

A Unified Framework for Time-Sensitive and Resilient In-Vehicle Communication: Integrating Automotive Ethernet, Wireless TSN, and IoT Enabled Vehicle Health Monitoring

John A. Prescott

Department of Electrical and Computer Engineering, Avalon University

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ABSTRACT

The rapid convergence of automotive electronics, connected mobility, and Internet of Things (IoT) diagnostics has precipitated an unprecedented demand for in-vehicle networks that are simultaneously deterministic, highbandwidth, low-latency, secure, and resilient. This article synthesizes recent developments across Automotive Ethernet, Time-Sensitive Networking (TSN), wireless TSN variants, Controller Area Network (CAN) transport adaptations, and IoT-enabled vehicle health monitoring to propose a unified conceptual framework for future in-vehicle communication architectures. Drawing directly from empirical studies, standards documents, and contemporary experimental analyses, the work articulates the fundamental trade-offs among latency, reliability, electromagnetic compatibility, and resource constraints; presents a methodological approach for evaluating protocol enhancements in heterogeneous vehicle contexts; and offers prescriptive, research-backed solutions to persistent challenges such as time determinism over shared media, wireless coexistence within the vehicle cabin, and secure health data transport for remote diagnostics. The article advances a taxonomy of communication patterns found in modern vehicles, maps those patterns to protocol primitives derived from IEEE TSN and automotive-centric transports, and explicates how scheduling, shaping, and prioritization mechanisms can be composed to meet end-to-end system requirements. Limitations and open research directions are discussed, including systematic validation methodologies and the need for toolchains integrating EMI/EMC simulation with protocol-level scheduling analysis. This comprehensive exposition aims to guide researchers and practitioners developing robust, standards-aligned in-vehicle networking solutions capable of supporting advanced driver assistance systems (ADAS), high-definition sensing, and continuous IoT health telemetry.

KEYWORDS

Automotive Ethernet, Time-Sensitive Networking, Wireless TSN, In-Vehicle Network, IoT Vehicle Health Monitoring, Controller Area Network, Real-time Scheduling

Introduction

The modern automobile has evolved from a mechanical transportation device into a distributed computational platform integrating sensing, actuation, infotainment, safety, and diagnostics subsystems. The architectural

complexity underlying this transformation is reflected in the diversity of in-vehicle communication technologies — from decades-old fieldbuses such as CAN to highspeed switched Ethernet, and from wireline domain controllers to wireless sensor arrays (Schmidt et al., 2015; Tuohy et al., 2013). At the same time, the IoT paradigm has permeated vehicular design, producing an emerging

class of systems that continuously monitor vehicle health and operational parameters and relay them for local or remote analytics (IEEE Access, 2024). These convergent trends create a core research and engineering challenge: how to design in-vehicle

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networks that simultaneously support deterministic, safety-critical flows for ADAS and control, highbandwidth streams for cameras and LIDAR, and reliable, secure telemetry for IoT-based health monitoring (Zeng et al., 2016; Hank et al., 2013).

Historically, automotive networks prioritized simple, reliable broadcast and event-driven messaging (e.g., CAN) optimized for low bandwidth but strong fault tolerance (Mahmud, 2009). More recently, the demands of advanced sensing and Ethernet-class payloads motivated a shift toward high-speed solutions such as Automotive Ethernet and the incorporation of TSN standards to provide time-sensitive guarantees over switched infrastructures (IEEE Std 1722-2016; Schmidt et al., 2015). Parallel research has investigated wireless in-vehicle sensor systems to reduce harness complexity and provide flexible sensing placement (ICCVE, 2013; Vrachkov & Todorov, 2019). Experimental work on wireless TSN and TSN traffic scheduling has begun to reveal the possibilities and limitations of achieving deterministic behavior over unpredictable wireless channels (ETFA, 2023; Journal of Communications and Networks, 2021).

Despite substantial progress, several literature gaps remain. First, much of the existing research treats wireline (Ethernet/TSN) and wireless subsystems as separate entities, with limited frameworks for their integrated analysis and co-design (Vrachkov & Todorov, 2019; ETFA, 2023). Second, the specific mapping of IoT vehicle health monitoring requirements onto TSN models and CAN transport overlays has not been exhaustively articulated in a standards-conscious manner (IEEE Access, 2024; ICECAI, 2024). Third, practical considerations such as electromagnetic interference (EMI) mitigation, PCB shielding for camera modules, and EMI impacts on time-sensitive traffic remain an underrepresented intersection between physical-layer engineering and protocol scheduling (Karim, 2025). This article aims to bridge these gaps by synthesizing the references supplied into a coherent

framework that can be used to evaluate, design, and validate next-generation in-vehicle communication systems.

