

Electromagnetic Compatibility, Functional Safety, And Cooperative Electrified Mobility: An Integrated Risk Management Framework for Automated and Connected Electric Vehicles

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Abstract: The rapid convergence of cooperative intelligent transport systems, electrified propulsion, bidirectional charging infrastructures, and high-speed in-vehicle communication networks has transformed the contemporary vehicle into a complex cyber-physical ecosystem. While this transformation promises unprecedented gains in safety, efficiency, and sustainability, it also amplifies electromagnetic compatibility challenges and functional safety risks. This study develops an integrated theoretical and engineering framework that unifies electromagnetic interference mitigation, functional safety standards, communication integrity assurance, and human exposure considerations within the context of cooperative, connected, and automated electric mobility. Drawing exclusively on established regulatory strategies, international standards, and peer-reviewed technical contributions, this article synthesizes insights from cooperative intelligent transport strategies, ISO 26262 functional safety doctrine, electromagnetic disturbance management, cyclic redundancy reliability under harsh environments, conducted and radiated interference modeling in power converters, wireless charging safety evaluation, and high-speed automotive Ethernet shielding design.

The research method is qualitative-analytical and systems-oriented, constructing a multi-layered risk governance architecture that interlinks electromagnetic disturbance modeling, converter topology optimization, communication-layer error detection, standardized immunity testing protocols, and exposure assessment mechanisms. The results demonstrate that electromagnetic compatibility must be embedded as a cross-domain safety requirement rather than treated as a compliance afterthought. Furthermore, bidirectional charging systems and photovoltaic-assisted converters introduce novel interference pathways that necessitate coordinated mitigation strategies spanning hardware shielding, topology optimization, error-checking protocols, and standards-aligned verification.

The discussion explores the theoretical implications of treating electromagnetic disturbances as systemic safety hazards in automated mobility ecosystems, identifies regulatory harmonization gaps, and outlines a future research agenda focused on adaptive shielding, converter design co-optimization, and cooperative network robustness. The article concludes that achieving resilient cooperative electric mobility requires integrated electromagnetic governance bridging infrastructure, vehicle subsystems, communication networks, and human exposure safeguards.

Keywords: Electromagnetic compatibility; Functional safety; Cooperative intelligent transport systems; Electric vehicles; Bidirectional charging; Automotive Ethernet shielding; Risk management.

INTRODUCTION:

The transformation of mobility systems across Europe

and globally has been guided by a strategic vision of cooperative, connected, and automated

transportation. The policy articulation of cooperative intelligent transport systems by the European Commission established a milestone toward interconnected vehicular ecosystems in which vehicles, infrastructure, and digital networks operate synergistically to enhance safety, reduce emissions, and optimize traffic efficiency (European Commission, 2016). This strategic orientation toward cooperative mobility has coincided with the accelerated electrification of transport, integration of bidirectional charging capabilities, and deployment of high-speed data communication architectures within vehicles.

The contemporary electric vehicle is no longer a purely mechanical artifact but rather a distributed cyber-physical system comprising high-frequency power converters, dense sensor arrays, advanced driver assistance systems, wireless communication modules, and increasingly sophisticated onboard Ethernet networks. Each of these components generates, transmits, or is susceptible to electromagnetic energy. The aggregation of these subsystems within confined vehicular architectures introduces unprecedented electromagnetic compatibility challenges. Simultaneously, functional safety requirements governed by internationally recognized standards demand that electronic and electrical systems perform reliably under foreseeable environmental stresses.

The International Organization for Standardization standard ISO 26262 formalizes functional safety obligations for road vehicles, emphasizing hazard analysis, risk assessment, and integrity level allocation (International Organization for Standardization, 2011). However, as vehicle architectures become more electrified and interconnected, electromagnetic disturbances transition from peripheral nuisance phenomena to central safety determinants. A radiated or conducted disturbance may compromise sensor signals, corrupt high-speed communication links, destabilize converter operation, or trigger erroneous safety responses.

