated into the ADAS domain controller.
- At higher levels of automation, building trust between the vehicle and the driver is key. Through standardized application programming interfaces (APIs), Aptiv is able to provide information about how the safety system is performing to the infotainment HMI, and the HMI can in turn present the information to the driver and build confidence in the safety system.
- For electric vehicles using wireless inductive charging, getting proper alignment with the charging pad is critical. Aptiv's driver assistance features can help navigate the vehicle into perfect alignment for optimum charging.
- Our sensing and perception approach is already processing- and energy-efficient, but next-generation algorithms for features such as adaptive cruise control will help further tune them for electric vehicles to take advantage of route topology and environmental conditions.

LIFECYCLE MAINTENANCE

The key to success is to allow the platform to evolve and adapt over time – while ensuring that revalidation and deployment costs are kept to a minimum.

Aptiv's Gen 6 ADAS platform supports over-the-air updates and enhancements for the entire life of a program. OTA updates provide a scalable, low-risk and cost-effective way for OEMs to improve the user experience over time. Continuous Integration / Continuous Deployment tooling allows OEMs to quickly develop those solutions.

Managing the updates is simpler and more secure because the platform centralizes the compute power in the vehicle. Updates only have to be downloaded to that central location rather than distributed throughout the vehicle, which means that only that central component must undergo rigorous testing when new software is loaded. A simplified OTA package can also keep costs down when it comes to cloud management and airtime usage.

There are multiple ways to handle OTA updates, failures and rollbacks, and the ADAS platform can be tailored to whichever approach an OEM prefers – from limited OTA updates, to several per year achieved through Wi-Fi and cellular, to frequent updates intended to meet demanding consumer expectations and ensure the highest possible levels of safety and reliability for L3 functionality and above.

To protect these systems, Aptiv is integrating end-to-end cybersecurity protections. We are strongly aligned with industry best practices such as ISO/SAE 21434 and UNECE WP29, and our edge compute and diagnostics capabilities allow us to closely monitor vehicle performance for irregularities.

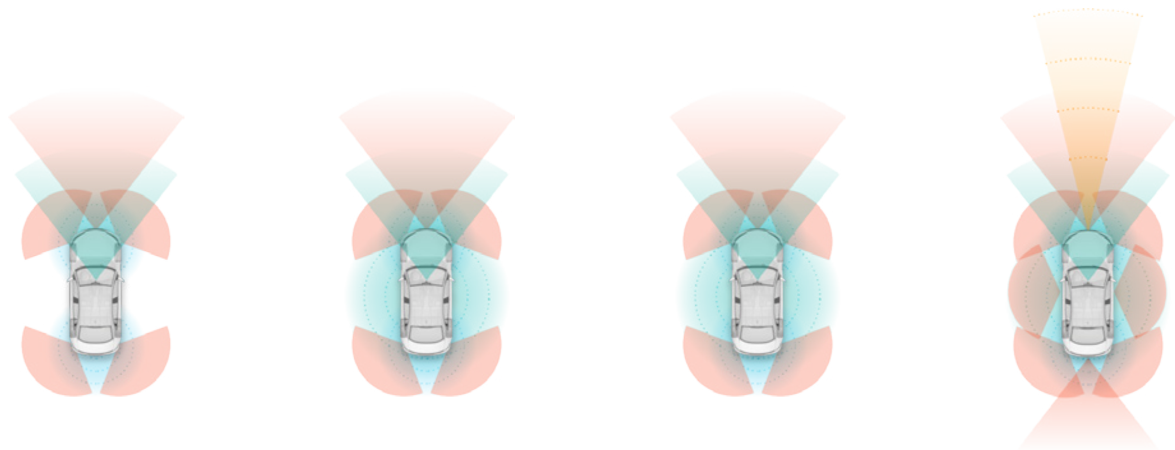
AN EYE TO THE FUTURE

Aptiv's Gen 6 ADAS platform is more than just a system or even a new generation of technology. This intelligent platform represents a fundamental shift in the way ADAS will be developed for vehicles for the foreseeable future. It is extensible, upgradeable and extremely flexible. OEMs can use the platform to grow capabilities over time in a model of continuous integration and continuous deployment, improving the consumer experience with every refresh. And every year, the platform can evolve to meet new challenges and new consumer demands.

These are the kinds of innovations that come from looking ahead to the future, as the pieces of the SVA™ vision come into focus. By standardizing where possible and providing tools to accelerate innovation, the platform not only provides the basis for this growth, it also allows the industry to advance its goal of bringing active safety to a greater number of people while simultaneously building vehicles with a differentiated user experience.

LEARN MORE AT APTIV.COM/ADASPLATFORM →

ADAS Software Features Overview



INCREASING FUNCTIONALITY

<table>
<tr><th>CATEGORY</th><th>CORE</th><th>PLUS</th><th>PRO</th><th>ULTRA</th></tr>
<tr><td>DRIVER AUTOMATION</td><td>Hands-On Assist</td><td>Hands-Off Highway Assist</td><td>Hands-Off Urban Assist</td><td>Highway Pilot</td></tr>
<tr><td rowspan="2">SPEED AUTOMATION</td><td></td><td></td><td colspan="2">Adaptive Cruise Control – Predictive</td></tr>
<tr><td colspan="4">Adaptive Cruise Control</td></tr>
<tr><td rowspan="2">STEERING AUTOMATION</td><td></td><td colspan="3">Lane Centering with Trailer, Hands-On Assist with Trailer</td></tr>
<tr><td colspan="4">Evasive Steer Assist, Lane Centering</td></tr>
<tr><td>SAFETY FEATURES</td><td colspan="4">Safe Exit Warning, Blind Spot Detection, Rear End Collision Warning, Emergency Steering Support, Automatic Emergency Braking, Longitudinal Traffic Braking, Moving Off Information System, Boundary Alert, Cross Traffic Alert & Braking, Intersection Collision Assist, Automatic High Beam Control, Drowsy Driver Detection, Traffic Sign Information, Lane Keep Assist</td></tr>
<tr><td rowspan="4">PARKING</td><td></td><td></td><td></td><td>Smart Summon</td></tr>
<tr><td></td><td></td><td colspan="2">Remote Park Assist, Memory Park Assist</td></tr>
<tr><td></td><td colspan="3">Automated Park Assistance, Reverse Assist</td></tr>
<tr><td colspan="4">Park Distance Warning, Low Speed AEB</td></tr>
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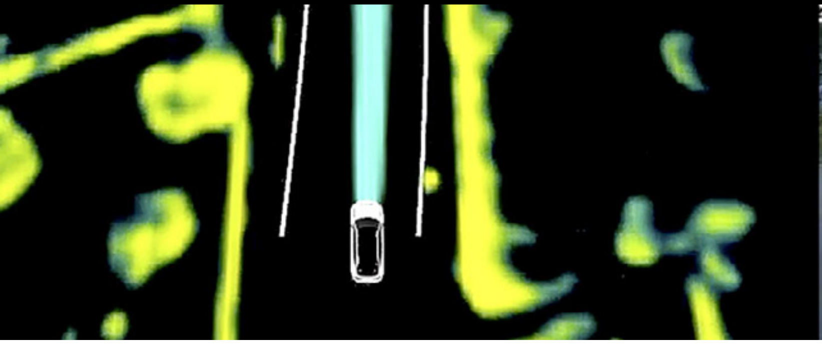


The Key to Truly Humanlike Driving

The world is always changing, and that is especially true of the roads we drive on. Think of changing traffic patterns, construction, obstacles, and pedestrians. Generally, human drivers are able to adapt to the variable conditions around them — for example, to determine whether they can take a certain path around an obstacle or should wait for that obstacle to move. To put it simply, humans have the ability to manage unexpected road conditions by reasoning and by tapping into prior experiences mapped into their neural networks.

As the industry heads toward higher levels of automated driving, the challenge is to give automated systems capabilities similar to those of humans so they can make better-informed decisions and drive like humans do. That means the system has to include a reasoning system that understands and contextualizes the scene around the vehicle and can predict how that scene is likely to change in the near future.

The Right Approach to Path Planning and Scene Prediction

There are many different approaches to enabling autonomous driving. One is to use rules and heuristics, or rules of thumb: If certain conditions exist, the vehicle performs specific actions. Another is to use a detailed model of the physical world and create a system that uses encoded knowledge to mimic the choices an “expert” would make.

Aptiv’s approach is to use a state-of-the-art neural network running on an efficient artificial intelligence (AI) accelerator. Instead of using heuristics, we use extensive driving data to teach the network to contextualize its surroundings, make sense of the world, make short-term predictions about what will happen in that world and decide on its next move.

That means that we can teach it to predict the behavior of other road users. If a pedestrian is standing at the side of the road, for instance, human drivers can usually predict whether that person is about to enter the road by observing their body or head orientation. An AI/machine learning (ML) system can learn how to do that as well.

In another example, suppose the car ahead of yours has stopped in the road. Is it stopped because of a traffic light? Should you wait? If so, for how long? Should you go around it? These are questions that the system considers based on what it knows about the behavior of other road users and the environmental context around the vehicle.

The Machine Learning Advantage

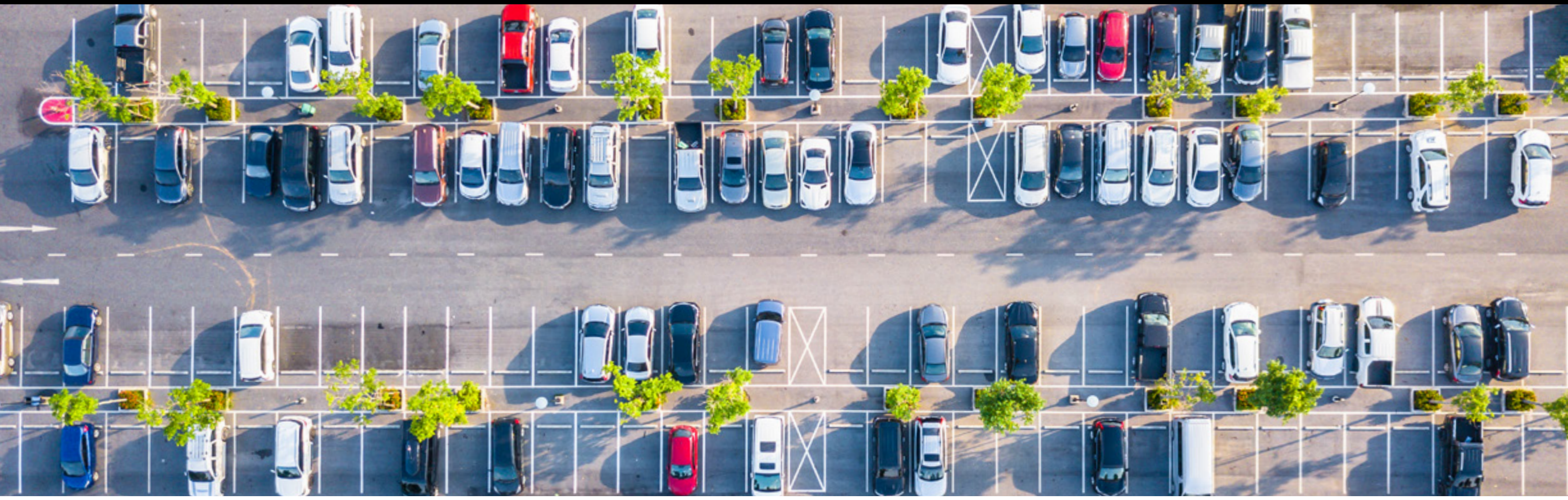
Aptiv's ML Behavior Planner system takes inputs from perception systems, mapping and localization functions, and ego-motion (the movement of the vehicle it is in). Sensors could include any combination of radars, cameras or even lidars. If a map is not available, the ML Behavior Planner can still use those other inputs to create a world model of the scene around the vehicle and determine the best path through it. Its AI/ML engine can infer lane boundaries — even if there are no lane markers — and biasing on irregular roads that lack clearly defined boundaries. In short, the ML Behavior Planner is a humanlike driver that can operate in both structured and unstructured environments.

The ML Behavior Planner outputs multiple potential driving paths that converge into a trajectory based on the overall navigational goal, safety considerations and laws. The final trajectory determines actions the vehicle will take, such as turning, changing lanes, braking or accelerating.

In this way, the ML Behavior Planner provides vehicle intelligence and behavior, regardless of the sensors and motion controllers available. Its abstraction gives OEMs the freedom to use a variety of sensors on one end and different planning technology on the other.

The baseline ML Behavior Planner can be refined to work in various regions, such as in left-driving or right-driving countries, or in places where roads are generally narrow or wide. In a sense, its driving style can be customized to match a target location.

The flexibility of the ML Behavior Planner is essential, especially as the industry continues to build steadily toward more autonomous vehicles. With additional and well-balanced data collection, the technology's ability to handle more complex situations increases without new software architectures having to be developed. In other words, over time, the system's capabilities improve as they get more driving experience, just like a human driver's skills do.



Intelligent Approach Expands Possibilities for Parking Automation

Parking assistance features like proximity warnings and driver-monitored hands-free parking have become common conveniences across most vehicle classes.

But as consumers increasingly demand more advanced parking features, it is becoming clear that autonomous parking systems must be designed as safety-critical technologies, not just as mere conveniences. A vehicle that is parking itself must be fully aware of nearby pedestrians, cognizant of all the available space around it and intelligent enough to use that information to execute the maneuver safely and efficiently.

That means that technologies used in advanced driver assistance systems (ADAS) for driving on local streets are critical to ensuring higher performance and safety when it comes to parking assistance. The same sensors and machine learning intelligence that power ADAS in complex urban driving scenarios and in difficult lighting and weather conditions will play key roles in automated parking as it evolves.

THE UNIVERSAL CHALLENGE

Parking is the expected conclusion of every vehicle trip, but the conditions under which this occurs can be as varied as an empty, well-lit parking garage, a driveway at night or a crowded parking lot in a rainstorm. Whether nosed in, backed in or parallel parked, every vehicle is expected to safely come to rest.

Automating that function across all conditions starts with robust sensing and perception capabilities. While many parking automation features rely primarily on ultrasonic sensors and cameras, state-of-the-art radar enhanced with artificial intelligence and machine learning (AI/ML) has significant advantages over other forms of sensing. Using radar to interpret a parking environment transforms the way in which a vehicle can plan and carry out parking tasks.

Enhanced radar data, fused with inputs from cameras and ultrasonic sensors, enables safe, reliable parking features with increasing levels of vehicle automation. For example, vehicles can use radar to identify an open parking space from a sufficient distance to pull into it directly, without going so slowly as to frustrate nearby drivers. Other sensing modalities often require the vehicle to first drive past the space when traveling at typical parking lot speeds. Intelligent systems can also map a parking area and be trained to navigate it later, and radar will let Level 4 autonomous cars safely drive away to park themselves in a garage and return on demand.

EFFICIENT, ROBUST PERCEPTION

Radar has significant advantages over both vision and ultrasonic sensors, creating more robust 360-degree sensing under a wider range of conditions. Because of these advantages, radar is increasingly becoming foundational for a wide range of ADAS features, but radar's advantages also enable OEMs to create parking features with greater capabilities over a broader operational design domain.