The objectives of this paper are threefold: (1) to analyze and consolidate the current state of automotive networking technologies relevant to time-sensitive and IoT health monitoring workloads; (2) to propose a methodological approach for assessing protocol performance in heterogeneous (wired/wireless) vehicular environments that is faithful to the constraints and metrics emphasized in the literature; and (3) to offer concrete solutions and research directions that address interoperability, determinism, security, and EMI concerns. Each claim and major assertion is grounded in the provided literature to ensure strict fidelity to the input references.

Methodology

This work follows a synthesis and conceptual-method development approach driven by close reading and cross-referencing of the provided literature, combined with constructive extrapolation where the texts indicate emergent directions rather than settled conclusions. The methodology proceeds in four stages: literature consolidation, requirement taxonomy derivation, protocol-level mapping, and evaluation framework specification. Each stage is described with the intent that practitioners can apply it to real systems or extend it for empirical validation.

Literature consolidation involved extracting salient themes from the supplied references — specifically, the properties and limitations reported for Automotive Ethernet, TSN scheduling and shaping algorithms, wireless TSN experimental outcomes, CAN transport considerations, and the architectural needs of IoT vehicle health monitoring systems (IEEE Std 1722-2016; Journal of Communications and Networks, 2021; ETFA, 2023; ICECAI, 2024; IEEE Access, 2024). For references that address related historical and foundational network evolution (e.g., ARPANET history, UNIX), the material was used only to contextualize the historical pathways leading to current automotive networking choices (AT&T, 2004; Sutton, 2004). The consolidation step was careful to preserve the claims, experimental findings, and standards positions as stated in the references.

Requirement taxonomy derivation translates vehicle use cases into quantifiable network requirements — latency

bounds, jitter budgets, throughput needs, reliability targets (packet-loss thresholds), security properties, and deployment constraints (e.g., wiring harness mass, EMI susceptibility). These metrics were derived directly from the application contexts described across the references: ADAS and camera streams (high bandwidth, bounded latency), sensor control loops (very low latency, high reliability), and IoT health monitoring

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telemetry (moderate bandwidth, intermittent but authenticated reporting) (Schmidt et al., 2015; IEEE Access, 2024; IEEE Std 1722-2016).

Protocol-level mapping is the core technical contribution methodology: each communication requirement is associated with candidate protocol primitives (e.g., TSN time-aware shaper, credit-based shaping, per-flow scheduled queuing, CAN transport segmentation and reassembly) and the necessary adaptations to make those primitives interoperable across wired and wireless segments. The mapping stage draws extensively on TSN simulation and experimental findings (Journal of Communications and Networks, 2021; ETFA, 2023), CAN transport implementations (ICECAI, 2024), and contemporary analyses of wireless solutions for automotive Ethernet (Vrachkov & Todorov, 2019).

Evaluation framework specification describes how to assess proposed designs. Building on experimental methodologies reviewed in ETFA (2023) and simulation studies in the Journal of Communications and Networks (2021), the framework prescribes a combination of timedomain trace capture (to measure latency/jitter), stress tests for bandwidth and queuing under overload conditions, EMI/EMC validated boards for hardware influence studies (Karim, 2025), and security penetration tests for telemetry data flows. Importantly, the framework recommends validation across realistic topology variations (centralized gateway vs. zonal architectures), with mixed traffic profiles that reflect simultaneous ADAS, infotainment, and IoT telemetry activity (Hank et al., 2013; Mahmud, 2009). Where the references included experimental parameterization, those parameters informed the suggested test vectors and traffic mixes.

Throughout the methodology, conservative inference was used: where the literature suggested trends but

lacked explicit quantitative detail, the article articulates the implications while flagging them as areas requiring empirical confirmation (ETF A, 2023; IEEE Access, 2024). The methodological aim is not to present novel experimental data but to produce a rigorous, referenceanchored framework that researchers and developers can operationalize.

Results

Because this paper synthesizes and structures existing evidence rather than presenting new experimental measurements, the "results" are conceptual outputs: a requirements taxonomy, a protocol primitive mapping table (explained textually), an integrated architecture blueprint described in detail, and a recommended validation plan. Each result is described and justified with explicit ties to the input literature.

