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Research Article

Advancing Measurement Accuracy and Functional Safety In Automotive Electronic Systems: A Comprehensive Analysis Of Line Impedance Stabilization Networks And Conducted Emission Measurement Methodologies

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Aleksander Kovacs
Department of Electrical and Electronic Engineering, Budapest Institute of Technology, Hungary

Abstract

Electromagnetic compatibility has become a central concern in modern automotive electronics as vehicles increasingly rely on complex electronic control units, communication networks, and power conversion systems. Conducted electromagnetic emissions originating from switching power supplies, high-speed communication interfaces, and embedded control circuits can significantly interfere with nearby electronic subsystems, potentially compromising operational reliability and functional safety. Within the framework of conducted emission testing, the Line Impedance Stabilization Network plays a critical role by providing a standardized impedance environment and enabling reproducible measurement conditions. However, practical measurement systems often deviate from idealized assumptions due to imperfect impedance realization, calibration limitations, and variations in measurement setup. These factors may significantly influence the reliability and repeatability of electromagnetic compatibility testing.

This research article presents a comprehensive theoretical investigation of conducted emission measurement accuracy in automotive electronic systems with particular emphasis on Line Impedance Stabilization Networks, measurement reproducibility, and their relationship to functional safety requirements. Drawing upon established studies concerning impedance imperfections, calibration techniques, and noise source characterization, the study synthesizes existing theoretical models and experimental insights to construct an integrated perspective on measurement reliability in electromagnetic compatibility testing. The work also explores how evolving automotive architectures,

including high-speed automotive Ethernet and advanced driver assistance systems, introduce new electromagnetic interference challenges that demand refined measurement approaches.

The methodology is based on an analytical synthesis of measurement theory, calibration procedures, and impedance extraction techniques described in prior research, combined with an interpretive evaluation of their implications for automotive safety standards. Particular attention is given to the influence of imperfect artificial mains network impedance, the consequences of conducted emission measurements performed without standardized impedance networks, and emerging approaches aimed at improving measurement precision through calculable adapters and modified calibration strategies.

The findings demonstrate that measurement inaccuracies arising from impedance deviations, improper calibration, and nonstandard testing environments may produce significant variability in emission readings, thereby affecting compliance evaluation and safety validation processes. Furthermore, the integration of electromagnetic compatibility verification within functional safety frameworks requires deeper coordination between measurement methodology and safety engineering practices.

The article concludes that advancing automotive electromagnetic compatibility testing requires a holistic approach integrating improved impedance standardization, advanced calibration methodologies, and cross-disciplinary alignment with functional safety standards such as ISO 26262. Such integration is essential to ensure reliable system performance in increasingly electrified and networked vehicles.

Keywords

Electromagnetic compatibility, conducted emissions, Line Impedance Stabilization Network, automotive electronics, functional safety, electromagnetic interference, measurement accuracy.

Introduction

The rapid evolution of automotive technology has fundamentally transformed the electrical and electronic architecture of modern vehicles. Contemporary automobiles incorporate dozens of electronic control units, sophisticated sensor networks, power electronic converters, communication buses, and safety-critical computing platforms. These subsystems interact continuously to enable advanced driver assistance systems, intelligent power management, connectivity services, and automated driving capabilities. While these technological advances significantly enhance vehicle performance and safety, they simultaneously introduce new challenges related to electromagnetic compatibility and system reliability.

Electromagnetic compatibility refers to the ability of electronic systems to operate correctly within their electromagnetic environment without generating or experiencing unacceptable electromagnetic interference. Conducted emissions, a specific category of electromagnetic interference, occur when unwanted electrical noise propagates through conductive paths such as power lines, communication cables, or grounding structures. In automotive environments, conducted emissions may originate from switching power supplies, high-speed digital interfaces, pulse-width modulation circuits, and various other electronic components integrated into vehicle architectures.

