Whitepaper

Virtual Redundancy: Enabling Software-Defined Vehicles Through Guarded Safety Architectures

How Virtual Redundancy can reduce safety-related hardware overhead by up to 30% while maintaining safety through runtime monitoring, OOD detection, and deterministic fallback mechanisms.

AI-driven Analytical Redundancy can reduce the need for costly physical duplication, but it becomes publishable and safety-credible only when wrapped by a deterministic, independently argued guardrail: runtime monitoring, uncertainty handling, Out-of-Distribution (OOD) detection, and safe fallback to a Minimal Risk State.

Executive Summary

Modern SDV architectures are reaching the limits of hardware-based redundancy. Instead of duplicating sensors, ECUs, and wiring, Analytical Redundancy uses virtual sensing to derive system states from existing vehicle data.

Robust and future proof safety is built upon a secure-by-design architecture using virtual redundancy. That pairs advanced AI capabilities with continuous runtime supervision, reliable deterministic fallback mechanisms, and precise operational boundaries.

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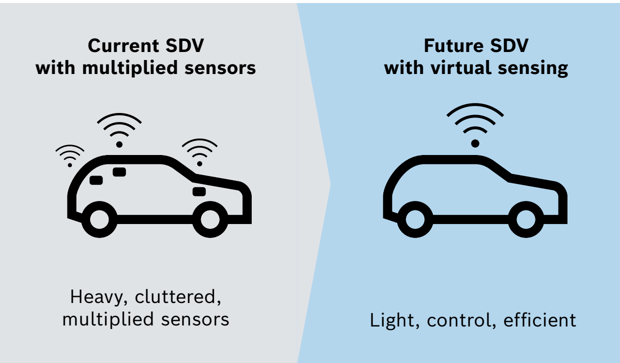
01.
The Challenge: Redundancy Bottleneck in SDV E/E Architectures

As software-defined vehicles introduce more software-driven and safety-relevant functions while consolidating functionality onto shared compute platforms, traditional hardware-centric redundancy becomes increasingly difficult to scale. Adding dedicated backup sensors, controllers, and wiring for every new safety requirement creates growing pressure on cost, weight, packaging, power consumption, and semiconductor availability.



Space & Weight Constraints: Additional wiring harnesses, brackets, and thermal support reduce architectural efficiency.

Cost Escalation: Relying on hardware redundancy for safety scaling results in higher Bill of Materials (BOM) costs, increased system complexity, and reduced architectural efficiency across SDV platforms.

Platform Reuse Pressure: Central and zonal E/E architectures shift the question from per-function redundancy to reusable platform safety patterns.

Safety Evidence Challenge: Replacing hardware redundancy with software-defined redundancy shifts the burden from hardware metrics to architectural containment, monitoring, and validation evidence.

02.
The Paradigm Shift: AI-Driven Analytical Redundancy

Conventional safety architectures rely on hardware redundancy to achieve fault tolerance. In software-defined vehicles (SDVs), however, this approach becomes increasingly difficult to scale due to cost, complexity, packaging constraints, and shared compute resources. Analytical Redundancy provides a software-defined alternative by generating virtual sensor information from existing vehicle data.

Instead of relying on dedicated backup sensors, AI models estimate system states using diverse inputs such as Perception Sensor-data, wheel speed signals, camera perception, and vehicle dynamics data. Beyond reducing hardware, Analytical Redundancy enables the reuse of existing data and redundancy resources across vehicle platforms, making it a scalable building block for future SDV architectures.

03.
The Solution:
A Guarded AI Safety Architecture

While AI enables software-defined redundancy, the safety argument must be made at the architectural level rather than relying on AI performance alone. The proposed system monitoring, a Guarded AI Architecture, combines AI capabilities with independent safety supervision and is framed by ISO/PAS 8800, SOTIF principles, and established ISO 26262 functional safety practices:

Primary AI Path:

→ High-performance AI models provide virtual sensing and state estimation, these models act as highly efficient black-box estimators that capture complex, non-linear relationships across diverse vehicle data sources.