Requirements taxonomy. The literature indicates that in-vehicle communication demands can be partitioned into three overlapping classes:

1. **Deterministic Control Flows:** Characterized by tight latency (<1 ms to tens of ms depending on control loop), minimal jitter, and high reliability. Such flows are typical for real-time control loops, sensor fusion for safety systems, and actuators in motion control. The need for determinism and safety certification has historically driven fieldbus designs and is a central motivator for TSN adoption (Mahmud, 2009; IEEE Std 1722-2016).
2. **High-Bandwidth Time-Bound Streams:** This class includes HD camera feeds, radar point clouds, and LIDAR data. These streams require substantial sustained throughput (tens to hundreds of Mbps per sensor) and bounded latency with moderate to tight jitter constraints, especially where fusion algorithms are timesensitive (Schmidt et al., 2015; Journal of Communications and Networks, 2021).
3. **Telemetry and IoT Vehicle Health Monitoring:** Continuous or periodic transmission of diagnostics, status updates, and predictive maintenance data. These flows are comparatively tolerant of latency but require

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secure, authenticated transfer and resilience to lossy links, as they may traverse wireless or cellular segments for remote diagnostics (IEEE Access, 2024; ICCVE, 2013).

This taxonomy reflects a consensus across the supplied references that different vehicular functions impose divergent and sometimes conflicting network requirements, and it underpins subsequent mapping and design choices (Zeng et al., 2016; Hank et al., 2013). Protocol primitive mapping. The literatures collectively

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endorse an ecosystem where protocol primitives are selected and composed according to the taxonomy above.

- **Time-Aware Shaping (TAS) and Gate Control:** TSN's time-aware shaping is recommended for deterministic control flows and scheduled high-priority sensor deadlines because it can reserve transmission windows and eliminate contention within a bridged network when properly time-synchronized (IEEE Std 1722-2016; Journal of Communications and Networks, 2021). The journal simulations showed TAS supports strict scheduling semantics for Ethernet-based in-vehicle networks.
- **Credit-Based Shaping (CBS):** Useful for smoothing traffic bursts on high-bandwidth streams to prevent interference with scheduled control traffic. CBS provides a way to guarantee bandwidth while offering elasticity for best-effort traffic (Journal of Communications and Networks, 2021).
- **Frame Preemption and Segmentation:** For mixed payloads crossing domains (e.g., CAN frames carried over Ethernet via CAN-to-Ethernet gateways), segmentation and preemption mechanisms reduce blocking times by allowing high-priority frames to preempt lower-priority, long frames (ICECAI, 2024; Schmidt et al., 2015).
- **Wireless TSN Adaptations:** Wireless TSN research suggests that achieving deterministic properties over wireless media requires coupling time synchronization protocols with PHY/MAC adaptations and cross-layer redundancy (ETFA, 2023; Vrachkov & Todorov, 2019). Experiments show that while wireless TSN can approach wired determinism under constrained topologies and careful scheduling, inherent channel variability necessitates redundancy, adaptive retransmission strategies, and conservative scheduling margins.
- **CAN Transport Over Higher Layers:** Implementations of CAN transport protocol stacks on higher-level languages and runtimes (e.g., C#) demonstrate that existing fieldbus semantics can be preserved while enabling richer gateway functionality and diagnostics when mapped to Ethernet/TSN backbones

(ICECAI, 2024).

Integrated architecture blueprint. Synthesizing the above primitives, the recommended architecture organizes the vehicle network into zonal domains connected by an Ethernet-based TSN backbone, with wireless sensor islands for low-bandwidth telemetry and selective sensors, and secure gateways for legacy CAN subnets and external IoT links. The blueprint emphasizes:

- Zonal computing nodes that aggregate local sensors and actuators, reducing harness length and localizing critical control traffic (Hank et al., 2013).
- A TSN backbone configured with TAS for control flows, CBS for sensor streams, and priority queues for diagnostics telemetry. The backbone is time-synchronized using IEEE-defined mechanisms (IEEE Std 1722-2016).
- Gateway modules implementing CAN transport and segmentation, providing translation between CAN message semantics and TSN scheduled flows, preserving timing constraints where necessary via strict scheduling and mapping of CAN message priorities to TSN priority code points (ICECAI, 2024).
- Wireless TSN sensor islands that use dedicated scheduling windows and redundant transmission patterns to mitigate wireless unpredictability (ETFA, 2023; Vrachkov & Todorov, 2019).
- Security enclaves that protect telemetry and OTA diagnostic channels with authenticated, integrity-protected tunnels; these are particularly emphasized for IoT telemetry flows that may traverse cellular networks (IEEE Access, 2024).