Compared with ultrasonic sensors — core components of many parking assistance systems — radar offers much longer range: potentially five to 10 times farther. This extended range significantly improves collision avoidance and enables new parking actions. For example, ultrasonic sensors can measure the size of a parking space only when directly in front of it, forcing the vehicle to drive past the space, back up, and return to enter it. Radar detects a suitable space between two parked vehicles from a farther distance, allowing the vehicle to directly maneuver into it.

In addition, recent advances in radar have expanded its field of view vertically so it can detect overhanging obstacles, such as tractor-trailer rigs or objects extending from the bed of a pickup truck.

Radar has key advantages over vision systems for accurately perceiving distance and distinguishing among objects. Radar detection inherently provides the distance to an object, while vision systems are limited by cameras' 2D perception. Vision systems have to rely on triangulation techniques while moving past objects to determine the distance to a given object in its field of view, such as a parked car, and the perception of distance with these systems declines at longer ranges. Radar is also better at distinguishing between one or two partially overlapping objects, such as pedestrians.

High availability

In addition, radar works in certain conditions, such as rain, fog and darkness, that make other sensors less reliable. Front-facing cameras rely on windshield wipers or headlights to keep their view clear, but cameras elsewhere around the vehicle lack those features. A buildup of salt, dust and grime, which may be a constant presence during severe weather, can degrade the performance of cameras and ultrasonic sensors, even triggering proximity alarms when ultrasonic signals bounce back from a heavy buildup of material on the surface of a sensor.

These conditions have much less effect on the transmission of radar waves, so radar units mounted around a vehicle can provide reliable 360-degree sensing in the widest possible range of driving scenarios.

INTELLIGENT PERCEPTION

Innovations in radar hardware and signal processing are building on the technology's inherent strengths, thus enabling new applications across the full range of vehicle automation, from parking to high-speed ADAS and autonomous driving.

Sensing gains precision

Emerging 3D air-waveguide technologies for radar antennas allow for the use of special radar beams tailored to specific applications. These technologies efficiently illuminate the environment with radar signals and receive the faint echoes that return with low loss, enabling higher precision while keeping costs down and sensor size the same. With 3D air waveguides, radar sensors receive more of the data needed to identify where objects are, how fast they are moving and even what they are, by feeding the data to machine learning systems to classify objects.

The latest generation of radar also adds a fourth dimension, sensing elevation. This allows the system to create a radar point cloud to model the surrounding environment in high definition, with important details such as low curbs, overhead signs and parking garage gates.

AI/ML: A force multiplier

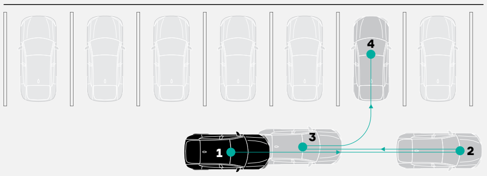
Artificial intelligence and machine learning are doing the most to transform the capabilities of radar. The growing power of flexible, centralized onboard computing platforms and the rapid development of pattern-recognition algorithms are helping to make this possible.

Radar has been used primarily to detect the location, direction and speed of vehicles and other highly reflective objects, especially for high-speed ADAS applications such as adaptive cruise control. Now, machine learning techniques like those used to train in-vehicle vision systems to distinguish among vehicles, pedestrians and roadside infrastructure are being applied to radar signals.

Better at Spotting Parking Spots

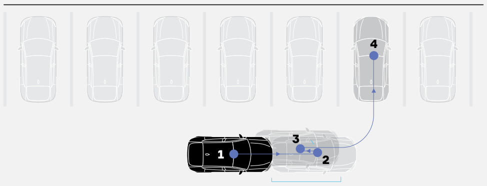
Several different sensing technologies can detect open parking spaces, but radar excels at detecting those spaces sooner at conventional parking-lot driving speeds.

Ultrasonic



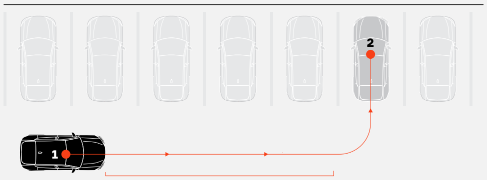
Detection only possible after passing the open spot

Cameras



A few meters away

Radar



15 meters away

Enhanced resolution, trained neural networks and more powerful radar reception algorithms give these intelligent systems greater ability to correctly identify stationary and less-reflective objects. In parking applications, the combination allows vehicles to analyze all potential obstacles in the environment, including partially occluded objects such as pedestrians walking behind cars.

Sensor fusion adds value

Vision remains essential to many parking applications for uses such as reading signs and identifying lane markings, and such data can be merged with radar inputs through sensor fusion. Readings from ultrasonic sensors, which provide low-cost short-range sensing, can also be merged with this data. Sensor fusion helps to build the best possible picture of the surrounding environment.

Radar is especially well suited to AI/ML processing compared with other sensing technologies. Unlike ultrasonic sensors, radar captures enough detail to be used for object classification. But it generates less overall data than vision systems, which take in unnecessary details such as vehicle color, so identifying hazards requires less computing power in the vehicle's core computing platform. In-vehicle preprocessing of data from radar sensors can further reduce computing requirements.

ADVANCED PARKING BREAKTHROUGHS

Next-generation parking assistance features benefit from advances in sensing and perception including AI/ML signal processing, for increased automation, availability and safety. Aptiv has developed several such applications.

Automated Park Assist

Automated Park Assist allows a vehicle to automatically find, enter and exit a parking spot. It controls the steering, speed, brakes and gearbox while the driver monitors the process from inside or outside the vehicle. Radar sensors scan a parking lot and identify a suitable space. The vehicle can then go directly to it and maneuver into it — and later leave the space — with no driver input. A neural network processes radar data using AI/ML to detect, track and identify all types of hazards while integrating vision to read signs and road markings.

As an SAE Level 2 automation feature, Automated Park Assist can operate only when the driver is paying attention and ready to take control, either in the vehicle or at a distance with a key fob or smartphone app that can stop the vehicle. This allows owners to park in spaces that are exposed to weather or too tight for the doors to open.

Memory Park Assist

This feature, first demonstrated by Aptiv at CES 2023, allows a vehicle to record the process of parking in a given location and later repeat it automatically with the driver present.

The first time a driver parks in a given location and instructs the system to record, Memory Park Assist detects and classifies all stationary objects in the environment, exclusively with radar enhanced with AI/ML. It uses this data to build a virtual map that remains in the vehicle, and the data recorded on subsequent trips is aggregated to keep the map current. If there is a major, permanent change in the area, Memory Park Assist will instruct the driver to retrain it.

Memory Park Assist models the scene using an occupancy grid, in which a radar reception algorithm classifies any stationary object in a given quadrant, such as a garage pillar, to a high degree of certainty. The virtual map, along with real-time sensor inputs, enables the vehicle to situate itself within the learned environment through simultaneous location and mapping.

Memory Park Assist self-maps the area without referring to any existing map, but it can also be aligned to a commercial map of the surrounding area when one is available. This feature — also known as home zone parking — is designed for navigating to a space or garage on private property, such as a home driveway. A Level 2 “summon” feature is possible using the same technologies without any further training.

Though designed initially as an SAE Level 2+ feature that requires driver monitoring from either inside or outside the vehicle, Memory Park Assist could be implemented as Level 4 — allowing vehicle autonomy within a limited domain — with enough redundant sensing and computing systems to ensure safety.

Reverse Assist

Reverse Assist is a driver-assistance system that helps with reversing maneuvers by automatically steering the vehicle along a memorized path. The driver retains control of acceleration and braking throughout the reversing maneuver. Reverse Assist memorizes the last 200 meters driven at a maximum speed of 36 km/hr, including steering wheel movements.

Smart Summon

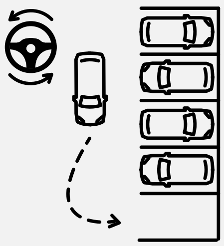
Smart Summon allows drivers to remotely call upon their vehicle to navigate out of a parking spot where it was previously parked. Smart Summon functions effectively when the user is within 65 meters of the parked vehicle. During the Smart Summon process, the user is in complete control. It’s crucial to maintain a clear line of sight to the car. The user can stop the vehicle at any moment by simply releasing a button, ensuring a secure and controlled experience.

Remote Park Assist

Remote Park Assist is similar to Automated Park Assist when the driver is outside the vehicle. When an appropriate parking space is found, the driver leaves the vehicle and activates the automated parking function through a mobile phone. After parking, the vehicle sends a parking completion message to the mobile phone.

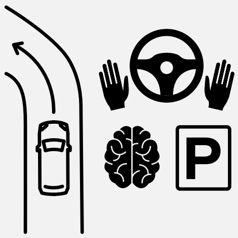
Advanced Parking Breakthroughs

Advances in sensing and perception enable several parking applications.



Automated Park Assist

allows a vehicle to automatically find, enter and exit a parking spot.



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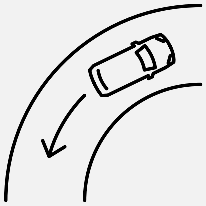
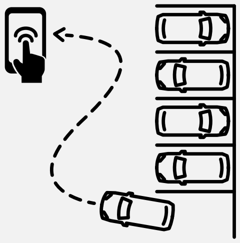


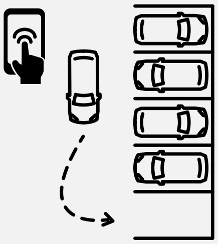
Reverse Assist

helps with reversing maneuvers by automatically steering the vehicle along a memorized path.



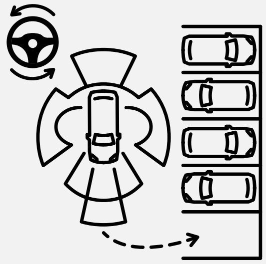
Smart Summon

allows drivers to remotely call upon their vehicle to navigate out of a parking spot where it was previously parked.



Remote Park Assist

allows a vehicle to automatically park when the driver is outside the vehicle.



Surround View

uses sensor fusion to combine data from various sensors in a view of the vehicle’s surroundings on the in-cabin display.

Surround View

This feature uses sensor fusion to combine data from radar, vision and ultrasonic sensors in a view of the vehicle's surroundings shown on the in-cabin display. It stitches together images from multiple surround-view cameras and can provide multiple viewing angles. Other information, such as the current steering path and distance warnings, can be overlayed onto the video image.

A SYSTEM APPROACH

Parking assistance is increasingly not just a convenience feature but a part of the continuum of vehicle automation, subject to all the real-world safety demands imposed on this technology. As parking assistance features evolve from Level 2 to Level 4 and beyond, unlocking increasing degrees of autonomy, the most capable and cost-efficient parking automation solutions will be those that combine ADAS cruising innovations with the power of AI-enabled radar.

An end-to-end ADAS platform provides a complete safety package, including features such as forward collision warning and automatic emergency braking, that can be extended into parking automation features with proven effectiveness and reliability. In addition, comprehensive ADAS development and testing generates a wealth of knowledge on nearly all types of driving scenarios, adding to the robustness of parking capabilities.

Parking assistance is a critical component of Aptiv's Gen 6 ADAS platform. The next-generation parking features described above, which were introduced with the platform, build on Aptiv's deep experience developing and manufacturing industry-leading automotive radar systems. Together with our Satellite Architecture, this platform allows OEMs to implement scalable, integrated ADAS capabilities in a modular, flexible and cost-effective way for increasingly intelligent real-time sensing and decision-making.

Aptiv's system approach to vehicle automation, which spans parking, ADAS cruising and ultimately autonomous driving, brings together a full safety package, a comprehensive sensor fusion platform, and access to extensive driving data. With a detailed road map and proven solutions on the market, we are able to partner with OEMs for parking automation and beyond.

Parking assistance is increasingly not just a convenience feature but a part of the continuum of vehicle automation, subject to all the real-world safety demands imposed on this technology.

ABOUT THE AUTHORS

Walter K. Kosiak
Engineering Manager, Advanced Safety Global Products

Walt Kosiak has spent his career at Aptiv innovating in the fields of integrated circuit design, passive safety systems, active safety and driver assistance, and automated vehicles. His areas of expertise include ADAS/AD feature/function algorithms, threat assessment and warning algorithms, radar and radar-vision fusion, adaptive cruise control systems, vehicle-to-everything communication, map-based electronic horizon technology, and rapid prototyping systems for automotive systems development. Walt is an inventor on 24 U.S. Patents and was a member of the team that completed the first U.S. coast-to-coast automated drive in 2015.

Gürhan Gümüssu
Parking Core Systems Lead Architect

Gürhan Gümüssu is responsible for leading and coordinating systems activities of Aptiv's parking feature development in the Global Product Organization. He has been with Aptiv for four years, contributing to system teams on various projects and supporting business pursuits. Before joining Aptiv, he worked at a global automotive manufacturer as systems engineer.

Kamil Ostrowski
Technical Program Manager, Active Safety Algorithm Development

Dr. Kamil Ostrowski leads the software development activities for parking at Aptiv. In his seven years at the company, he has helped successfully launch products related to radar, vision and features for multiple customers. Previously, he worked for a U.K. OEM and in the railway industry. Kamil holds a doctoral degree from the University of Liverpool, U.K., with a research focus on advanced control algorithms for the powertrain domain. He is currently pursuing an executive MBA at Poznan University of Economics and Business.