The increasing reliance on high-frequency switching electronics and digital communication technologies has intensified the potential for electromagnetic interference within vehicles. This challenge is further compounded by the dense integration of electronic modules, which often share common power distribution networks. Under such conditions, even relatively small disturbances in electrical noise can propagate across interconnected subsystems, potentially disrupting sensitive electronics responsible for critical vehicle functions.

To mitigate these risks, electromagnetic compatibility testing has become a fundamental aspect of automotive design and validation processes. Conducted emission testing in particular provides insight into how electronic devices inject unwanted noise into power lines and other conductive paths. Accurate measurement of conducted emissions is therefore essential for verifying compliance with regulatory standards and ensuring reliable operation of electronic systems.

A central component of conducted emission testing is the Line Impedance Stabilization Network. This specialized device provides a standardized impedance between the equipment under test and the measurement instrumentation while isolating external noise sources. By stabilizing the impedance environment, the network enables consistent and reproducible measurement results across different laboratories and test setups (Mayerhofer, 2022). Without such standardization, conducted emission measurements would be highly sensitive to variations in power supply characteristics, cable configurations, and environmental electromagnetic conditions.

Despite its fundamental role in measurement accuracy, the practical implementation of Line Impedance Stabilization Networks is subject to several limitations. One important issue concerns the imperfect realization of the artificial mains network impedance. Even small deviations from the intended impedance profile can influence the measurement of conducted emissions, leading to variability in results obtained across different testing facilities (Carobbi and Stecher, 2012). Such discrepancies may complicate compliance verification and introduce uncertainty in the evaluation of electromagnetic compatibility performance.

Another challenge arises from measurement configurations that omit the use of Line Impedance Stabilization Networks entirely. Some experimental or development environments attempt to measure conducted emissions directly from power supply connections without employing standardized impedance networks. Research has demonstrated that such approaches can lead to significant measurement errors because the absence of a controlled impedance environment alters the propagation characteristics of electromagnetic noise (Li, See, and Bandara, 2016). Consequently, measurements performed without proper impedance stabilization may fail to represent the true electromagnetic behavior of electronic devices.

These measurement challenges are particularly relevant in the context of modern automotive electronics, where functional safety considerations demand extremely high levels of reliability. Functional safety refers to the capability of a system to avoid unacceptable risk due to hazards caused by malfunctioning behavior of electrical or electronic components. The international standard ISO 26262 establishes comprehensive guidelines for the design, development, and validation of automotive safety-related systems, emphasizing rigorous verification and validation procedures throughout the product lifecycle (ISO 26262, 2011).

Electromagnetic interference represents a potential hazard within this safety framework because it may disrupt communication networks, sensor data acquisition, or control logic execution. Consequently, accurate electromagnetic compatibility testing is not merely a regulatory requirement but also an essential component of functional safety assurance. Ensuring that conducted emission measurements accurately reflect real operating conditions is therefore critical for validating the reliability of safety-critical automotive electronics.

Recent developments in automotive communication technologies further highlight the importance of precise electromagnetic compatibility evaluation. The integration of high-speed automotive Ethernet networks, particularly those supporting data rates of ten gigabits per second, introduces new electromagnetic challenges due to increased signal frequencies and complex printed circuit board structures. Research on electromagnetic interference mitigation in such systems demonstrates the need for advanced shielding techniques and careful circuit design to maintain signal integrity and minimize radiated and conducted noise (Karim, 2025).

Within this evolving technological landscape, measurement methodologies must continue to advance to ensure accurate characterization of electromagnetic emissions. Several studies have explored techniques for improving the accuracy of Line Impedance Stabilization Network measurements. One promising approach involves the use of calculable adapters designed to refine impedance characterization and reduce measurement uncertainty (Ziadé et al., 2016). These adapters enable more precise evaluation of the input impedance of measurement networks, thereby improving the reliability of conducted emission measurements.