Validation plan. The recommended evaluation plan borrows experimental configurations and test vectors from the ETFA (2023) experimental analysis and the Journal of Communications and Networks (2021) simulations:

- Time-synchronization fidelity tests under varying loads to verify TAS window alignment and guard band sufficiency.
- End-to-end latency and jitter profiling for representative flows — control loops, camera

streams, and telemetry — with stress testing that injects simultaneous large-payload bursts and variable wireless losses.

- EMI/EMC impact studies using shielded vs. unshielded designs to observe effects on both PHY layer error rates and higher-layer timing guarantees; this is informed by hyperlynxvalidated shielding studies demonstrating physical layer effects on camera PCB performance (Karim, 2025).
- Gateway stress testing with mixed CAN/Ethernet load to evaluate segmentation, preemption, and reassembly latency characteristics (ICECAI, 2024)
- Security threat modeling and penetration tests for telemetry channels, including replay, spoofing, and man-in-the-middle scenarios, aligning with IoT system security practices (IEEE Access, 2024).

Each element in the results set is substantiated by evidence and experiments reported in the provided references, thereby grounding the conceptual outputs in empirical and standards literature.

Discussion

The consolidation and mapping presented above illuminate several core insights and trade-offs that must guide future research and engineering in in-vehicle networks. The discussion unpacks these insights, articulates limitations of existing approaches, examines counter-arguments, and identifies promising research trajectories.

Determinism vs. Bandwidth: TSN as a unifying fabric. The literature positions TSN (including TAS and CBS) as a credible unifying fabric for delivering determinism over Ethernet backbones while supporting high-bandwidth sensor streams (IEEE Std 1722-2016; Journal of Communications and Networks, 2021). The strength of TSN lies in its ability to provide scheduled transmission opportunities and bounded queuing behavior. However, the efficacy of TSN depends critically on precise time synchronization across nodes and conservative design of guard bands to accommodate drift and jitter. The counter-argument, voiced in part by fieldbus proponents, is that legacy fieldbus technologies offer simplicity and predictable timing without the overhead of complex scheduling infrastructure (Mahmud, 2009).

While that argument retains merit for low-bandwidth local control, the scale and data rates of modern sensors render pure fieldbus approaches increasingly impractical for complete system designs (Schmidt et al., 2015). Thus, a hybrid approach — using TSN for backbone and zonal aggregation, with fieldbus compatibility preserved via gateways — emerges as a pragmatic compromise (Hank et al., 2013; ICECAI, 2024).

Wireless TSN: opportunity and caveats. Wireless TSN experiments (ETFA, 2023) demonstrate that wireless media can be adapted to support time-sensitive flows given stringent constraints: constrained topologies, additional redundancy, and often lower determinism ceilings compared with wired counterparts. Wireless introduces variability from multipath, interference, and mobility, which degrade timing guarantees. Proponents point to the benefits of reduced harnessing complexity and flexible sensor placement (ICCVE, 2013; Vrachkov & Todorov, 2019). Opponents emphasize the safety implications of relying on wireless links for controlcritical traffic. The middle ground recommended by the references is to restrict wireless TSN to non-safetycritical telemetry or to redundancy channels that augment wired connections rather than replace them outright (ETFA, 2023; IEEE Access, 2024). Where wireless is used for time-sensitive functions, protocol stacks must include cross-layer adaptation, adaptive retransmission windows, and explicit redundancy to meet reliability targets.

CAN transport over Ethernet and gateway semantics. The practical necessity of supporting legacy CAN networks — given the large installed base of CAN ECUs — requires careful gateway designs that preserve timing semantics when mapping CAN to TSN. Implementations that run CAN transport logic on modern runtimes (e.g., C# implementations) show that bridging semantics can be implemented with flexibility and advanced diagnostics (ICECAI, 2024). The challenge is to manage blocking times, fragmentation overhead, and priority inversion when long Ethernet frames intersect with short, high-priority CAN messages. Frame preemption and segmentation mechanisms are valuable mitigations (Schmidt et al., 2015), but they introduce implementation complexity, particularly for hardware offload. The literature suggests that a well-engineered gateway with hardware acceleration for segmentation and preemption can reconcile the semantic gap while achieving acceptable latency bounds (ICECAI, 2024).

IoT vehicle health monitoring: priorities and protocols. The integration of IoT telemetry into the in-vehicle network raises unique concerns. Vehicle health data often lacks the strict deterministic constraints of control traffic but demands strong data integrity, confidentiality, and provenance for diagnostics and predictive maintenance (IEEE Access, 2024). The literature highlights that telemetry can be mapped to lower-priority TSN or separate VLANs and secured end-to-end using authenticated tunnels. The trade-off is that placing telemetry on the same physical backbone as safety-critical traffic increases risk unless robust isolation and scheduling policies are applied. The recommended architecture separates telemetry logically (via queues and VLANs) and enforces security through gateway-based authentication and cryptographic transport where telemetry may leave the vehicle (IEEE Access, 2024).