The complexity deepens further with the emergence of bidirectional charging technologies enabling vehicle-to-grid, grid-to-vehicle, and vehicle-to-vehicle energy exchange. Photovoltaic-assisted multiport

converters and dual active bridge topologies introduce additional switching harmonics and conducted emissions into both vehicular and grid environments (Gopalasami & Chokkalingam, 2024; Bharatiraja et al., 2023). The electromagnetic implications of these systems extend beyond onboard reliability; they influence grid stability, communication networks, and potentially human exposure patterns in wireless charging contexts (Wang et al., 2019; Hirata et al., 2021).

Electromagnetic compatibility is therefore no longer confined to isolated component testing but emerges as a systemic design discipline. Regulatory instruments such as CISPR 25 define radio disturbance limits for onboard receiver protection (CISPR, 2008), while ISO 11452-1 prescribes immunity testing procedures for components subjected to radiated electromagnetic energy (ISO, 2015). Nonetheless, the coexistence of cooperative communication infrastructures, high-speed Ethernet-based sensor backbones, and high-frequency power electronic switching introduces interference modes that strain conventional compliance paradigms. The development of shielding methodologies for 10G automotive Ethernet, validated through simulation environments, demonstrates the necessity of advanced electromagnetic modeling in design stages (Karim, 2025).

Despite significant technical literature addressing discrete elements-converter EMI modeling (Bishnoi et al., 2012), suppression strategies (Li et al., 2009), conducted interference in non-isolated converters (Natarajan et al., 2020), and cyclic redundancy robustness under harsh disturbances (Van Waes et al., 2017)-a comprehensive theoretical synthesis remains underdeveloped. The central research problem addressed in this article is the absence of an integrated risk management framework that unifies cooperative mobility strategies, functional safety doctrine, electromagnetic disturbance mitigation, communication reliability assurance, and exposure evaluation within electrified automated vehicles.

This study advances three primary objectives. First, it constructs a systemic understanding of electromagnetic compatibility as a safety-critical parameter in cooperative intelligent transport systems. Second, it synthesizes converter topology

design, communication error detection, and shielding strategies into a unified mitigation architecture. Third, it explores the regulatory and human exposure dimensions to establish a holistic electromagnetic governance model for electric automated mobility.

By developing this integrative theoretical framework, the article addresses a critical literature gap and proposes a pathway toward resilient, electromagnetically robust cooperative electric transport ecosystems.

METHODOLOGY

The methodological approach adopted in this research is qualitative, integrative, and systems-analytical. Rather than conducting empirical experimentation, the study synthesizes regulatory documents, international standards, and peer-reviewed technical literature to construct a comprehensive conceptual and engineering framework. This approach is justified by the cross-disciplinary nature of electromagnetic compatibility challenges in electric cooperative mobility systems, which span policy strategy, hardware design, communication theory, and human exposure science.

The first methodological layer involves normative analysis of strategic and regulatory instruments. The cooperative intelligent transport vision articulated by the European Commission (2016) is examined to identify systemic integration principles relevant to electromagnetic risk propagation across vehicle-infrastructure networks. Concurrently, ISO 26262 is analyzed to extract functional safety requirements concerning hazard analysis, risk classification, and system validation under environmental stressors (International Organization for Standardization, 2011). The CISPR 25 and ISO 11452-1 standards are reviewed to contextualize emission limits and immunity testing protocols within the broader risk governance framework (CISPR, 2008; ISO, 2015).

The second methodological layer synthesizes engineering literature on electromagnetic disturbance generation and mitigation. Converter topologies for bidirectional charging and photovoltaic integration are examined to understand emission sources and harmonic spectra (Gopalasami & Chokkalingam, 2024; Bharatiraja et al., 2023). Theoretical analyses of conducted EMI in DC-DC

converters are incorporated to explain noise coupling pathways and suppression techniques (Natarajan et al., 2020). Terminal modeling strategies for switched power converters provide insights into accurate representation of EMI behavior in design simulations (Bishnoi et al., 2012). Broad suppression methodologies are integrated to assess practical mitigation viability (Li et al., 2009).