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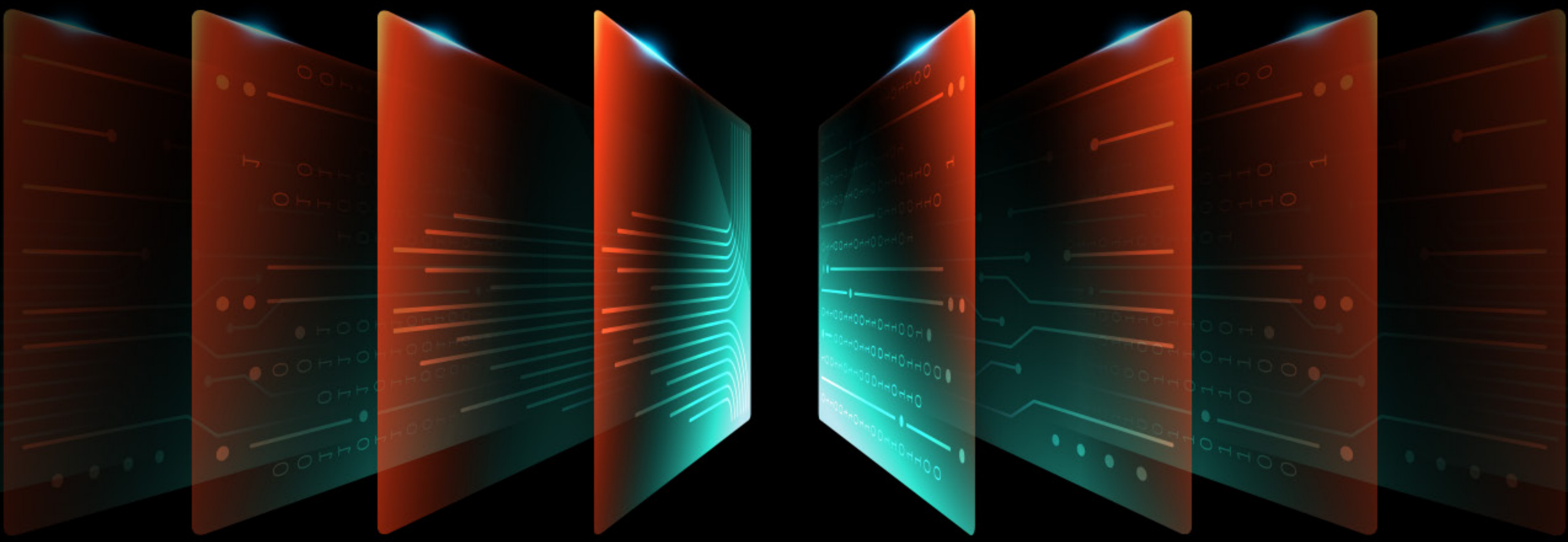
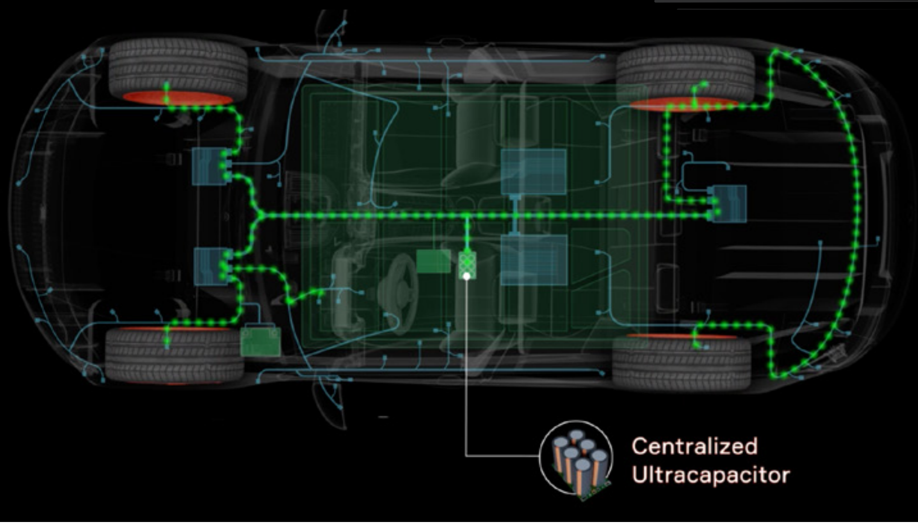
Optimized Power Distribution

APTIV AT CES 2025





Safety-Critical Systems Demand New Approach to Backup Power

Today's vehicles increasingly include automated driving features and are moving toward hands-off or even fully autonomous driving. These technologies require high levels of functional safety so that a vehicle does not become a hazard in the event of a single-point or multipoint failure scenario. Designing for those scenarios presents major engineering challenges, including providing safety-critical components with highly reliable and fail-operational electrical power.

Enter the ultracapacitor — a compact, lightweight energy storage unit that can stabilize a vehicle's 12V or 48V powernet while also supplying emergency power to safety-sensitive components should a collision or electrical failure occur. Coupling long-life ultracapacitors to the 12V powernet through a multiphase bidirectional DC-to-DC converter allows the module to both absorb and deliver electrical power.

This approach has distinct advantages over battery technology. Ultracapacitors weigh less than lead-acid batteries, are less expensive than lithium-ion batteries, have a much longer lifespan than either type and are ideally suited for quick bursts of power.

In short, such a module is the natural choice to meet the requirements of today's vehicles, which increasingly rely on electrical power to perform functions that are essential for consumers' safety.

REDUNDANCY REQUIRED

OEMs are increasingly equipping their automobiles with more active-safety devices and higher electrification. These features impose higher demands on a vehicle's electrical system and increase the consequence of electrical power failure. In response, the industry is developing regulatory standards to reduce risk, such as requirements for electrical system redundancy.

Traditional vehicles satisfy the power redundancy requirements by having two power sources: a lead-acid battery (which is expected to transition to lithium-ion in future vehicles) and an alternator attached to an internal combustion engine (ICE). These power sources support the 12V powernet that connects to the electronic controls throughout the vehicle. For actual control of steering and braking, the two redundant sources are the advanced driver-assistance system and the human drivers themselves.

However, there are several limitations to this approach:

- **Reliability.** Battery trouble is often listed as a top cause of roadside breakdowns. For example, Transparency Market Research indicates that jump starts and battery assistance together were the top roadside service given in 2022, other than towing. Batteries have been shown to be maintenance-intensive, and any safety-critical functions of the car must be disabled until the operator services the battery. For some modern cars equipped with many electronic safety devices, that means the entire car might be unsafe to drive until a malfunctioning battery is serviced. And of course, a dead battery means a vehicle can't start in the first place.
- **Engine-off mode.** Newer designs reduce fuel consumption using engine-off technologies, eliminating the alternator's power contribution when the engine is not running. Engine-off mode also deactivates the power steering pump and the vacuum system used for braking, so it is typically used only when the vehicle is at a full stop. A weak battery might not be able to restart the engine, leaving a vehicle stranded in a roadway.
- **Gliding.** Many automakers are demonstrating "gliding," where the engine may turn off during periods of zero torque demand. This may happen when the vehicle is motion, such as when the driver releases pressure on the accelerator pedal. In this case, the vehicle will lose power redundancy, power steering and braking ability when the engine turns off. Some automakers are therefore implementing two batteries in their ICE vehicles to maintain electrical redundancy.

The ideal solution would excel at providing quick bursts of power, have a long anticipated lifespan and be lighter and less expensive than competing solutions.

Battery electric vehicles use a high-voltage battery pack system and a large DC-to-DC converter to convert high-voltage power from the battery to 12V for the vehicle powernet. This is the primary power source, but the automaker must then also include a separate 12V battery for redundancy. The alternative solution is to use two DC-to-DC converters, but they must not share any common failure points in the high-voltage battery pack to maintain full redundancy. Plus, it is preferable to have dissimilar technologies providing the redundancy, so that the same conditions don't necessarily cause the same failures in both.

Autonomous driving further increases the requirements for redundant power. Hands-free driving — that is, Level 3 or higher — requires not just redundant power sources but also redundant electrical systems. This can be imagined as a right-side and a left-side powernet, with each one having fully redundant power sources, fuse boxes and wire harnesses. If one of the powernets were to fail — for example, due to a collision — the powernet on the other side of the vehicle would continue to function. That way, the system could be fail-operational, and could potentially execute a minimum risk maneuver to bring the vehicle to a stop or transfer control to the human driver.

THE ULTRACAPACITOR OPTION

With so many critical functions in a vehicle increasingly dependent on uninterrupted electrical power, automakers require a solution that will continue to provide power even if the primary power source fails. The ideal solution would excel at providing quick bursts of power, have a long anticipated lifespan and be lighter and less expensive than competing solutions.

Ultracapacitors are far superior to batteries in all of these respects.

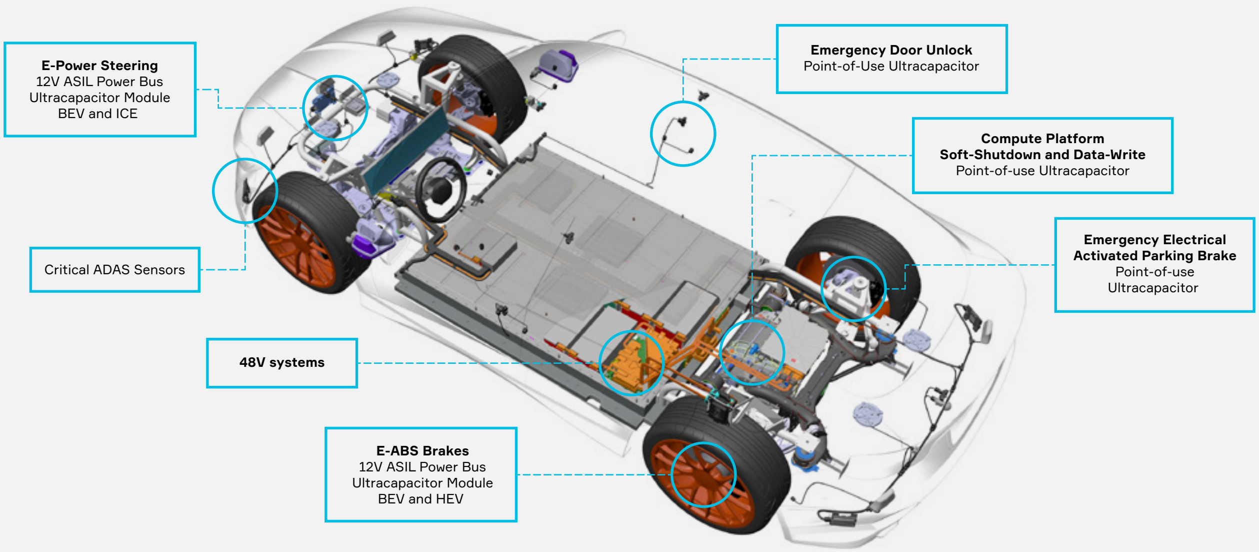
They store positively and negatively charged ions and use a liquid electrolyte to facilitate the flow of energy — so, unlike in batteries, no electrochemical reactions are involved. This results in much faster charge and discharge times and makes ultracapacitors a natural choice for automotive applications that require bursts of power or quick storage, such as when energy is recaptured through regenerative braking.

Ultracapacitors weigh about 60 percent less than lead-acid batteries. Lithium-ion batteries, meanwhile, are expensive and cannot provide the same surge current that ultracapacitors or lead-acid batteries can, especially at low temperatures.

Ultracapacitors also have a much longer lifespan than batteries because there are no physical or chemical changes speeding up degradation. A typical battery can handle several hundred to several thousand charge cycles, whereas an ultracapacitor can withstand more than 1 million. Ultracapacitors are more stable than batteries,

A Variety of Applications

Ultracapacitor technologies can serve as backup to specific safety-critical functions throughout a vehicle.



do not contain heavy metals, and have an operating temperature range of between -40º C and 65º C.

While the use of ultracapacitors in automotive applications has been limited, one successful and well-known ultracapacitor implementation in automobiles is the airbag. The airbag must function in even the worst of collisions, which may disable or incapacitate the vehicle's electrical power system. Therefore, the airbag may contain an ultracapacitor to store electrical energy in case the vehicle's electrical network is incapacitated, ensuring that a redundant, highly reliable power source is always available.

Ultracapacitors can be made large enough to provide backup power to other specific safety-critical functions, such as an electrically activated parking brake, an e-antilock braking system or an electrically activated transmission lock.

Batteries, in contrast, have had uneven performance in emergency scenarios. For example, a cellular emergency roadside service at one time incorporated a lithium-manganese dioxide nonrechargeable one-time-use battery. In an emergency situation where the vehicle power was incapacitated, the system could issue a final emergency beacon. Unfortunately, the lithium battery suffered lifetime problems, largely because the mounting location was subjected to sun exposure and high temperatures.

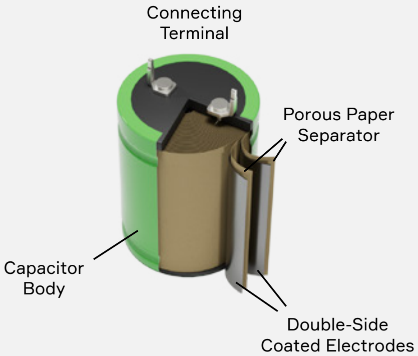
UNLOCKING ITS POTENTIAL

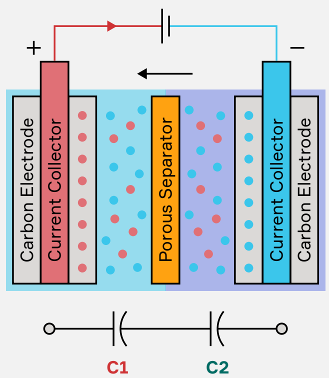
The energy storage and power delivery capabilities of an ultracapacitor are concentrated on the upper end of its operating voltage, according to the governing equation Joules (Energy) = 0.5 CV2, where C is the capacitance in Farads and V is the capacitor voltage. To make the most of an ultracapacitor, Aptiv controls its voltage by using a small, compact bidirectional DC-to-DC converter. This allows full utilization of the entire voltage band of the ultracapacitor, including the energy-dense top region. Since power is also a function of voltage, the higher the voltage the ultracapacitor is storing, the more power will be available.

Aptiv's patent pending algorithm controls the DC-to-DC converter and ultracapacitor voltage, charging the ultracapacitor to the maximum possible voltage while also reserving a small amount of headroom in case a load transient occurs. If the module detects a spike on the

Inside the Ultracapacitor

Although ultracapacitors share many attributes with batteries, no electrochemical reactions are involved.





powernet voltage, the DC-to-DC converter responds by absorbing the excess energy, storing it in the ultracapacitor's reserve headroom. Similarly, if the module detects the powernet sagging into brownout territory, the DC-to-DC converter activates to pump charge out of the ultracapacitor to stabilize the bus voltage. In case of severe failures, the ultracapacitor will discharge the entirety of its energy to help maintain powernet voltage for as long as possible.

For example, one implementation can store 3,500 Joules (Watt-seconds), able to output in excess of 100 amps of current for a few seconds to keep the powernet alive. This is enough energy for an emergency anti-lock brake activation, electronic door unlock, electrically activated parking brake application, or for the central vehicle controller to data dump its memory banks. Called Aptiv Rapid Power Reserve (ARPR), the device continually computes its energy capacity and power delivery capability and can update the vehicle's control computer in real-time.

Aptiv can scale the power capability of ARPR by varying the size of the ultracapacitors, the phases of the DC-to-DC converter, and control algorithm calibrations. ARPR can handle the inductive load dumps from steer-by-wire systems, filter bus voltage fluctuations, stabilize the bus voltage, and provide emergency power, all while performing self-diagnosis and providing real-time energy and power updates to critical vehicle systems.

PROOF POINTS

Aptiv Rapid Power Reserve leverages ultracapacitor and DC-to-DC converter technologies to address the challenges of modern automotive evolution in the following ways:

- Highly reliable power delivery according to ISO 26262 functional safety criteria
- Maintenance-free and service-free performance for the duration of the automotive lifecycle (typically seven to 10 years), a metric that batteries cannot match
- Power delivery across a wide temperature range (typically -20° C to 55° C), which surpasses most battery chemistries except lead-acid
- Delivery of enough energy to perform the final safety-critical functions of a vehicle that is experiencing incapacitation or multiple failure modes, which usually lasts for milliseconds or seconds
- High power density that can discharge in times ranging from milliseconds to seconds
- Lighter weight and a smaller volumetric footprint than lithium-ion battery types, which are designed to discharge over many minutes or hours instead of milliseconds or seconds
- Lower cost than other redundant power sources, such as lithium-ion batteries or redundant DC-to-DC converters

THE RIGHT CHOICE

The combination of long life and wide operating temperatures make the ultracapacitor module an attractive redundant energy storage solution to supply point-source power for critical safety loads.

