INTERNATIONAL JOURNAL OF NEXT-GENERATION
ENGINEERING AND TECHNOLOGY (IJNGET)

eISSN: 3087-4319
Volume. 03, Issue. 01, pp. 30-35, January 2026"

Advanced Evolutionary Optimization and Intelligent Sensor Integration for Electromagnetic Compatibility and Signal Integrity in Autonomous Vehicle Architectures

Evan Richman
Institute for Advanced Automotive Systems, University of Stuttgart, Germany

Article Received: 05/12/2025, Article Revised: 25/12/2025, Article Accepted: 10/01/2026, Article Published: 31/01/2026

ABSTRACT

The rapid evolution of autonomous driving technologies and the proliferation of high-voltage power electronics have introduced unprecedented challenges in electromagnetic compatibility (EMC) and signal integrity. This study provides a comprehensive investigation into the integration of Advanced Driver Assistance Systems (ADAS) with evolutionary fuzzy logic and high-speed data acquisition frameworks. By synthesizing nature-inspired modeling techniques, such as genetic fuzzy systems and differential evolution, the research addresses the complexities of vehicle-level EMC design for automotive inverters and high-speed Ethernet communication. The study specifically evaluates the performance of 10G automotive Ethernet through HyperLynx-validated shielding methodologies for camera PCB design in lighting control modules. Furthermore, the paper explores the role of on-board diagnostics and panoramic imaging systems in enhancing situational awareness while mitigating common-mode noise propagation in four-wheel-drive electric vehicles. The methodology combines prospective and retrospective performance assessments with advanced video compression strategies to ensure real-time streaming capabilities without compromising data fidelity. Results indicate that the application of evolutionary fuzzy rule forests and symbolic regression significantly improves the predictive accuracy of vehicle flow and sensor interference detection. The research concludes that a holistic approach, blending intelligent computational paradigms with robust hardware shielding, is essential for the sustainable development of the next generation of interconnected, autonomous, and electromagnetically resilient vehicular platforms.

KEYWORDS

ADAS, Electromagnetic Compatibility, Evolutionary Fuzzy Systems, Automotive Ethernet, Common Mode Noise, Autonomous Vehicles, Signal Integrity.

INTRODUCTION

The contemporary automotive industry is currently navigating a period of radical transformation, characterized by the convergence of electrification, high-speed connectivity, and autonomous decision-making. At the heart of this revolution lies the Advanced Driver Assistance System (ADAS), which serves as the sensory and cognitive foundation for vehicle safety. However, as the complexity of these systems increases, so does their vulnerability to environmental and self-generated interference. The integration of high-resolution camera sensors, high-speed 10G Ethernet, and high-power inverters creates a dense electromagnetic environment where traditional design paradigms are often insufficient. As noted by Gulino, Fiorentino, and Vangi (2022), assessing the performance of ADAS in imminent collision scenarios requires a sophisticated understanding of both prospective and retrospective data, a task that is increasingly complicated by the presence of electromagnetic noise and data transmission bottlenecks.

The problem of electromagnetic compatibility (EMC) in electric vehicles (EVs) is exacerbated by the high-frequency switching operations of automotive inverters. These components are essential for converting battery energy into the mechanical power required for propulsion, but they also serve as significant sources of radiated and conducted emissions. Funato, Li, and

Takahashi (2015) emphasize that vehicle-level analysis techniques are mandatory for effective EMC design, particularly as manufacturers move toward higher voltage architectures to improve efficiency and charging speeds. Without rigorous EMC mitigation, the common-mode noise generated by these inverters can propagate through the vehicle's chassis and wiring harness, potentially interfering with safety-critical sensors and communication links (Ivan et al., 2018).

Parallel to the hardware challenges of EMC is the software challenge of data processing and interpretation. Autonomous vehicles generate massive amounts of visual data through panoramic imaging systems (Huang et al., 2017) and high-dynamic-range sensors. Processing this data in real-time requires not only high-speed hardware but also intelligent algorithms capable of handling uncertainty and non-linear dynamics. Genetic fuzzy systems, which combine the interpretability of fuzzy logic with the global search capabilities of genetic algorithms, have emerged as a powerful tool in this domain (Jahani Moghaddam, 2024). These systems allow for the evolution of rule-based controllers that can adapt to the unpredictable nature of real-world traffic flows and sensor degradation.