EMI/EMC and physical-layer realities. A recurring theme in the provided references is the physical layer's impact on system behavior. Recent work validating shielding strategies for 10G Automotive Ethernet and camera PCB design demonstrates that EMI mitigation is not merely an electrical engineering exercise but directly influences higher-layer timing and reliability, particularly for camera links supporting ADAS (Karim, 2025). Shielding, connector selection, and cable routing must therefore be considered early in network architecture design because PHY errors and retransmissions can erode TSN scheduling margins and compromise determinism. The counter-argument that "protocol fixes can mask hardware shortcomings" is valid; the literature recommends co-design and validation across layers, combining EMI simulation tools with protocol timing analyses (Karim, 2025; Journal of Communications and Networks, 2021).

Interoperability and standards alignment. Standards (e.g., IEEE Std 1722-2016) provide a baseline for interoperability, but vendor implementations and evolving profiles for automotive use remain fragmented (IEEE Std 1722-2016; Hank et al., 2013). The literature suggests fostering industry common profiles and test suites that combine TSN scheduling conformance with automotive safety certification processes.

Standardization gaps persist in wireless TSN extensions and in precise mappings for CAN over Ethernet, implying that active collaboration between standards bodies and automotive OEMs is essential to accelerate reliable adoption (Vrachkov & Todorov, 2019; ICECAI, 2024).

Limitations of the current synthesis. This article synthesizes existing literature and proposes a reference framework; however, the absence of novel empirical measurements limits the ability to provide quantitative performance claims beyond what the references report. Additionally, while the proposed validation plan is detailed, executing it requires access to hardware testbeds, EMI labs, and representative vehicle topologies. Finally, some references used here provide high-level or domain-specific findings that need further harmonization into universal parameter sets — an area identified for future research.

Future research directions. The literature and the preceding analysis point to several high-impact research avenues:

- Cross-layer co-design toolchains that combine EMI/EMC simulation with TSN schedule synthesis tools, enabling designers to iterate rapidly between hardware and protocol choices (Karim, 2025)
- Wireless TSN robustness strategies that incorporate machine learning for channel prediction and adaptive redundancy scheduling to reduce conservative guard bands and increase utilization (ETFA, 2023; Vrachkov & Todorov, 2019).
- Formal verification methods for gateway mapping semantics, ensuring that CAN timing and priority properties are preserved under various load conditions and that preemption/segmentation mechanisms do not introduce unsafe behaviors (ICECAI, 2024).
- Standardized test suites and certification profiles that combine TSN conformance, CAN compatibility tests, and security penetration assessments to foster trust across vendors and OEMs (IEEE Std 1722-2016; Hank et al., 2013).
- Empirical studies that quantify the trade-offs between zonal vs. centralized architectures for different vehicle classes, sensor configurations, and use cases (Hank et al., 2013).

Collectively, these directions respond directly to the literature's identified gaps and to the practical constraints of vehicle engineering.

Conclusion

The evolution of in-vehicle networking toward a heterogeneous, time-sensitive, and IoT-enabled ecosystem demands architectures that balance determinism, bandwidth, resilience, and security. This article synthesized contemporary findings from standards, experimental studies, and design analyses to propose a unified framework in which TSN over Automotive Ethernet serves as the backbone for determinism and high-bandwidth flows, CAN and other legacy fieldbuses are bridged through carefully engineered gateways, and wireless TSN is employed selectively for non-safety-critical or redundant channels. Crucially, the framework emphasizes cross-layer codesign — integrating physical layer EMI considerations with protocol scheduling — and prescribes a rigorous validation plan drawing on recent empirical work.

Designers must accept trade-offs: wired TSN offers superior determinism but at the cost of harness complexity; wireless reduces harness mass but necessitates redundancy and conservative scheduling margins; IoT telemetry requires careful isolation and strong security while remaining flexible in latency expectations. The future of automotive networking will be defined by the ability of the industry to operationalize standards, share conformance profiles, and develop toolchains that bridge electromagnetics and protocol timing. The research agenda outlined here — from codesign toolchains to formal verification of gateway semantics — provides a pathway for achieving robust, standards-aligned in-vehicle communication systems that can support the next generation of vehicle functionality.

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