Aptiv Rapid Power Reserve is an ultracapacitor module that provides instantaneous backup power to safety-critical systems such as steering and braking. Aptiv's solution combines battery management control software with power electronics to deliver maximum performance at an optimized cost and power density. As the only supplier of both the brain and the nervous system of the vehicle, Aptiv is uniquely positioned to provide solutions that optimize the entire vehicle architecture.

ABOUT THE AUTHOR

Stephen Moore
Director of Battery Management Systems

Stephen Moore has extensive technology, manufacturing and business experience in the lithium battery and advanced energy fields. He is the author of multiple patents and publications relating to control algorithms, battery algorithms, hybrid electric vehicles and battery technology. He was the founding chairman of the International Electrotechnique Commission (IEC) regulatory and standardization body TC21/SC21A for Large Capacity Secondary Lithium Cells and Batteries and was the founding chairman of the NEMA Grid-Interconnected Energy Storage Council.

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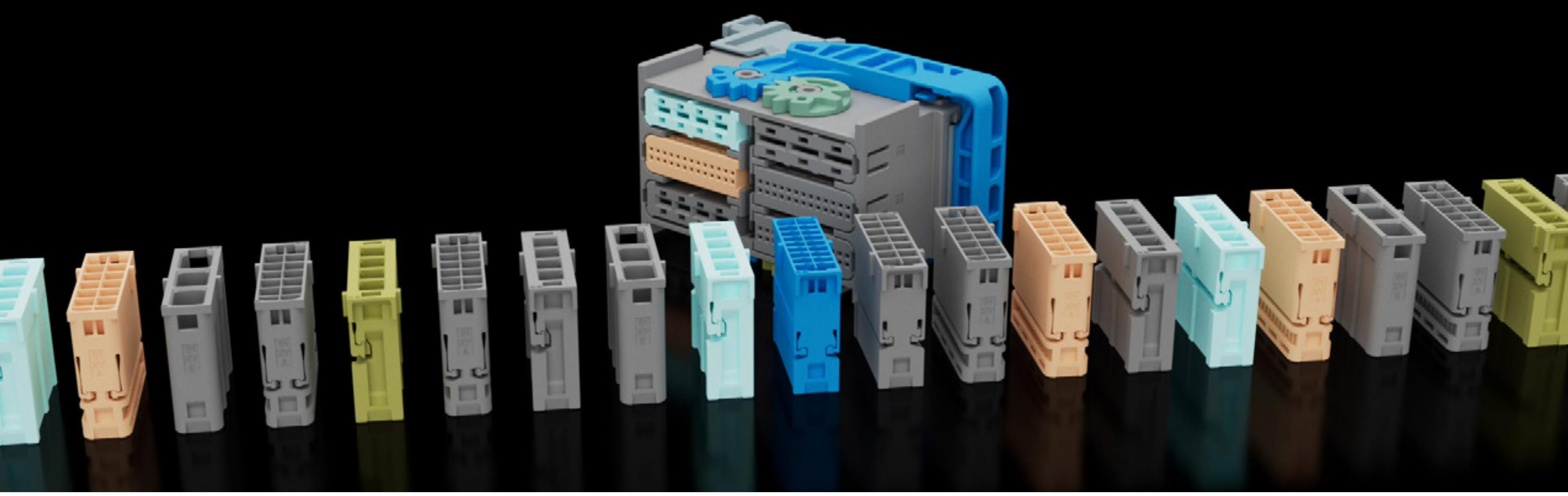


Modular Connectors Clear the Way for Automation Innovation

The complexity of automotive electrical/electronic architectures is staggering, and it continues to increase as more devices and more data communications and power circuits are added to deliver ever more advanced features to consumers.

Body wiring harnesses in today's vehicles can include more than 2,000 wires and 600 connectors. Because of those harnesses' size and flexibility, the assembly process is extremely difficult to automate, and it can take 40 to 80 hours for workers to assemble a single harness manually.

Moving to modular connectors will be critical to incorporating more automation into the harness assembly process. Modular connectors enable the creation of simplified harness kits, the use of auto-plugging and better quality control. An ideal modular connection system will offer maximum flexibility in the quantity and types of connections while maintaining standardized dimensions for use with automated systems. Done right, this one innovation can unlock a wealth of possibilities in assembly automation.

MULTIPLE CHALLENGES

To keep up with consumer demand, automakers are continually adding advanced capabilities to their vehicles. While the capabilities are often enabled by software, the software requires sensors to take in data from the outside world and actuators to perform software-defined actions. All of the devices and peripherals throughout the vehicle require data communications connections and electrical power lines.

Of course, the software also requires compute hardware. Traditionally, OEMs have added an electronic control unit (ECU) every time a new capability has been introduced, but that approach has become unsustainable with the sheer volume of capabilities being added and the resulting complex network of ECUs and devices.

The industry has responded with two key shifts to simplify the vehicle architecture: zonal architectures and centralized compute, both of which are key tenets of Aptiv's Smart Vehicle Architecture™ approach. A vehicle's device connections are terminated at several zone controllers, which consolidate data communications onto backbones that lead to centralized compute modules. The centralized compute uses sophisticated software to up-integrate the functions that had been handled by individual ECUs. These changes simplify the electrical/electronic architecture and segment the wiring harnesses into smaller, more manageable zones.

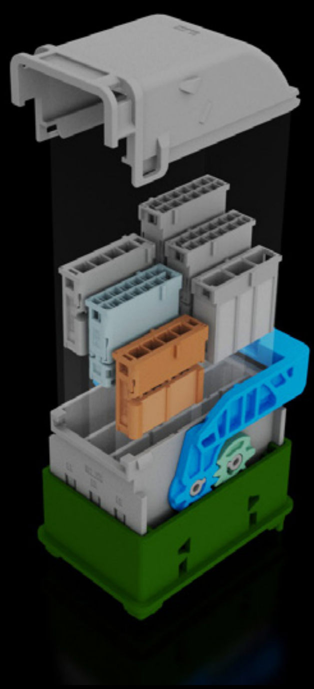
However, to fulfill the promise of zonal architectures and centralized compute, zone controllers need to be designed to accommodate a lot of connections in a limited space.

Furthermore, the smaller wiring harnesses associated with vehicle zones present an opportunity for increased automation, but connectors traditionally have not been designed with automation in mind. In the coming years, labor costs are expected to continue to rise, and labor availability is expected to continue to shrink, so automation will become an important factor in production. In addition, the automotive industry is looking for ways to leverage automation to better manage supply chain risks by moving harness production closer to vehicle assembly.

The missing piece of the puzzle is a new style of connector that can enable automation, achieve the connector density required and meet all of the requirements of today's architectures while giving OEMs the flexibility they need for their individual architecture designs. That is where modular connectors come in.

THE RIGHT FIT

Modularizing connectors allows different types of connections to be assembled into the same housing.



THE MODULAR REVOLUTION

Modular connectors represent a simple yet powerful concept. Instead of terminating cables with a mix of interfaces that have different sizes and shapes, modular connectors use a standard size and shape (typically rectangular), regardless of the type of interface being supported. One module might be constructed to accommodate, say, three connections at $4.8mm^2$, and another might accommodate 26 miniaturized connections at $0.5mm^2$. But under a modular approach, the outside dimensions of the rectangular connector modules would be exactly the same.

The next step is to create standard housings for the modules to fit into. A typical housing might fit four modules, but housings could be created to accommodate as many as eight modules, or even just a single module.

Ideally, the housing would be designed to stabilize and balance the connection, keeping four contact points in place as the housing is mated to the header and ensuring that the connection is made cleanly across all of the modules within it.

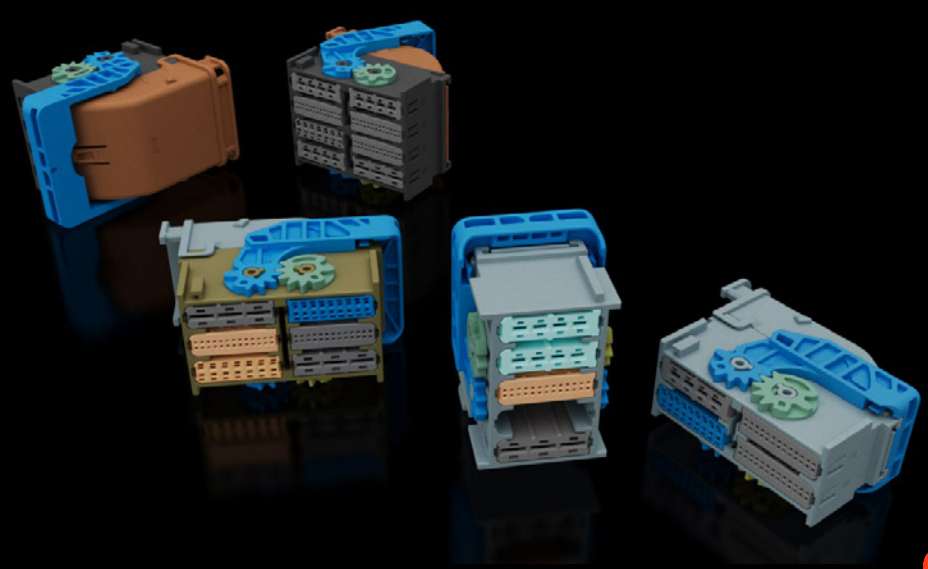
MODULAR VS. MIXED VS. HYBRID

Several major types of automotive connection systems have emerged to solve different challenges:

- Modular connection systems consist of building blocks of various terminal types and sizes, packaged in high-volume, standardized modules that can be aggregated into a collector housing
- Mixed connection systems combine multiple terminal sizes (e.g., 1.2, 0.50, 2.8, etc.)
- Hybrid connection systems combine data terminals with standard signal and power terminals (e.g., H-MTD®, MCA)

MIX AND MATCH

Standard housings can be designed to accommodate different numbers of modules, in different orientations, depending on the design requirements.



BENEFITS OF MODULAR CONNECTORS

This approach to connectors has several key benefits over other types:

Auto-plugging. Because they are designed for auto-plugging during harness assembly, modular connectors can reduce the risk of wire damage during plugging, which in turn enables wire gauge reductions. Lower wire gauges result in less mass and cost.

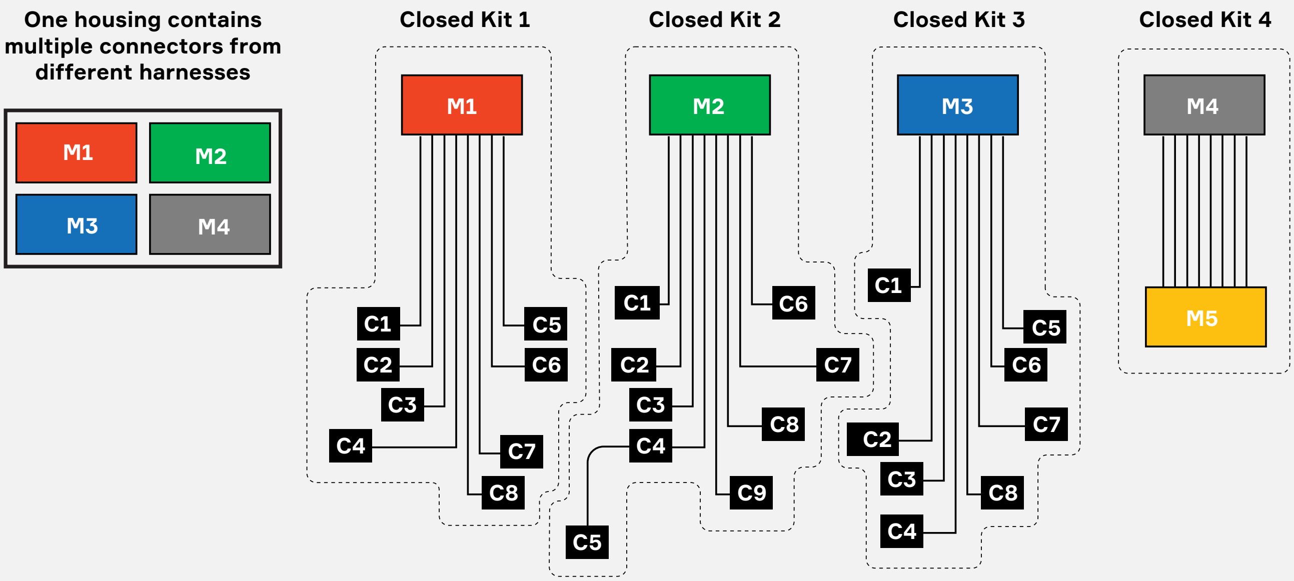
Terminal mix and grouping options. By accommodating a mix of terminals, modular connectors enable optimal closed kits during harness manufacturing, improving quality. The mix also allows for the optimal I/O for the device requirements.

Flexibility. With various housing options available, manufacturers can choose the one that best matches their devices' footprint and I/O needs. Because the housings can work with any module, manufacturers can easily swap modules out in the future for modules that have a different terminal mix. This is especially important as data needs grow over time and data standards evolve.

Smaller harness kits. Zonal architectures segment a vehicle's electrical/electronic architecture, and manufacturers can take that concept a step further by segmenting zones into smaller wiring harnesses that join at the point of the zone controller. Each harness kit could terminate at a module, and those modules could be grouped within a housing where they would meet the zone controller.

HARNESS SEGMENTATION

Modular connectors allow manufacturers to use smaller wiring harnesses that connect at the same location. Smaller harnesses are easier to handle and enable assembly automation.



THE RISE OF AUTOMATION

Modular connectors fit well with an automation strategy. The standard shapes and sizes of the connectors and housings are easy for robots to grasp and assemble. With components becoming more miniaturized, they are becoming too small for humans to handle; modular connectors enable automated assembly.

The smaller wiring harnesses are less unwieldy for a machine to handle than a full wiring harness is. Kitting design is an integral part of the wiring harness and architecture design, and modular connectors enable the creation of simplified harness kits — quality-controlled, with no swapped pins and no back-outs.

QR codes printed on modules can enable a robot to read the code and verify the module's placement. In addition, by printing QR codes on modules, everything can be easily traced. Traceability is key for ensuring the quality of these critical vehicle components.

BRINGING IT ALL TOGETHER

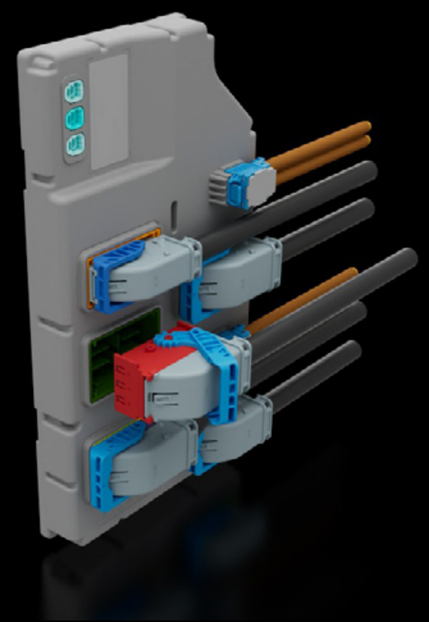
To maximize the benefits of automation, connection systems must be designed to work hand in hand with the electrical distribution systems that they terminate. With long-standing expertise in both areas, Aptiv is working to increase assembly automation of low-voltage harnesses from 15 percent in 2023 to more than 60 percent by 2030.