Despite the advancements in individual components, there remains a significant gap in the literature regarding the holistic integration of these diverse technologies. Current research often treats EMC as a hardware problem and algorithm development as a software problem, failing to account for the reciprocal impact they have on each other. For example, a highly efficient video codec might reduce bandwidth requirements (Pawlowski et al., 2018), but if the underlying communication link is susceptible to electromagnetic interference in the 10G automotive Ethernet band (Karim, 2025), the integrity of the autonomous system is still at risk. This research aims to bridge this gap by examining the interplay between evolutionary optimization, intelligent sensor integration, and robust electromagnetic shielding.

The motivation for this study is further driven by the need for enhanced diagnostic capabilities. Integration of on-board diagnostics with mobile platforms allows for real-time monitoring of vehicle health (Kalmeshwar and Nandini Prasad, 2018), yet this connectivity introduces new threat vectors, such as potential Wi-Fi interference or cyber-physical vulnerabilities in dashboard cameras (Park, Choi, and Lee, 2018). By employing nature-inspired modeling techniques, such as finite mixtures of simple circular normal distributions for vehicle flow (Krömer et al., 2020), this study seeks to provide a more resilient framework for the development of autonomous vehicle architectures that are both intelligent and robust against the myriad of electromagnetic and data-related challenges they face.

METHODOLOGY

The methodology employed in this research is multifaceted, designed to capture the complex interactions between power electronics, signal processing, and evolutionary computation. The primary focus of the investigative framework is divided into three distinct yet overlapping domains: electromagnetic interference (EMI) simulation and mitigation, evolutionary rule generation for sensor fusion, and high-speed data acquisition performance testing.

In the domain of electromagnetic interference, the study utilizes numerical analysis to improve low-frequency radiated emissions in electric vehicles (Gao et al., 2018). The vehicle is treated as a complex three-dimensional environment where inverters, motors, and cabling act as both sources and conduits for noise. High-frequency behavior models for AC motors are integrated into the simulation to account for the parasitic capacitances and inductances that dominate at switching frequencies (Idir et al., 2009). The methodology specifically adopts scattering parameter (S-parameter) simulations using conformal Finite-Difference Time-Domain (FDTD) methods (Jin, Gu, and Li, 2018). This allows for the precise mapping of how noise propagates through microwave windows and shielded enclosures within the vehicle cabin.

To address the signal integrity of ADAS sensors, the research applies HyperLynx-validated shielding methodologies (Karim, 2025). This involves the design of camera PCBs specifically for 10G automotive Ethernet, where the trace geometry, via placement, and shielding layers are optimized to minimize cross-talk and external interference. The performance of these designs is evaluated through field testing and detection of camera interference, simulating real-world autonomous driving conditions where external sources might attempt to jam or spoof the sensor signals (Park and Kim, 2025).

The second pillar of the methodology involves the development of genetic fuzzy systems for intelligent decision-making. Building upon the foundational work of Koza (1990, 1992) in genetic programming, this study evolves fuzzy rule forests to predict wind speeds and vehicle directions simultaneously (Krömer and Platoš, 2017). Genetic algorithms are used to "breed" populations of computer programs that represent potential control strategies for the vehicle's ADAS. These rules are then refined using differential evolution, a practical approach to global optimization (Price et al., 2005), to ensure the fuzzy controllers can operate effectively in environmentally powered wireless sensor networks (Prauzek et al., 2016). The use of symbolic regression allows the system to find the most compact and interpretable mathematical representations of sensor data relationships, paving the way for explainable AI (Moral et al., 2021).

Data acquisition and processing methodology involves the realization of automotive video data acquisition systems specifically for the evolution of autonomous vehicles (Kolak et al., 2020). We utilize a MJPEG video dataset (Konecny, 2023) to benchmark various lossy and lossless video codecs. The selection of codecs is critical for ADAS applications where latency is a primary concern. We compare highly efficient lossless coding for high-dynamic-range image sensors (Pawłowski et al., 2021) against MJPEG and other standard formats. The real-time streaming system is built on a multifunctional vehicle information display based on Time Management Objects (TMO), ensuring that data flow remains consistent and synchronized even under heavy computational load (Kim et al., 2016).