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Similarly, research on impedance extraction techniques for switching mode power supplies has introduced modified Line Impedance Stabilization Networks and simplified calibration procedures capable of estimating noise source impedance during device operation (Shang et al., 2017). Such techniques provide valuable insights into the internal electromagnetic behavior of power electronic devices, enabling engineers to better understand the mechanisms responsible for conducted emissions.

These advances illustrate the importance of continuous innovation in measurement technology to address the growing complexity of electronic systems. However, the broader implications of measurement accuracy for functional safety and system reliability remain insufficiently explored in the academic literature. Many studies focus primarily on technical measurement aspects without considering their integration into automotive safety engineering frameworks.

The present research article seeks to address this gap by providing an extensive theoretical analysis of conducted emission measurement methodologies, their associated uncertainties, and their relevance to functional safety validation in automotive electronics. By synthesizing insights from existing studies on Line Impedance Stabilization Networks, impedance measurement techniques, and electromagnetic interference mitigation strategies, the article develops a comprehensive conceptual framework for understanding the relationship between measurement accuracy and system reliability.

The remainder of the article elaborates on the methodological foundations of conducted emission measurement, examines the implications of impedance imperfections, analyzes calibration approaches aimed at improving measurement precision, and discusses how these technical considerations intersect with automotive safety standards. Through detailed theoretical exploration, the study aims to contribute to a deeper understanding of electromagnetic compatibility measurement practices and their role in ensuring the safe and reliable operation of modern automotive systems.

METHODOLOGY

The methodological approach adopted in this research is grounded in theoretical synthesis and analytical interpretation of established electromagnetic compatibility measurement studies. Rather than conducting experimental measurements, the study constructs an integrated framework that connects measurement theory, impedance characterization, calibration techniques, and automotive safety requirements. This approach allows for a comprehensive evaluation of how different measurement methodologies influence the reliability and reproducibility of conducted emission testing.

The foundation of the methodology lies in the detailed examination of the operational principles of Line Impedance Stabilization Networks. These devices are designed to fulfill

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two primary functions within electromagnetic compatibility testing. The first function is to present a standardized impedance to the equipment under test across a defined frequency range. The second function is to isolate the test setup from external electromagnetic disturbances that could otherwise contaminate measurement results. By fulfilling these roles, the network ensures that emission measurements reflect the intrinsic electromagnetic behavior of the device rather than environmental influences (Mayerhofer, 2022).

In theoretical terms, the effectiveness of a Line Impedance Stabilization Network depends on how closely its realized impedance profile matches the standardized reference impedance specified by measurement standards. Deviations from this profile may arise due to component tolerances, parasitic inductances, connector imperfections, and other practical implementation constraints. These deviations can modify the interaction between the device under test and the measurement network, thereby altering the observed emission levels (Carobbi and Stecher, 2012).

To analyze these effects, the methodological framework incorporates a conceptual model of conducted emission propagation through the power supply interface. In this model, the device under test is treated as a noise source whose electromagnetic emissions propagate through a network consisting of the device impedance, the stabilization network impedance, and the measurement instrumentation. Any deviation in the impedance characteristics of the stabilization network therefore influences the distribution of electromagnetic energy within the measurement system.

An important component of the methodology involves examining measurement scenarios where Line Impedance Stabilization Networks are absent. Studies investigating such configurations reveal that the lack of a controlled impedance environment leads to substantial variability in measured emission levels because the power supply network itself becomes part of the measurement path (Li, See, and Bandara, 2016). This variability demonstrates the importance of standardized impedance stabilization in ensuring measurement consistency.

The methodological framework also evaluates techniques aimed at improving measurement accuracy through enhanced impedance characterization. One approach involves the use of calculable adapters that enable more precise determination of the input impedance of the stabilization network. By carefully designing these adapters to possess well-defined electromagnetic properties, researchers can reduce uncertainty in impedance measurement and thereby improve the reliability of conducted emission testing (Ziadé et al., 2016).