Modular connectors are fundamental to the implementation of that strategy. Not only do they enable auto-kitting and auto-plugging, but the resulting smaller harness kits are easier for robots to handle — meaning that they can handle more taping, apply more body clips, and generally take on more assembly tasks that previously had to be done manually. Aptiv's tests have shown that robots will be able to work two to three times faster as well.

As the only provider of both the brain and the nervous system of the vehicle, Aptiv is uniquely positioned to lead the industry in the evolution of this area, where the brain and nervous system meet, and many more innovations are still to come.

PLUG AND PLAY

Housings containing dozens of modularized connectors can be mated to headers integrated into major architectural components – such as zone controllers – in one swing of the lever.



ABOUT THE AUTHOR

Andreas Urbaniak
Senior Product Engineer

Andreas Urbaniak oversees designs for modular connectors, working with teams across Aptiv and with customers to develop products and process technologies to meet customer needs. He has been with Aptiv for more than 20 years, developing new and innovative products, including 48V support, miniaturized housing systems, and connector sealing elements.

Marek Manterys
Senior Manager – EDS Core Engineering, Manufacturing Engineering Strategy and Automation

Marek Manterys defines, controls and implements the Automated EDS Manufacturing roadmap at Aptiv, ensuring that it is aligned with customer needs and rolling it out to manufacturing operations. He has been with Aptiv more than 16 years, holding positions as a technical process innovation manager and EMEA Manufacturing Excellence Center manager.

Tony Knakal
Product Line Director, Traditional Interconnects – Americas

Tony Knakal is responsible for Aptiv's global housing business, ensuring that Aptiv has the right products available to meet customer needs for low-voltage interconnects now and in the future. Tony has been with Aptiv since 2020, supporting both high- and low-voltage interconnect solutions. Prior to joining Aptiv, Tony held roles in product and program management for automotive lithium-ion batteries and in the defense industry.

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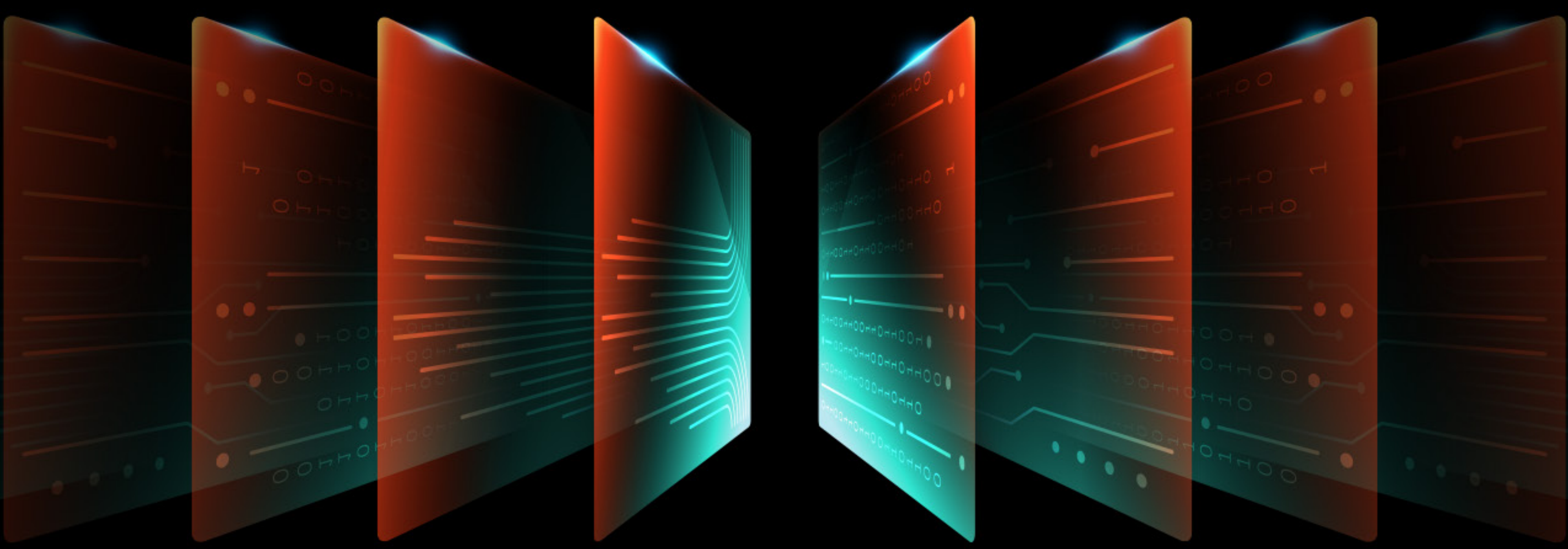
Software and AI/ML

APTIV AT CES 2025



The Intelligent Edge:
A New Frontier for AI Innovation

AI systems have evolved. Over the past few years, they have moved far beyond data analysis and real-time insights, now accessing vast amounts of structured and unstructured content to generate new ideas, solve complex problems, and suggest practical actions. Generative AI, powered by large language models (LLMs) and advanced frameworks, is unlocking unprecedented possibilities.

AI is primarily trained, built, deployed, and operated in the cloud. That's because current-generation AI demands extensive computational power, storage, and networking. It relies on specialized chips that are available only in large data centers that require reliable power and water resources.

However, while AI is developed in the cloud, its full potential will ultimately be unlocked at the edge, where people will directly experience and interact with AI-driven technologies.

Early industry examples of edge-based AI include facial and fingerprint recognition on mobile devices and autonomous systems such as robots, drones, autonomous vehicles, and surveillance systems.

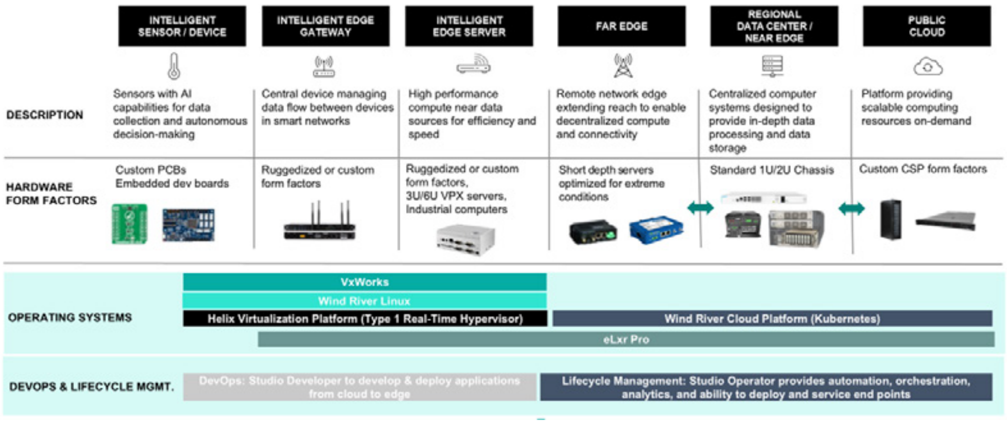
In the years ahead, the intelligent edge will democratize AI adoption and inference across industries, inspiring as-yet-unimagined applications. Success requires a robust platform that is secure, high performing, and efficient in both power and computational ability.

HONING THE INTELLIGENT EDGE

The current generation of embedded and edge systems serves industries such as aerospace, defense, industrial, medical, automotive, and telecommunications. Much of these systems' application logic relies on statically compiled code or dynamically loaded libraries, with minimal embedded intelligence. IoT technologies allow basic telemetry data from these devices to be collected, stored, and analyzed in the cloud. The resulting dashboard-driven descriptive analytics and machine learning-based predictive analytics have made a real difference for those industries and the humans who depend on them.

But that transformation is just the beginning. With the integration of diverse sensors into devices and rapid advancements in nanoscale chip technology, significantly more data can be captured and processed directly at the edge, without needing to route to the cloud. Additionally, silicon manufacturers are embedding AI capabilities within systems-on-chip (SoCs), which allows compact AI runtimes and enables frameworks to run on a variety of processors, including MPUs, MCUs, NPUs, CPUs, GPUs, FPGAs, and ASICs. These capabilities span silicon architectures such as x86, Arm, and RISC-V. They require real-time operating systems and Linux, which are predominant in embedded and edge systems, to support AI at the edge.

WIND RIVER PORTFOLIO ENABLES THE INTELLIGENT EDGE ACROSS EMBEDDED, EDGE, CLOUD



We expect the intelligent edge to support diverse silicon and the applications that run on it. That means new generations of distributed computing environments must be optimized for power and compute efficiency, compact AI runtimes and frameworks, hardware virtualization, application containerization, and DevSecOps and AIOps for AI-enabled applications.

Building the intelligent edge will create plenty of business benefits, such as:

- **Real-time decision-making:** Devices can analyze data in real time, which is essential in sectors where split-second decisions are crucial.
- **Lower latency:** Processing data closer to its source makes it possible to reduce the time to send information to and from centralized cloud platforms.
- **Improved security and privacy:** When sensitive data is processed locally at the edge, it doesn't have to be transferred to the cloud, lowering the risk of data breaches.
- **Bandwidth efficiency:** As the number of connected, intelligent devices grows, the network bandwidth strain is reduced; massive amounts of raw data do not need to be sent across the network to the cloud.
- **AI-driven insights:** With AI and machine learning (ML) capabilities integrated at the edge, devices can autonomously learn and adapt, gradually improving performance.

Today, the intelligent edge is defined by a fragmented, heterogeneous landscape of silicon architectures, semiconductor providers, operating systems, and tools.

To achieve its full potential, the intelligent edge will have to grow and eventually span the edge-to-cloud continuum, as well as the entire lifecycle of AI-powered applications, devices, and systems. Achieving this future requires a seamless edge-to-cloud infrastructure. Together, the intelligent edge and intelligent cloud will enable an AI-powered world where the physical and digital realms merge seamlessly.

It starts with a diverse portfolio that includes the right set of features. Anyone building applications for these environments needs a consistent operating environment across the data plane, control plane, management framework, and security infrastructure.

Wind River® has a comprehensive software portfolio. It includes real-time operating systems, Linux offerings, hypervisors, DevOps services, lifecycle management solutions, and, most recently, eLxr Pro, our enterprise-grade Linux solution. These tools — and the wisdom and experience gathered from our decades in the industry — help our customers and partners harness the power of the intelligent edge to build, operate, and maintain AI-driven applications across diverse industries.

We aren't stopping there. Wind River is also building an ecosystem and strategic partnerships with cloud hyperscalers, semiconductor partners, IHVs, ISVs, and AI startups. Each of them offers critical technologies that help our customers incorporate the intelligent edge into their plans to unlock new opportunities.

By Avijit Sinha, Wind River President

Wind River Studio's Unified Development Speeds Aptiv Software Rollouts

Automotive software development is increasingly challenging, but time to market is more important than ever. Complex, continually evolving applications and requirements have led to long development and update cycles. Developers depend on internal teams and partners distributed around the world, who struggle to collaborate. They need a faster, more unified way to build and update code.

URGENCY CLASHES WITH COMPLEXITY

Aptiv faces these challenges in creating high-quality software quickly for major OEMs. For increasingly connected software-defined vehicles, even minor functional enhancements can become vast global projects when they need to address cybersecurity, functional safety, communications and other requirements. An average software project at Aptiv involves a team of 100 to 150 people — and can include as many as 500 — often dispersed across a minimum of two or three locations and time zones.

Typically, fragmented workflows have prevented smooth, efficient collaboration. Each team had to accumulate its own tools, artifacts, pipelines, CI/CD (continuous integration/continuous deployment) toolchains and other assets. Code developed by one team would not work for another because the teams had been working in different environments or at different stages of the V-model, which describes the development and testing phases of the project. As software moved between teams, it could take hours to ramp up the same development environment, with its unique dependencies, just to reproduce a bug.

Development across disjointed workflows, such as when developing according to the V-model, was often a manual process. At each gate in the process, the entire stack might need to be recertified and recompiled. Each testing team would have to track down the right test methods and physical or virtual testbeds, and test results would then be stored in different locations and software management platforms, without standardized use of a common methodology. As a result, some development teams completed new releases only once per quarter, on a longer than necessary timeline to roll out updates and bug fixes.

Challenge

- Reduce time to release software updates
- Improve collaboration among software engineers dispersed across regions
- Eliminate duplication of efforts

Solution

- Adopted Wind River Studio Developer to standardize development and delivery workflows
- Shared common tools and test benches across global teams of developers
- Automated time-consuming tasks while optimizing existing tool investments

Results

- Increased developer productivity by as much as 25%
- Increased utilization of development and test hardware by up to 40%
- Achieved 68% faster scans and 20% faster builds

GETTING ON THE SAME PAGE

To increase developer productivity and shorten time to market, Aptiv is adopting Wind River Studio Developer, an end-to-end integrated DevSecOps (development, security and operations) platform. Studio lets developers view and share a consistent set of software tools on demand in the cloud through a single pane of glass that is common throughout the organization. Engineers at multiple sites can operate as true teams: building, testing and deploying code in common environments and workspaces instead of continually reconciling and redoing one another's work.

Studio comes with a standard set of high-performance development tools and standardized methodologies. Teams can also add their own internal and third-party tools from Wind River Studio Gallery. Out of the box, Gallery includes more than 30 tools specifically curated for intelligent systems and embedded use cases. The platform maintains all tools and other assets, including updated pipelines, build environments and workflows, for internal and external teams subject to built-in access controls.

This level of deep integration across the platform accelerates speed to market in several ways. Built-in tools let developers automate previously time-consuming tasks. The platform includes automated traceability to find the code written for specific requirements and verify its functionality, even long after its release. Continuous certification removes the hurdle of manually recertifying code at each stage in development, even for minor steps such as changing the name of a variable.

Studio simplifies testing by making all physical and virtual test platforms, and all previous test results, visible and accessible via the dashboard. It also includes tools for creating feedback loops to test features in the field. Combined with automation, this accelerates the pace of testing and, with it, the frequency of releases and updates.

STANDARDIZATION PAYS OFF

Aptiv is currently using Studio in 20 projects, growing to about 60 by the end of 2024, and the platform is already delivering significant benefits.

Developer productivity has increased as much as 25 percent on teams using Studio's Pipeline Manager for workflow automation. By improving access to test infrastructure, Studio has also increased utilization of development and test hardware by up to 40 percent.

Faster build-and-scan tools available with Studio are also accelerating projects. One team saw 68 percent faster scans and 20 percent faster builds compared with its existing high-performance build toolchains. Another team, using integrated third-party build-and-scan tools from Wind River Studio Gallery, achieved 25 percent build-and-scan improvement over its existing Jenkins toolchain.