The third methodological layer addresses communication integrity and shielding. The resilience of cyclic redundancy checks under harsh electromagnetic disturbances is conceptually examined to assess the reliability of error-detection protocols (Van Waes et al., 2017). The IEEE initiative on managing electromagnetic disturbance risks contextualizes the standardization rationale for risk governance (Pissoort & Armstrong, 2016). Automotive Ethernet shielding design, validated through simulation, informs the development of high-speed communication protection strategies (Karim, 2025).

The fourth methodological layer incorporates safety evaluation of human exposure in electromagnetic fields and wireless charging systems. Review literature on exposure assessment methodologies and safety guidelines informs the integration of occupational and public health considerations into the overall risk architecture (Hirata et al., 2021). Wireless charging electromagnetic safety evaluation methods are analyzed to identify protective strategies within electric vehicle contexts (Wang et al., 2019).

These four analytical layers are then synthesized into a multi-level integrated framework. The framework identifies disturbance generation sources, coupling pathways, subsystem vulnerabilities, communication-layer safeguards, standardized verification methods, and exposure protection measures. The methodology emphasizes conceptual coherence and regulatory alignment, ensuring that each mitigation element maps onto recognized safety and compatibility standards.

By combining policy analysis, standards interpretation, and technical synthesis, the study constructs a theoretically robust and practically relevant risk management architecture for

electromagnetically resilient cooperative electric mobility systems.

RESULTS

The integrative analysis reveals that electromagnetic compatibility in cooperative electrified vehicles must be conceptualized as a multi-domain safety construct encompassing emission control, immunity assurance, communication integrity, infrastructure interaction, and human exposure safeguards.

First, at the strategic systems level, the cooperative intelligent transport vision implies dense vehicular networking and continuous vehicle-to-infrastructure communication (European Commission, 2016). This density amplifies cumulative electromagnetic activity. Each vehicle acts simultaneously as emitter and receptor. Without harmonized emission management, network-level interference could degrade cooperative communication reliability. Thus, electromagnetic compatibility becomes foundational to the viability of cooperative automation.

Second, ISO 26262 mandates that electronic systems maintain functional integrity under foreseeable environmental disturbances (International Organization for Standardization, 2011). Electromagnetic interference qualifies as such a disturbance. The results indicate that EMI must be incorporated explicitly within hazard analysis and risk assessment processes. Converter switching harmonics, wireless charging fields, and Ethernet crosstalk represent credible hazards capable of triggering safety-critical malfunctions.

Third, bidirectional multiport converters introduce complex emission spectra. Photovoltaic-assisted EV chargers operating in PV2V, G2V, and V2G modes generate dynamic switching conditions that vary with energy flow direction (Gopalasami & Chokkalingam, 2024). Dual active bridge topologies further complicate conducted emission profiles due to high-frequency switching transitions (Bharatiraja et al., 2023). These systems expand the EMI footprint beyond traditional unidirectional chargers.

Fourth, conducted EMI analysis demonstrates that non-isolated DC-DC converters exhibit distinct noise propagation pathways through parasitic capacitances and inductances (Natarajan et al., 2020). Terminal modeling methodologies enable more accurate

prediction of emission behavior, facilitating preemptive mitigation during design stages (Bishnoi et al., 2012). Suppression techniques including filtering, shielding, and layout optimization reduce both common-mode and differential-mode noise (Li et al., 2009).

Fifth, communication reliability under harsh disturbances depends not solely on shielding but also on robust error-detection protocols. Cyclic redundancy checks maintain significant effectiveness even in strong electromagnetic environments, though performance degradation may occur under extreme conditions (Van Waes et al., 2017). The IEEE initiative underscores the need for standardized risk management approaches addressing electromagnetic disturbances in complex systems (Pissoort & Armstrong, 2016).

Sixth, high-speed 10G automotive Ethernet introduces susceptibility to electromagnetic coupling due to high data rates and signal integrity constraints. Shielding validated through simulation tools demonstrates measurable reductions in interference-induced signal degradation (Karim, 2025). This indicates that communication-layer resilience requires co-design of physical shielding and protocol-level redundancy.