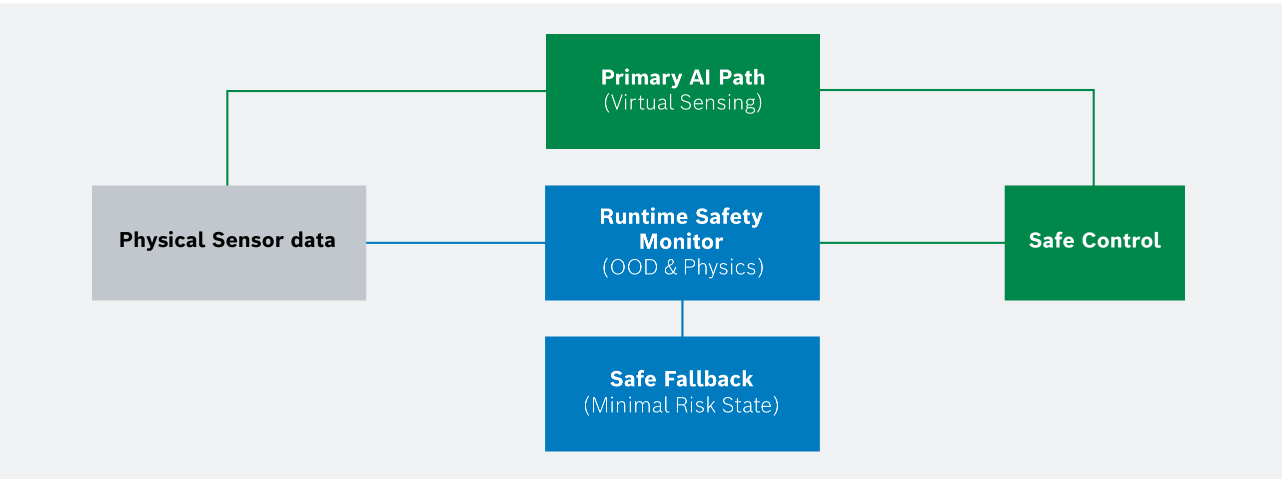
Runtime Safety Monitor (RSM):

→ An independent and verifiable monitoring layer continuously evaluates:

→ Out-of-Distribution (OOD) Detection identifying scenarios outside the validated operating domain.

→ Uncertainty Quantification – measuring the confidence of AI outputs in real time.

Limiting Logic and Safe Fallback:



If excessive uncertainty or OOD conditions are detected, control is transitioned to a deterministic fallback path, such as a physics-based estimator or degraded operating mode. This ensures a safe transition toward a Minimal Risk State.

The combination of AI, monitoring, limiting logic, and fallback mechanisms creates a reusable Safety Envelope that can be deployed across SDV platforms and software generations.

04.
OEM Business Impact

Analytical Redundancy delivers benefits beyond safety. By reducing dependency on dedicated backup hardware, OEMs can improve platform scalability, integration efficiency, and software flexibility. The OEM Business Case: Key Quantified Impacts

E/E Hardware Costs: Up to 30% Lower Safety Hardware Overhead – Less dedicated redundancy, lower BOM, and reduced integration effort.

Weight & Range: Higher Vehicle Efficiency – Significant weight savings, directly translating into increased BEV range.

Life Cycle Value: Enables OTA-up gradable safety (SOTIF / ISO 8800/ ISO26262) over the entire vehicle life cycle, avoiding costly physical hardware recalls.

Time-to-Market: Faster Time-to-Market through simulation-first development and software-hardware decoupling, reducing development integration times by up to 40%.

05.
Conclusion

Software-defined vehicles require redundancy concepts that scale with centralized compute, platform reuse, and continuous software evolution.

Analytical Redundancy, combined with a Guarded AI Safety Architecture, reduces reliance on hardware redundancy while maintaining a robust safety argument through runtime supervision, deterministic fallback mechanisms, and comprehensive validation.

The true value of Virtual Redundancy is not only the reduction of hardware cost and complexity, but the creation of a scalable software-defined safety architecture for future SDV platforms.

Learn more about our
software-defined vehicle portfolio:

Imprint

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Contact us now

Get in touch with our expert team. We are looking forward to support you with our expertise to find out more about the future of mobility.

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