GATEWAY TO NEXT-GENERATION DEVELOPMENT

Aptiv's experience with Studio demonstrates its potential to accelerate development by unifying teams around a common, consistent set of software assets in the cloud. It can bring the full benefits of DevSecOps to automotive OEMs facing growing demands for rapid innovation.

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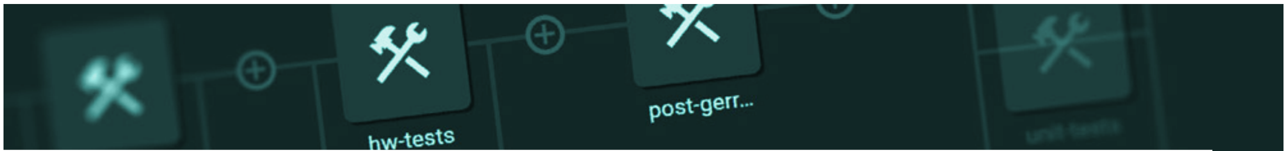


Aptiv Integrates Existing Toolchain Investments With Wind River Studio

Many development teams have invested heavily in a variety of tools that are required to create complex and safety-certified embedded software at a high level of quality. As they look to move to a more comprehensive, end-to-end DevSecOps platform, ripping out the old systems and replacing them is often not a viable option. They need a platform that will meet them where they are today while allowing them to improve their development environment well into the future.

SCATTERSHOT APPROACHES TO TOOLING AND PROCESSES

Like many others in its industry, automotive software maker Aptiv had invested in tools for every facet of the build process, including static analysis, dynamic analysis, security, code review, code formatting and quality checks. Testing, such as unit, module, integration, smoke, regression and system tests, is a very significant part of the process across different stages, and all of those tests must be monitored and analyzed.

Each development team in the organization had its own approach to using those build tools, and not all teams were even using the same ones. For example, there was no mechanism in place to enforce compliance with Aptiv's process of code reviews or unit test coverage. That meant that some teams would postpone those key steps until late in the development cycle, when it was more difficult and time-consuming to fix any bugs. There was also no visibility into how well a project was meeting quality goals along the way; it was evident only late in the development process.

ACCOMMODATING EXISTING TOOLS

To address those challenges, Aptiv's radar team was one of the first development groups in the company to implement Wind River Studio Developer. Studio brings development tools and processes into a single environment and automates the software build process — but it does so by integrating with existing tools. For example, Aptiv was able to integrate it with Coverity for static analysis, Gerrit for code review and Git for version control.

Challenge

- Increase efficiency in development of safety-certified embedded software
- Improve utilization of current software development tools and adherence to processes
- Gain better visibility into code quality on an ongoing basis

Solution

- Rolled out Wind River Studio Developer
- Leveraged pre-integration of third-party tools
- Used merge gates to enforce quality control along the way

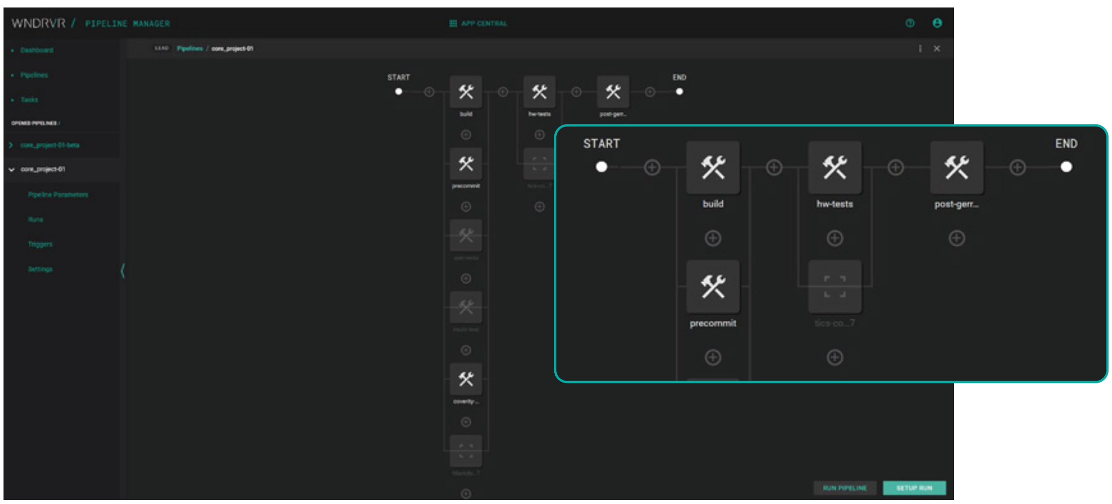
Results

- Ensured that developers perform all required checks
- Enforced policies across development groups
- Received ongoing reporting of code quality

While organizations can integrate tools without Studio, one of its key benefits is that it allows integration without IT having to get involved every time. Aptiv's IT staff used Studio to configure tools as reusable building blocks up front, so developers and even managers can now set up the tools for individual projects through Studio's easy-to-use interface. The process is more efficient now that the people directly involved in the development process have the ability to optimize the environment for their specific needs.

Importantly, Aptiv also was able to integrate dashboards to provide continuous updates on the health of a project. Studio provides data from other tools to a dashboard, allowing visibility into which developers are meeting the standards put in place — and which are not — on any given day, and project managers can see how the projects are progressing on those metrics over time.

Aptiv's initial implementation of Studio for a radar project took several months, but rolling Studio out to a subsequent project took just two weeks.



ENFORCED COMPLIANCE FOR BETTER CODE

With merge gates visibly in place, Aptiv is able to enforce peer review and other checks before new code is allowed to be integrated with the rest of the project. Software development best practices are being followed. Through dashboards, project managers can see when peer reviews are happening, unit tests are being conducted and static analysis warnings are being resolved. Any issues with code are being addressed earlier in the development process.

Aptiv found that Studio makes it easier to get new software developers up to speed because the mandatory process of automated checks means that even entry-level engineers can be confident that their code is stable before it is merged into the larger project.

For next steps, Aptiv is looking to integrate more of its testing tools into its Studio pipelines, including software-in-the-loop and hardware-in-the loop tests, which are very important considerations for automotive radars. Advanced test orchestration through the Studio Test Automation framework and Wind River Studio Virtual Lab will allow teams to better manage which tests get called, and to automatically collect results.

With the integration that Studio offers, Aptiv now is able to use its best-of-breed development tools in the way they were meant to be used — and it is ready to roll Studio out to more of its development teams.

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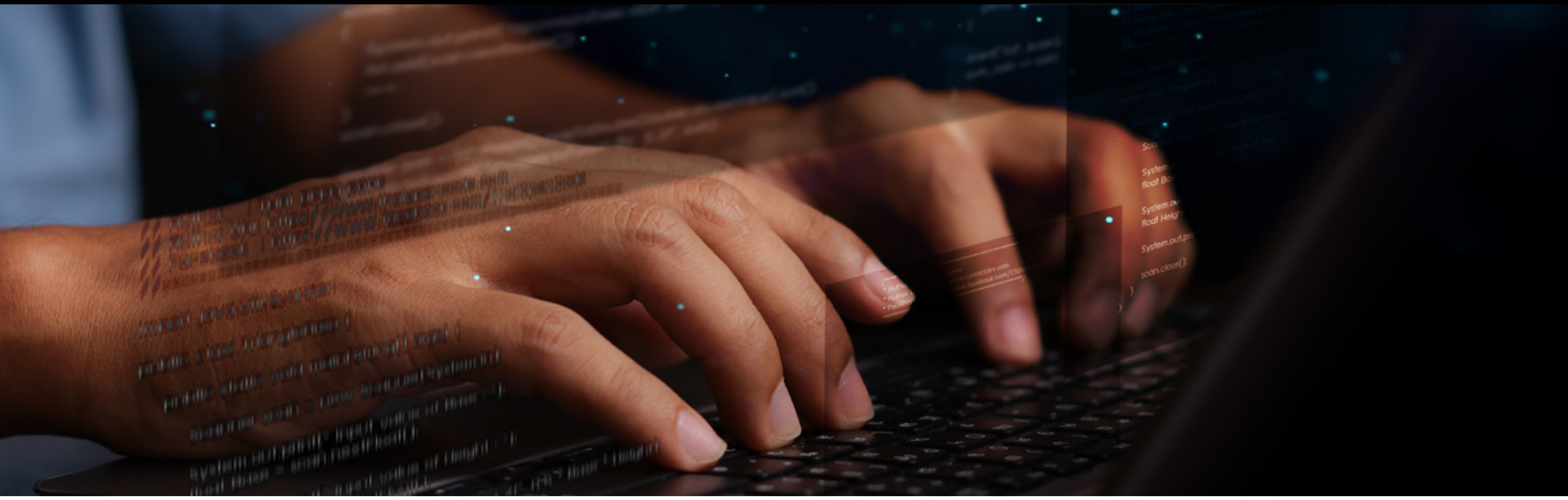


RTOS and Linux Are Defining In-Vehicle Computing – Together

As the industry moves from function-specific hardware and software to centralized in-vehicle computing and software-defined vehicles, it is clear that Linux will play a significant role in future vehicle platforms. Linux has a long and proven history in other industries and is extremely flexible, which makes it a natural choice for automotive applications.

But as OEMs introduce applications with specialized requirements — especially around functional safety for fully or partially automated driving — there is a need for a real-time operating system (RTOS) that is optimized for deterministic latency in safety-critical use cases.

In evaluations of potential future in-vehicle software architectures, it is important to understand the relative strengths of Linux and RTOSes and how they complement each other in this changing landscape.

KEY DIFFERENCES

Not all applications have the same timing requirements, and the differences among those applications necessitate different approaches to the operating systems that support them.

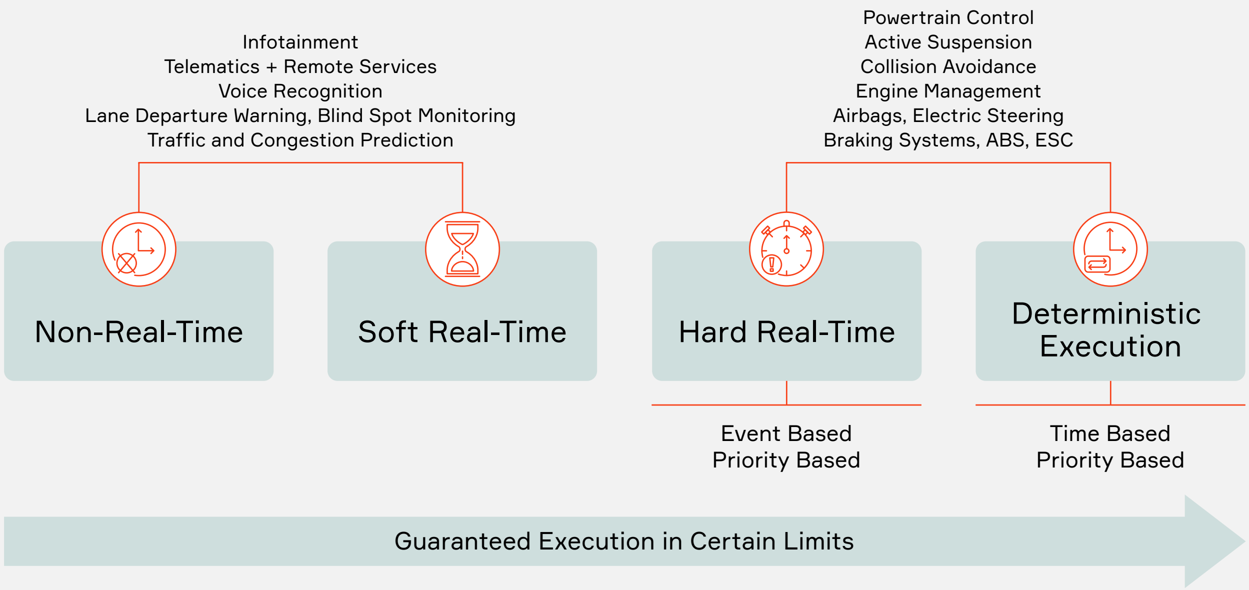
Some applications do not need to guarantee that they will complete their tasks within a specific time frame. The application should run as fast as possible, but minor delays are acceptable. Automotive examples include telematics, remote services and traffic prediction. These are non-real-time (non-RT) applications.

With other applications, a delay might result in a less-than-optimal user experience. In the automotive world, these applications include some functions of advanced driver-assistance systems, such as lane-departure warning and blind-spot monitoring. They deliver important, timely information but do not require an immediate response by the driver. The OS needs to enable the scheduling of tasks but does not need to guarantee predictable performance or the protection of the tasks from interference from other applications. These are considered “soft” RT applications.

But for other applications, a delay could have serious consequences. Examples include software functions that control a vehicle’s movement, such as automatic emergency braking, lane changing, and autonomous vehicle maneuvering to avoid collisions. These are called “hard” RT applications, and they are often safety-critical.

What Is Real-Time?

A real-time system can guarantee that tasks consistently execute in a specific time constraint. Determinism is the characteristic that describes how consistently a system executes tasks within a time constraint. In a deterministic system, the sequence of executing tasks is always the same.



The contenders

As a general-purpose operating system, without modifications, Linux is suitable only for applications where delays can be tolerated.

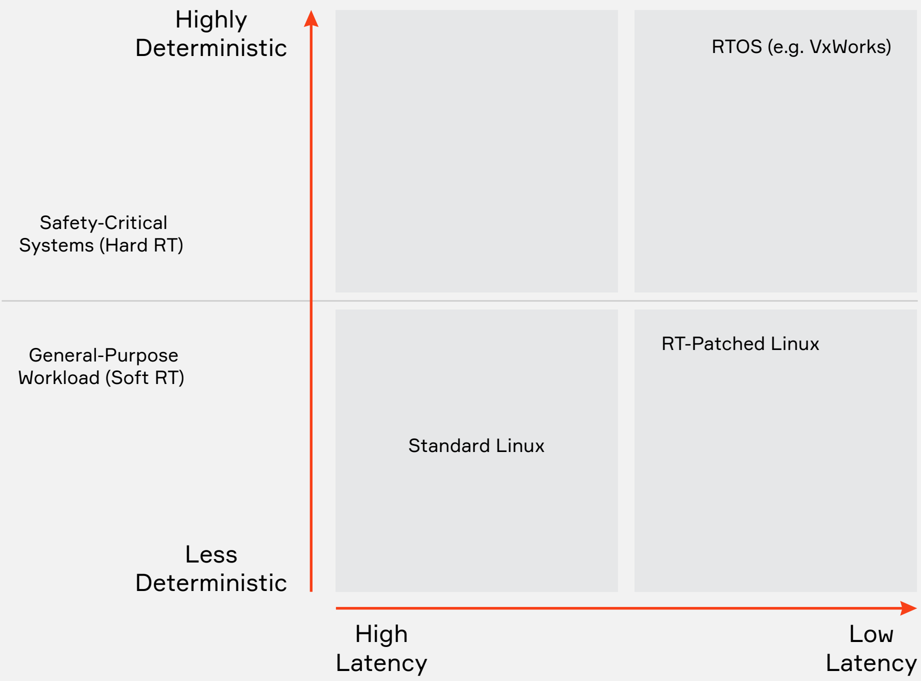
Linux has proliferated across enterprises and industries partly due to its low cost and vast ecosystem of open-source developers and tools. OEMs have adopted or evaluated Linux for a wide range of vehicle applications, and it has already proven ideal for some.