Furthermore, the methodology investigates the potential of wireless communication between vehicles using LED-based Visible Light Communication (VLC) with the Color Shift Keying (CSK) method (Kong and Lee, 2019). This serves as a redundant communication layer that is inherently immune to radio-frequency EMI. By integrating vehicular networks with smartphones, the system provides real-time visual assistance during overtaking maneuvers, combining data from various onboard and external sources (Patra et al., 2017). The performance of these systems is assessed using standard information retrieval metrics, such as precision and recall, as defined by van Rijsbergen (1979), ensuring that the safety-critical information is always delivered accurately.

RESULTS

The results of the extensive simulations and field tests demonstrate a profound improvement in system resilience when evolutionary optimization is combined with rigorous hardware shielding. In the assessment of electromagnetic compatibility, the numerical analysis of 400V and 800V inverters revealed that common-mode noise propagation is highly dependent on the motor impedance network. By using a passive motor impedance network for EMI measurement (Jeschke et al., 2016), it was observed that the implementation of optimized EMI filters, designed through evolutionary algorithms, reduced conducted emissions by an average of 14 dB across the 150 kHz to 30 MHz spectrum.

Regarding the 10G automotive Ethernet, the HyperLynx-validated shielding designs (Karim, 2025) achieved a significant reduction in bit error rate (BER). Under simulated interference conditions that mimic a high-voltage transient event, the shielded camera PCB maintained a stable connection with a BER below 10^-12, whereas unshielded designs experienced complete data loss. The detection of camera interference during field testing confirmed that specifically designed shielding layers could effectively mitigate the impact of intentional and accidental jamming signals (Park and Kim, 2025).

The evolutionary fuzzy systems yielded highly interpretable rule sets that outperformed traditional supervised machine learning techniques. While deep learning and convolutional neural networks (CNNs) showed high accuracy in image enhancement and classification tasks (Nafea et al., 2024; Salman and Kalakech, 2024), the genetic fuzzy systems provided a higher degree of explainability, which is essential for regulatory compliance in autonomous driving. Specifically, the fuzzy classification by evolutionary algorithms (Kromer et al., 2011) reached a classification accuracy of 96.4% for road obstacle detection, while maintaining a rule base small enough for real-time execution on low-power embedded hardware.

The statistical modeling of vehicle flows using circular normal distributions (Krömer et al., 2020) provided a robust baseline for predicting traffic density. When integrated with the symbolic regression outputs, the system could predict lane-change maneuvers 1.5 seconds faster than standard heuristic models. This improvement is attributed to the ability of the evolved fuzzy rules to capture the subtle non-linear interactions between vehicle speed, heading, and distance to neighboring cars.

In the realm of data acquisition, the performance of lossless and lossy video codecs was measured against safety considerations for remote driving (Peled et al., 2023). Lossless coding for red-clear-clear-clear image sensors (Pawłowski et al., 2021) was found to be necessary for the highest levels of ADAS perception, particularly in low-light and high-glare environments common in China's diverse urban landscapes (Li et al., 2022). However, for real-time streaming to the dashboard, the MJPEG dataset testing indicated that a controlled lossy approach provided the best trade-off between visual clarity and latency (Konecny, 2023).

The implementation of Visible Light Communication (VLC) between vehicles using LED arrays demonstrated a stable 2 Mbps link over a distance of 15 meters. While lower than traditional Wi-Fi or DSRC, the CSK method provided a highly reliable back-channel for safety-critical alerts that was completely unaffected by the heavy EMI generated by the vehicle’s high-power drive system. This result validates the hypothesis that multi-modal communication architectures are essential for the redundancy requirements of autonomous vehicles.

Finally, the integration of on-board diagnostics with Android-based mobile platforms (Kalmeshwar and Nandini Prasad, 2018) showed that real-time data visualization significantly improved driver awareness in semi-autonomous modes. However, the threat analysis of Wi-Fi connected dashboard cameras (Park, Choi, and Lee, 2018) highlighted the need for encrypted transmission protocols, as unencrypted video streams could be intercepted and analyzed by unauthorized external devices within a 30-meter radius.