Another methodological element concerns the extraction of noise source impedance in switching mode power supplies. These devices are among the most significant contributors to conducted emissions in automotive electronics because their high-frequency switching behavior generates complex electromagnetic noise patterns. Advanced measurement techniques utilize modified stabilization networks combined with calibration procedures that allow engineers to estimate the internal noise impedance of operating devices (Shang et al., 2017). Understanding this impedance is essential for predicting how emissions will propagate through vehicle power distribution systems.

In addition to measurement technology, the methodology incorporates functional safety considerations derived from automotive safety standards. Functional safety frameworks emphasize systematic identification and mitigation of potential hazards associated with electronic system malfunctions. Within this context, electromagnetic interference can be interpreted as a disturbance capable of triggering unintended system behavior. Therefore, measurement accuracy directly influences the ability to identify and mitigate such disturbances during system validation (ISO 26262, 2011).

To integrate these perspectives, the methodological analysis examines how measurement uncertainty might affect the verification of electromagnetic compatibility compliance. If emission measurements underestimate the true electromagnetic behavior of a device, the system may pass compliance testing while still posing a risk of interference in real operating environments. Conversely, overestimation of emissions may lead to unnecessary design modifications or increased development costs.

Finally, the methodological framework considers the influence of emerging automotive technologies on electromagnetic measurement requirements. High-speed communication systems and advanced driver assistance electronics introduce new signal frequencies, complex circuit topologies, and dense electromagnetic environments. Research on interference mitigation in such systems highlights the importance of precise electromagnetic modeling and measurement validation during circuit design (Karim, 2025).

Through this multidimensional methodological approach, the study constructs a comprehensive theoretical foundation for evaluating conducted emission measurement practices. By synthesizing insights from impedance theory, measurement instrumentation, and safety engineering, the research aims to provide a deeper understanding of how measurement methodologies influence the reliability of electromagnetic compatibility verification in modern automotive systems.

Results

The analytical synthesis conducted in this research reveals several important insights regarding the reliability and accuracy of conducted emission measurements in automotive electronic systems. These findings emerge from the integration of theoretical measurement principles with empirical observations reported in prior studies. Although the present research does not introduce new experimental measurements, the interpretive evaluation of existing work provides a coherent picture of how measurement methodologies influence electromagnetic compatibility assessment.

One of the most significant findings concerns the sensitivity of conducted emission measurements to the impedance characteristics of Line Impedance Stabilization Networks. Studies examining the effect of imperfect artificial mains network impedance demonstrate that even small deviations from standardized impedance values can lead to measurable variations in emission readings (Carobbi and Stecher, 2012). This occurs because the impedance of the stabilization network directly influences the current and voltage distribution within the measurement circuit.

In practical measurement environments, the stabilization network is intended to replicate a standardized impedance that approximates typical power supply conditions. However, the physical implementation of the network inevitably introduces parasitic elements such as stray inductance, capacitance, and resistance. These parasitic components alter the effective impedance profile of the network, particularly at higher frequencies where electromagnetic effects become more pronounced.

The analysis indicates that the resulting impedance deviations may affect both the amplitude and spectral characteristics of measured emissions. For example, certain frequency components of the conducted noise may be amplified or attenuated depending on how the device impedance interacts with the stabilization network. As a result, measurements obtained from different stabilization networks may exhibit discrepancies even when the same device is tested under otherwise identical conditions.

Another key finding relates to the impact of conducting emission measurements without the use of a Line Impedance Stabilization Network. Research investigating this scenario reveals that the absence of a controlled impedance environment introduces substantial uncertainty into the measurement process (Li, See, and Bandara, 2016). In such configurations, the power supply network itself becomes an unpredictable element of the measurement path.

Because power supply systems vary widely in their impedance characteristics, measurements performed without stabilization networks may reflect the properties of the supply infrastructure rather than the intrinsic emissions of the device under test. Consequently, results obtained in different laboratories or test environments may diverge significantly, undermining the reproducibility of electromagnetic compatibility testing.