In contrast, an RTOS is designed exclusively for real-time applications, with features that guarantee that a given input will produce the same outcome on time, every time. The RTOS enables RT applications to reserve OS resources at specific times and use them to complete tasks by strict deadlines. It ensures that events take place at the correct time, not just as soon as possible. These characteristics are indispensable for hard RT applications.

In addition, RTOSes have fewer lines of code compared with general-purpose OSes. This gives OEMs several benefits. From a security perspective, less source code translates into less surface area for attackers to target, reducing risk and the work required to mitigate it. That said, it is still important to use an RTOS designed with a secure development lifecycle. In terms of safety, a smaller, less complex OS takes less effort to certify for functional safety standards. These advantages can help OEMs bring a vehicle to market faster.

Right Tools for the Job

Different variations of operating systems are appropriate for different applications within a vehicle.



Running RT workloads on an RTOS can also reduce costs. With less source code, an RTOS has lower CPU and memory requirements, which can translate into a lower hardware bill of materials. If an RTOS has been precertified for safety, this saves OEMs the considerable cost of certifying it themselves. In addition, RTOSes — especially their source code and APIs — change more slowly, reducing maintenance and security costs, preserving an OEM's investment, and reducing the need to re-certify the operating system due to changes.

MODIFYING LINUX FOR SOFT RT APPLICATIONS

While RTOSes are the clear choice for hard RT applications, several Linux patches now make it possible to run soft RT applications on versions of Linux.

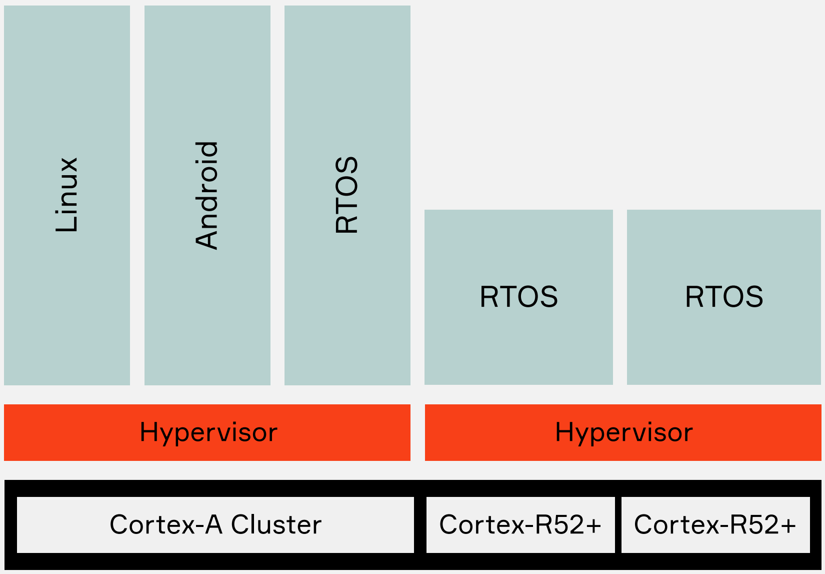
These allow OEMs to shift some real-time functions from an RTOS to Linux, but doing so may affect performance and manageability in some ways, including the following:

Timer slack

A patch to the Linux kernel increases the resolution of kernel timers by making it possible to wake up the CPU more frequently. This allows for nanosecond precision, which some RT application threads require. However, waking up the CPU more often may increase power consumption and reduce CPU efficiency. The patch also enables more accurate timing in RT threads but does it by using timer slack, a technique that delays events in threads with normal timing policy. This can cause more jitter in asynchronous applications.

Mix and Match

Various operating systems can coexist side-by-side on the same hardware, but they should be logically separated via a hypervisor, and on different cores as needed.



Process suspension

Because RT systems are engineered to execute the current top-priority task on deadline, it is often necessary to use a custom scheduling method rather than the Linux kernel's standard method. If an RT process is trying to use 100 percent of a CPU, the kernel's standard scheduling method suspends the process for 50ms every second. A patch for RT support deactivates the suspension mechanism, but this feature is so essential to the kernel's scheduling system that removing it may cause instability or failure.

There is industry momentum behind making Linux more applicable for safety-critical applications, including an initiative called Enabling Linux in Safety Applications (ELISA), which is working with member companies, certification authorities and standardization bodies to establish how Linux can be used as a component in safety-critical systems.

HOW RTOS AND LINUX CAN COEXIST

By running all hard-RT vehicle applications on an RTOS and devoting Linux to non-RT and soft-RT workloads, OEMs enjoy the inherent benefits of the RTOS while minimizing the complexity of Linux. This is likely to reduce software development and maintenance costs and improve security.

Centralizing onboard processing gives OEMs an ideal opportunity to run Linux and an RTOS side by side. Shared computing platforms can host multiple OSes running applications with different levels of criticality by using two key technologies: software virtualization through a hypervisor, and hardware isolation on separate processor cores.

Software virtualization

Soft-RT applications can run on the same set of cores as Linux and other OSes in a virtualized system that allows the flexible use of resources. (See example in sidebar.) Each OS runs in its own virtual machine, with a hypervisor (such as Wind River Helix Virtualization Platform) managing common memory, computing resources and processor cores across a cluster of ARM Cortex-A performance cores. Within applications, containerization may provide a further layer of virtualization for more flexible development and maintenance.

Hardware isolation

Safety-critical applications can run on one or more RTOSes and coexist on the same system-

USE CASE: AUTOMATIC EMERGENCY BRAKING

One example of how Linux and an RTOS might work together in a vehicle is the implementation of automatic emergency braking, a hard-RT application.

As a vehicle approaches an object, its cameras, radars, lidars and inertial sensors send data to zone controllers, which forward the data to the central vehicle controller. Software running on Linux on that device uses computer vision and machine learning algorithms to fuse the sensor inputs and put them in context.

The Linux software sends that data to the braking regulator, a small application connected to the braking system. The braking regulator runs on a safety-certified RTOS to ensure that it can apply the brakes at precisely the right time. By applying an algorithm to the contextualized sensor data, the braking regulator constantly calculates the risk of a crash and applies the brakes when necessary.

on-a-chip as non-safety-critical applications, but isolated on a "safety island" using Cortex-R cores — as long as the RTOSes, the hypervisor and the cores are rated to support ASIL-D risk levels. The safety island may contain multiple OSes virtualized through a hypervisor. Isolation on the safety island prevents failures in less-critical applications from crashing applications that affect life safety.

Evolving with hardware architectures

These configurations can be implemented in current and future vehicle architectures with varying degrees of centralization in domain architectures, zonal architectures or a combination. In all cases, middleware is the essential glue that enables communication and coordination among all containers, applications and OSes in the vehicle. Multiple OSes will run on many cores under one software stack, with cores assigned to different OSes as necessary.

EMBRACING THE POSSIBILITIES

The trend away from purpose-built electronic control units and software in favor of software-defined vehicles has opened up space in vehicles for a variety of OSes, including Linux. With high performance and a large development ecosystem, Linux complements deterministic, safety-certified RTOSes. OEMs that understand the benefits and limitations of each can deploy them on centralized hardware with unprecedented flexibility, improving future vehicles and making development faster and more cost-effective.

In 2022, Aptiv acquired Wind River, which specializes in providing tools that support robust, reliable and secure embedded solutions, including Wind River Linux and the Wind River VxWorks RTOS. Both offer unique strengths for automotive applications and draw from a long pedigree of supporting safety-critical operations in other industries.

ABOUT THE AUTHOR

Rob Woolley
Principal Technologist, Wind River

Rob Woolley is a Principal Technologist at Wind River in the CTO Office. He has 25 years of experience with both enterprise and embedded Linux and more than 15 years with the VxWorks RTOS. He is actively involved with the open source community as the maintainer of the Robot Operating System framework for OpenEmbedded and participates in Zephyr RTOS and ELISA from the Linux Foundation. His current focus is on using cloud-native technologies to orchestrate workloads on edge devices, including software-defined vehicles.

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What Is Cloud-Native in Automotive?

Cloud-native is an approach to cloud computing that is essential to expanding functionality and streamlining software development and deployment in automotive. Cloud-native vehicles will become intelligent edge devices, not only evolving through software updates delivered via the cloud but also leveraging the vast processing power available in the cloud for specific functions.

However, to optimize the benefits of a cloud-native approach, vehicles must be designed from the beginning with cloud-native in mind. Some features and services will always have to run on the vehicle — such as safety-critical applications — which means that the vehicle's hardware and software architecture must be engineered to balance processing between onboard compute and the cloud.

But what are the benefits of cloud computing that make rearchitecting the vehicle worth the effort? In other words, why does the automotive industry have its head in the cloud?

What is driving cloud computing?

In the automotive industry, vehicles are evolving beyond mere modes of transportation and are becoming software-defined devices on wheels. Consumer demand for increased software functionality has made a cloud-native approach essential.

Compute power is expensive, and there are already more than enough features competing for limited onboard processing power. Cloud connectivity offers a powerful computing resource to enable premium user-experience features, reduce costs or both by offloading processing power to the cloud, thus enabling OEMs to reduce vehicle hardware costs while improving performance. Finally, there are some features or services that are possible only by aggregating inputs from other devices — including a fleet of vehicles — which naturally favors the cloud for consolidation, analytics and input back to the vehicle.

Will vehicles run entirely in the cloud?

Cloud-native principles have already revolutionized various industries, including web development and IT. Consumer electronics have shifted more of their processing to the cloud as well. Most mobile device applications are designed to minimize their footprint and rely on cloud processing to perform their primary functions. However, this level of cloud interconnectivity is not appropriate for many automotive applications. As a result, vehicles will not run entirely in the cloud anytime soon.

Low latency and cybersecurity are essential for safety-critical systems, so core vehicle functions must be able to completely rely on local high-performance compute resources. But the cloud can still enable OEMs to expand functionality over time and generate new revenue streams, and 5G connectivity opens up new opportunities for processing at the edge, such as low-latency processing at local base stations.

By leveraging the cloud for additional processing tasks, vehicles can run more powerful algorithms for long-term vehicle and behavioral data analysis. This will enable them to deliver incremental feature improvements for end users, enable predictive maintenance, optimize performance and reduce downtime. Through the digital feedback loop, cloud-native solutions support scalable data processing, allowing for historical trend analysis and strategic decision-making based on comprehensive, aggregated datasets at the fleet level to improve software development and automation.

Benefits of cloud-native in the automotive industry

Cloud-native development offers immense potential to revolutionize the automotive industry in various domains. Here are some of the other benefits of a cloud-native approach:

- **End-user personalization:** A cloud-native approach makes it easier for OEMs to introduce new features through over-the-air updates, allowing them to generate new revenue streams and enabling vehicles to feel like new to customers every day. OEMs could even use vehicle data to offer customized features such as a battery management software designed around a user's specific driving patterns.

- **IoT connectivity and V2X:** Cloud-native development enables internet of things (IoT) communication — improving the safety, comfort and convenience of vehicles by allowing them to communicate with a wide range of devices. For example, support for vehicle-to-infrastructure communication through 5G enables a vehicle to communicate directly with traffic lights to find out exactly when a red light will turn green, which lets it save energy and time by maintaining a steady speed as it approaches. Vehicle-to-grid is another example of vehicle-to-everything that lets EVs communicate with the public power grid; this gives OEMs greater control over the charging process so they can optimize charging cycles and extend the overall life of the battery. Software-as-a-service could enable OEMs to easily employ each of these use cases by subscribing to an independently managed application via an API — with software updates, bug fixes and general software maintenance being handled by the SaaS provider.

- **Scaling compute:** Cloud computing allows developers to dynamically scale compute resources based on demand. Packaging applications and their dependencies into software containers makes them easy to deploy across different environments, and utilizing services gives developers the flexibility to make changes to independent software functionalities without affecting adjacent services.

- **Shared mobility:** Down the line, a cloud-native infrastructure will be necessary to enable shared mobility. By providing a scalable infrastructure for processing vast amounts of real-time data, a cloud-native architecture will support ride-hailing, vehicle tracking and route optimization, allowing seamless coordination between users and services.

Cloud-native requires an end-to-end approach

Executing a cloud-native vehicle architecture comes with unique requirements. Cloud-native vehicles need a hardware architecture that is independent of the software that runs on it, and the ability to make targeted updates to safety-critical systems.

A microservices architecture helps achieve this by breaking complex monolithic software applications into smaller, more manageable components that are easier for developers to update and maintain. This type of modular approach enables greater scalability, resilience and agility compared with traditional, monolithic applications.

A DevSecOps platform that enables continuous integration, continuous deployment and continuous testing is essential to managing the lifecycle of the vehicle during development and after the point of sale.

As the only provider of an integrated vehicle brain and nervous system, Aptiv is well equipped to help OEMs adopt a cloud-native approach. We are integrating our Smart Vehicle Architecture™ technologies with Wind River Studio, a cloud-native toolset for developing, deploying, operating and servicing mission-critical intelligent systems across the edge.

What Is Middleware in Automotive?

Middleware is a type of software used in the automotive industry as a bridge between a compute platform's operating system and the applications that run on it.

Middleware has existed in IT and other industries for many years, but the automotive industry has unique software development challenges that require special consideration. As vehicles evolve into increasingly complex software-defined devices, managing communication and interactions between hardware and software components becomes a complex juggling act.

Despite increasing efforts to centralize, it is not uncommon for today's vehicles to have more than 100 electronic control units (ECUs). These small compute devices control specific functions, such as power steering, climate control and airbags. Middleware bridges the gap between such varied software and hardware platforms, making it easier to design, build, test, deploy and update applications.

Middleware is crucial in the transition to software-defined vehicles. Without it, over-the-air updates would be impractical and prohibitively expensive — requiring each of those 100-plus ECUs to be reprogrammed independently.

Middleware abstracts software from hardware

Middleware enables a service-based architecture, where software services are modular and reusable across different vehicle models or platforms. By abstracting the software and input/output (I/O), middleware allows applications to focus on high-level functions rather than low-level hardware specifics — separating the signal layer from the application layer.

Middleware operates in between the application layer and the operating system. That is what the "middle" in middleware refers to. Middleware uses that position to abstract applications from the hardware, meaning developers do not have to program applications with instructions for communicating with each of the various devices in a vehicle. Instead, developers create applications that communicate at a higher level with interfaces in the middleware, and the middleware handles the rest.

Think of middleware as similar to a USB adapter; the computer the adapter connects to is like the compute platform on a vehicle. The adapter adheres to certain standards to safely communicate with the computer and is indifferent to the devices that are connected to it. Thanks to the standardized ports, the user can use the adapter to interface with a variety of devices.