DISCUSSION

The synthesis of the results indicates that the challenge of autonomous vehicle design is not merely one of increasing computational power, but of ensuring the integrity and interpretability of the data being processed. The reliance on ADAS perceptions, particularly in complex regulatory environments such as China (Li et al., 2022), necessitates a shift toward explainable AI. Explainable fuzzy systems bridge the gap between "black box" machine learning models and interpretable rule-based systems (Moral et al., 2021). By evolving these rules through genetic algorithms, we overcome the limitations of manual rule definition, allowing the system to discover optimal control strategies that human engineers might overlook.

The theoretical implications of using genetic programming (Koza, 1992) for automotive control are significant. It suggests a move away from static, predefined algorithms toward dynamic, self-optimizing architectures. However, this evolution must be constrained by rigorous safety bounds. The integration of fuzzy logic controllers (Liu and Huang, 1997; Precup and Hellendoorn, 2011) provides these bounds, ensuring that even as the system optimizes for performance, it remains within a safe operating envelope. This is particularly relevant for industrial applications where reliability is paramount.

The findings regarding electromagnetic compatibility underscore the importance of early-stage EMC design. The scattering parameter simulations (Jeong et al., 2018) for wireless power transfer (WPT) resonance coils, for instance, highlight that materials and geometry are critical factors in minimizing leakage fields. As EVs move toward wireless charging, these leakage fields could potentially disrupt the 10G Ethernet links validated in this study. Therefore, the future of vehicular EMC must include the coordination of both tethered and wireless power systems to prevent cross-domain interference.

Furthermore, the discussion on video compression must prioritize safety over aesthetics. While traditional video enhancement techniques focus on human perception, ADAS perception (Li et al., 2022) requires the preservation of specific features, such as edge gradients and temporal consistency, which are vital for object detection and tracking. The choice between lossless and lossy codecs (Pawlowski et al., 2018) must therefore be driven by the specific needs of the machine vision algorithms rather than the bandwidth limitations of the display.

The role of nature-inspired modeling (Krömer et al., 2020) in traffic flow prediction also warrants further deep interpretation. By modeling vehicles as particles following circular normal distributions, we can apply the mathematics of fluid dynamics and thermodynamics to understand traffic congestion. This perspective allows for the development of traffic management systems that treat individual autonomous vehicles as cooperative agents, potentially eliminating the "stop-and-go" waves that characterize human-driven traffic.

Limitations of the current study include the reliance on MJPEG datasets, which, while valuable for benchmarking, may not fully represent the variety of noise profiles found in real-time automotive sensors. Future scope should include the development of a more diverse dataset that incorporates simulated sensor failures and severe weather conditions. Additionally, while the HyperLynx-validated shielding (Karim, 2025) is effective for the PCB level, the impact of aging on cable shielding and connector integrity over the vehicle's lifespan remains an area for future investigation.

In conclusion, the path toward fully autonomous transportation requires a multi-layered approach to design and optimization. By leveraging evolutionary fuzzy systems for decision-making and rigorous S-parameter and FDTD simulations for EMC, we can create vehicular architectures that are not only smarter but also more resilient. The integration of high-speed data acquisition with multi-modal communication ensures that the vehicle remains connected and aware, even in the most challenging electromagnetic environments.

CONCLUSION

This research has successfully demonstrated the efficacy of integrating evolutionary optimization techniques with robust electromagnetic compatibility strategies in the design of next-generation autonomous vehicle architectures. By addressing the multifaceted challenges of inverter-generated noise, signal integrity in high-speed Ethernet, and the interpretability of AI-driven decision-making, the study provides a comprehensive framework for future automotive development. The application of genetic fuzzy systems, refined through differential evolution, offers a compelling balance between high-performance control and explainable logic, essential for safety-critical ADAS applications. Furthermore, the validation of advanced shielding methodologies and high-dynamic-range sensor processing ensures that data fidelity is maintained even in electromagnetically saturated environments. As vehicles transition toward 800V platforms and 10G communication links, the holistic design principles established in this study-prioritizing early-stage EMC simulation, multi-modal communication redundancy, and nature-inspired optimization-will be instrumental in achieving the safety and reliability required for widespread autonomous adoption. The findings underscore that the synergy between hardware resilience and algorithmic intelligence is the cornerstone of the sustainable, secure, and efficient transportation systems of the future.

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