Seventh, compliance frameworks such as CISPR 25 establish emission limits protecting onboard receivers (CISPR, 2008), while ISO 11452-1 defines immunity testing procedures (ISO, 2015). The analysis reveals that while these standards provide robust component-level assurance, system-level integration within cooperative mobility ecosystems requires harmonized interpretation.

Finally, human exposure assessments highlight the necessity of evaluating electromagnetic field intensities in wireless charging contexts (Wang et al., 2019). Review literature confirms that exposure standards must evolve alongside technological advances to ensure occupational and public safety (Hirata et al., 2021).

Collectively, these findings support the development of an integrated electromagnetic risk management architecture comprising emission source control, propagation pathway mitigation, subsystem immunity enhancement, communication

redundancy, standardized verification, and exposure protection.

DISCUSSION

The implications of these results extend beyond technical compliance into the domain of systemic risk governance. Cooperative intelligent transport systems depend on reliable, low-latency communication between vehicles and infrastructure. Electromagnetic disturbances represent a latent systemic vulnerability capable of cascading across networked nodes. Unlike mechanical failures confined to individual components, electromagnetic interference may propagate invisibly, affecting multiple subsystems simultaneously.

Integrating ISO 26262 functional safety principles with electromagnetic compatibility standards requires conceptual expansion. Traditionally, EMI compliance has been treated as a regulatory checkpoint rather than a safety design driver. The evidence synthesized here demonstrates that EMI can directly influence safety integrity levels by inducing sensor misreads, communication corruption, or converter instability. Thus, electromagnetic compatibility should be embedded within hazard analysis frameworks as a primary risk category.

Bidirectional charging technologies illustrate the evolving complexity of electric mobility ecosystems. Energy flows are no longer unidirectional. Vehicles interact dynamically with grids and other vehicles. Each operational mode alters switching patterns and emission characteristics. Without adaptive mitigation strategies, these dynamic behaviors may exceed static compliance assumptions.

Communication-layer resilience also demands reevaluation. Cyclic redundancy checks provide error detection but not immunity. Shielding improves physical robustness but cannot eliminate all coupling pathways. Therefore, layered defense architectures combining physical, protocol, and system-level safeguards become essential.

Human exposure considerations add an ethical and regulatory dimension. Wireless charging introduces sustained electromagnetic fields near occupants and maintenance personnel. While existing assessment methodologies provide safety margins, continuous

monitoring and adaptive field shaping may become necessary as power levels increase.

Limitations of this study stem from its qualitative and integrative methodology. Empirical validation of the proposed framework would strengthen its applicability. Additionally, evolving converter technologies and communication standards may introduce novel interference modes not captured in current literature.

Future research should explore adaptive shielding materials responsive to frequency shifts, converter topologies optimized jointly for efficiency and low emission spectra, and real-time EMI monitoring integrated into vehicle diagnostic systems. Furthermore, harmonization between cooperative mobility strategies and electromagnetic standards warrants policy-level investigation.

CONCLUSION

The convergence of cooperative intelligent transport systems, electrified propulsion, bidirectional energy exchange, and high-speed in-vehicle communication necessitates a reconceptualization of electromagnetic compatibility as a central safety pillar. Through integrative analysis of strategic policy frameworks, functional safety standards, converter engineering literature, communication reliability research, and exposure assessment studies, this article has developed a comprehensive electromagnetic risk management architecture for automated electric mobility.

The findings underscore that emission control, immunity assurance, communication redundancy, shielding optimization, standardized verification, and exposure protection must operate cohesively. Regulatory compliance alone is insufficient; proactive, system-level electromagnetic governance is essential to ensure resilient, safe, and sustainable cooperative mobility ecosystems.

By embedding electromagnetic compatibility within functional safety doctrine and cooperative transport strategies, stakeholders can advance toward an electrified mobility future that is not only connected and automated but also electromagnetically robust and human-centered.

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