Middleware provides developers with the same freedom. It standardizes the interface between vehicle hardware and software applications and acts as a translator to ensure that applications can communicate effectively with various hardware systems without needing to be tailored to each specific component.

Applications communicate through middleware

Vehicle applications communicate using a variety of data formats and standards. While APIs govern the flow of data between software components, middleware manages communication across different systems, ensuring APIs can effectively interface with hardware through standardized protocols.

For example, an OEM may want to offer a climate control app through its infotainment system. When the user selects a desired temperature, the infotainment application informs the middleware about the user commands, and then the middleware translates those commands based on specific hardware and I/Os and sends the signals to the appropriate devices, such as the compressor, the fans and the flaps.

The infotainment system does not need to know the mechanics of climate control because the middleware acts as an intermediary. As a result, developers can focus on creating a positive user experience for consumers instead of focusing on integration.

Operating systems communicate through middleware

Automotive middleware is also essential to enable communication between a vehicle's operating system and its application software. It enables communication and data exchange between different components of a vehicle's software architecture — between apps within the same operating system domain, between different operating system domains on the same ECU and between ECUs.

Aptiv's central vehicle controller (CVC) can have multiple operating systems running at once, including Linux, AUTOSAR classic and a real-time operating system such as VxWorks. Middleware enables the applications running on all of these operating systems to communicate seamlessly.

Middleware improves testing and accelerates development and integration

Because middleware decouples software and hardware development, developers can begin testing software earlier. Simulation testing using software-in-the-loop can run on any standard desktop computer, allowing software developers to create new features at a faster pace. Shifting testing earlier also helps catch bugs faster, reduces costs and speeds up time to market.

Middleware can facilitate container orchestration, which enables developers to manage and update applications in a modular way without having to worry about systemwide dependencies. Similar to cloud environments, where containers are used to isolate applications and manage their deployment, in-vehicle containers allow software components to run in isolated environments.

With the help of an in-vehicle container orchestrator, applications can be deployed, updated and tested independently of each other, making the software development lifecycle far more agile. For instance, developers can create isolated test environments for new features, simulate their behavior in real time and deploy updates over the air without disrupting the entire vehicle system. This container-based approach ensures faster integration and testing because it isolates potential issues and reduces the complexity of testing different systems together.

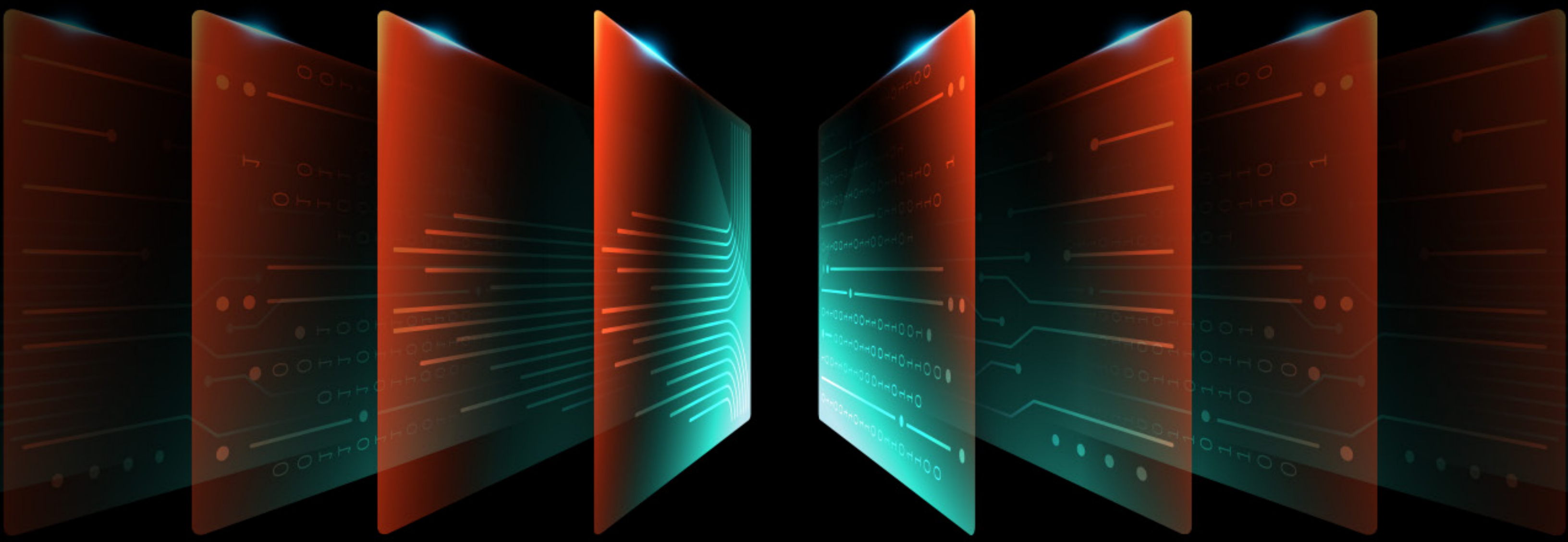
In this model, middleware acts as the layer that manages communication between containers and the underlying hardware, ensuring that each application has access to the necessary resources, such as processing power, memory or specific hardware components like sensors and actuators.

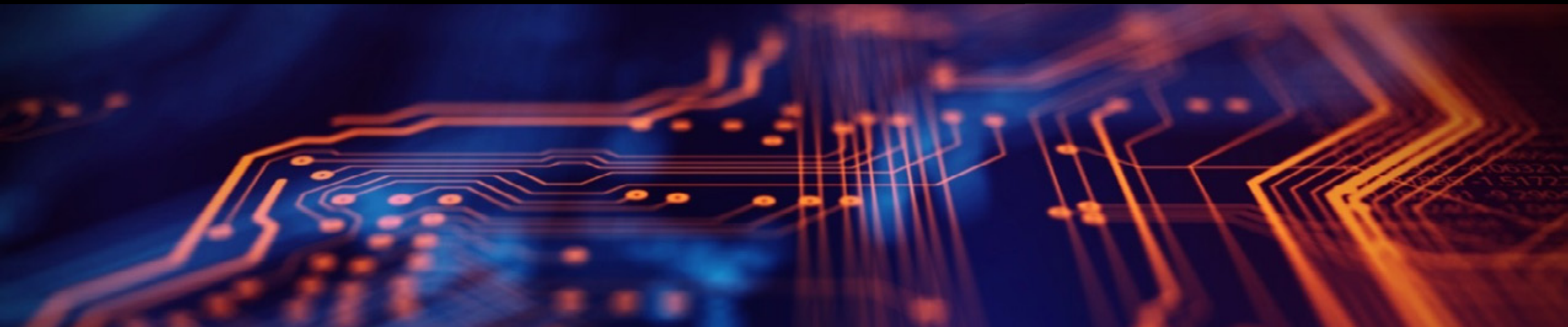
Middleware is one piece of an end-to-end solution

Aptiv and Wind River bring together middleware, operating systems and hypervisors as an integrated solution to accelerate software development and improve software reuse, so OEMs can spend less time integrating and more time designing brand-differentiating features.

Sustainability

APTIV AT CES 2025





Achieving Design and Manufacturing Efficiencies on the OSP

When designing high-performance compute (HPC) platforms to support software-defined vehicles, the first steps are to consolidate domain functionality and to abstract software from hardware. But there are distinct advantages in going a step further and isolating the main system-on-a-chip (SoC) onto a system-in-a-package, or SiP.

A SiP bundles the SoC with a couple of other key components, such as additional memory and power management integrated circuits, into a standard-size package that can then be soldered directly onto the mainboard of an HPC device.

The mainboard has all of the interfaces required for data coming into the HPC and data going out. For example, a mainboard for an HPC device such as Aptiv's open server platform (OSP) for user experience would hold deserializers for video streams coming from interior sensing cameras, outputs for high-definition displays, audio interfaces, an Ethernet switch and any other communications interfaces, such as Bluetooth, Wi-Fi, GNSS and USB. The mainboard would also contain a "housekeeping" microcontroller to handle communications inside the vehicle, oversee the peripheral startup sequence and manage the sleeping and waking up of the SoC.

Using a SiP decouples the development of the mainboard with all of its connections and peripherals from the development of the SoC and its higher-level software.

What makes SiP easy to swallow

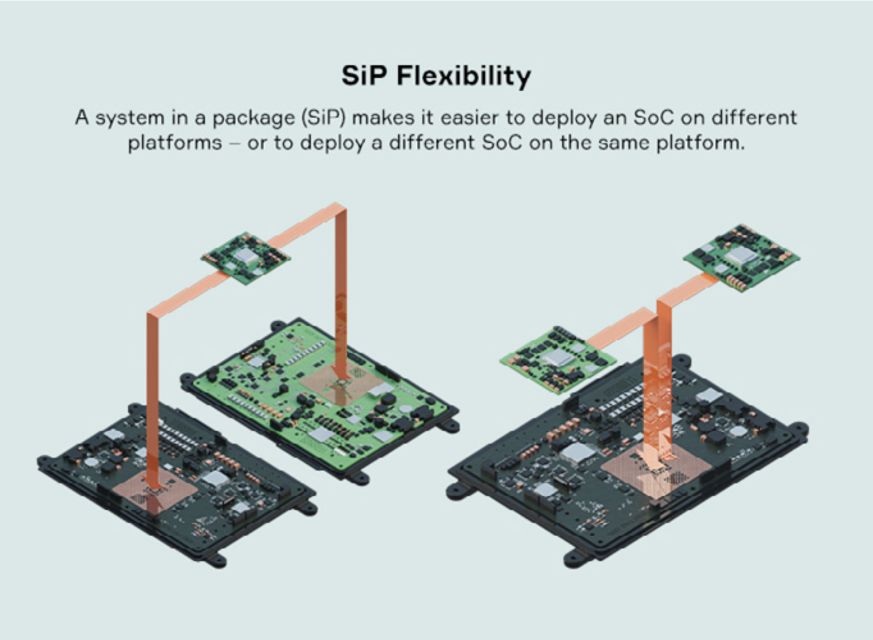
While SiP has long benefited the computer industry, applying this approach to automotive yields several distinct advantages.

First, it enables OEMs to easily replace one SoC with another, which is a key capability for building supply chain resiliency. With minor changes to base-level software, two SiPs with the same footprint — each with a different SoC — can be interchanged onto the same mainboard. In the past, moving from one SoC to another could take up to 26 weeks; with a SiP, the migration could be just six to eight weeks.

Second, decoupling the manufacturing of the mainboard and the SiP allows each to be developed separately. An SoC requires more layers on the board, so it can save costs to have an SoC on the smaller SiP board.

Third, this interchangeability promotes scalability. An OEM could use the same mainboard with different vehicle models, from entry-level to premium, and just use a different SiP to support a different level of functionality. Alternatively, designers could drop the same SiP into different mainboard form factors for different vehicles. Depending on where it fitted within a vehicle, an HPC device could have a very different shape, and designers would only have to focus on developing the mainboard to meet those size and shape requirements before adding in the fully developed SiP.

Fourth, Aptiv believes the SiP approach could be applied to all compute throughout a vehicle. While the highest-profile HPC device in Aptiv's Smart Vehicle Architecture™ product portfolio is the OSP, the SiP design is also able to achieve the same advantages in the central vehicle controller for lower-level functions, or even in a zone controller. Some vehicle architectures may use hybrids of these devices — such as a combination central vehicle controller and zone controller — and the SiP approach is suitable there, as well. In all cases, OEMs can save time and cost by validating SiPs separately from each of the devices in which they reside.



Part of the big picture

To be sure, abstracting the software from the hardware is another key enabler, and the hardware design must support that approach. By using tools such as middleware, the Wind River Helix hypervisor and the VxWorks real-time operating system, developers can swap out one SiP for another and maintain the same software functionality.

But with a SiP approach, the SiP — not the entire board — becomes the platform. That means software maintenance is easier. If there is a bug on the platform, it can be fixed on the SiP — no matter what mainboard it is attached to.

In short, a SiP-based architecture provides the hardware flexibility that OEMs need to create software-defined vehicles, given global supply chain uncertainty, scalability requirements and the need to evolve over time. Aptiv uses SiPs in our products to achieve supplier flexibility, and we are creating our own SiPs for future compute products.

Building A Sustainable Future

Every day, our employees around the world are developing innovative, sustainable products and services to power the software-defined future. A reflection of our values, sustainability permeates every aspect of our business, from how we develop our employees and serve our partners to how we support our communities and preserve our environment. From the sensor to the cloud, our unique full-system expertise enables us to anticipate the future needs of our customers and invest in the technologies necessary to make the world a better, safer place for generations to come.

As a global leader in the development and delivery of mission-critical intelligent systems, Aptiv understands that sustainability is a transformational journey that relies on our ability to support our people, products, platforms and planet. Our legacy has been built on our passion for innovation, which drives our teams around the world to continue to push the boundaries of what's possible.

It all starts with our employees — our most valuable asset — and we are committed to ensuring that they have the resources and training necessary to live our values while developing sustainable solutions to solve our customers' toughest challenges. We continue to invest in our world-class facilities, including our new technical center in Bengaluru, India, which opened last year, as well as in the development and retention of our global team. We continue to prioritize culture-defining experiences, including our annual Aptiv Innovation Awards, recognizing outstanding contributions from individuals and teams across functions and geographies. This annual event celebrates the many ways our people are transforming what we do — provide our customers with flexible, full-system solutions that enable the life-cycle management of their products — and how we do it.

To realize a future with zero accidents and emissions, we are developing solutions with a safe, green and connected impact in mind. Aptiv active safety technologies are currently deployed across more than 55 million vehicles worldwide, and last year we introduced industry-leading solutions – including battery management software, power electronics and automated parking systems — that improve vehicle safety and performance. We also expanded our portfolio of recycled-plastic products to include transmission brackets, wire shields and floor side rails. Our platforms enable customers to accelerate the path to the fully electrified, software-defined vehicle. Aptiv's Smart Vehicle Architecture™ (SVA™) enables OEM partners to reduce weight, mass, labor and, ultimately, CO_2 emissions. And Wind River Studio works with a cloud-native software architecture and virtualized hardware to help customers across industries lower embedded software life-cycle costs, shorten time to market, accelerate innovation and capture new revenue opportunities.

By doing the right thing, the right way, we continue to reduce our environmental footprint and are on track to reach our 2025 sustainability goals and carbon neutrality by 2040. We remain focused on ensuring that our operations are streamlined and minimize risks to the environment, human rights, and data security across our supply chain. We continue to build diverse teams that develop innovative solutions with a positive impact on the environment. We are proud to be recognized by Ethisphere as one of the World's Most Ethical Companies for the 12th consecutive year — a reflection of the strength of our Code of Conduct, which serves as the basis for putting our values into action.

This report outlines our annual progress and the commitments we have made to our customers, communities and employees in making the world a better place. As we navigate the complexities of an ever-changing world, we do so with purpose, integrity and an unyielding dedication to building for a sustainable future.

Kevin P. Clark
Chairman and Chief Executive Officer

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