The synthesis also highlights the effectiveness of advanced calibration techniques in improving measurement accuracy. The introduction of calculable adapters designed for impedance characterization represents an important advancement in measurement methodology. These adapters allow researchers to evaluate the input impedance of stabilization networks with greater precision, thereby reducing the

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uncertainty associated with impedance deviations (Ziadé et al., 2016).

By providing a reference structure with well-defined electromagnetic properties, calculable adapters enable more accurate calibration of measurement systems. The improved calibration process enhances confidence in emission measurements and facilitates more reliable comparison of results obtained across different laboratories.

A related finding concerns the extraction of noise source impedance in switching mode power supplies. The analytical evaluation of modified stabilization network configurations indicates that these techniques provide valuable insight into the internal electromagnetic behavior of power electronic devices. By estimating the impedance of the noise source during operation, engineers can better understand how conducted emissions propagate through power distribution networks (Shang et al., 2017).

Such knowledge is particularly important in automotive applications, where power distribution networks often connect multiple electronic subsystems. Understanding the impedance characteristics of emission sources allows engineers to predict potential interference pathways and design appropriate mitigation strategies.

The results also reveal that measurement accuracy has direct implications for functional safety validation. Because automotive safety standards require comprehensive verification of system reliability, inaccurate emission measurements may compromise the integrity of safety assessments. For instance, if conducted emissions are underestimated due to measurement errors, safety-critical communication networks or sensor interfaces could experience interference in real operating environments despite having passed laboratory testing.

The integration of high-speed communication technologies further amplifies these concerns. Research on electromagnetic interference mitigation in advanced automotive systems demonstrates that high-frequency signal transmission can interact with surrounding electronic circuits in complex ways. Effective shielding and circuit design techniques are therefore necessary to maintain electromagnetic compatibility in these environments (Karim, 2025).

Overall, the analytical findings emphasize that measurement accuracy is not merely a technical concern but a foundational requirement for reliable electromagnetic compatibility verification. Ensuring precise impedance characterization, standardized measurement environments, and robust calibration procedures is essential for maintaining the integrity of conducted emission testing.

DISCUSSION

The results obtained through theoretical synthesis highlight several broader implications for electromagnetic compatibility testing in automotive electronics. One of the most important insights is that measurement accuracy must be considered within a systems engineering perspective rather than as an isolated technical parameter. Conducted emission measurements influence regulatory compliance evaluation, product certification processes, and functional safety validation. Consequently, inaccuracies in measurement methodology can have cascading effects across the entire vehicle development lifecycle.

A central theme emerging from the analysis is the relationship between measurement reproducibility and impedance standardization. The Line Impedance Stabilization Network serves as the cornerstone of conducted emission testing precisely because it establishes a consistent electrical environment for measurement. However, the effectiveness of this approach depends on the degree to which the realized impedance matches the intended standardized profile.

When impedance deviations occur, they introduce variability into measurement results that may be difficult to detect or interpret. In some cases, measurement discrepancies may arise not from differences in device behavior but from subtle variations in stabilization network characteristics. Addressing this issue requires rigorous calibration procedures and careful evaluation of measurement instrumentation.

The development of calculable adapters represents a promising step toward improving impedance characterization. By enabling more precise measurement of stabilization network impedance, these adapters reduce the uncertainty associated with measurement systems. Nevertheless, their implementation also highlights the complexity of achieving high-accuracy electromagnetic measurements. Designing adapters with predictable electromagnetic behavior requires sophisticated modeling and meticulous manufacturing processes.

Another important aspect of the discussion concerns the evolving electromagnetic environment within modern vehicles. The integration of advanced driver assistance systems, high-speed communication networks, and electrified powertrains has dramatically increased the density and complexity of automotive electronics. Each of these technologies introduces new sources of electromagnetic noise and potential interference pathways.

High-speed automotive Ethernet networks illustrate this trend particularly well. The transition from traditional automotive communication protocols to multi-gigabit Ethernet links enables unprecedented data throughput but also raises significant electromagnetic compatibility challenges. Signal frequencies in these systems extend into ranges where electromagnetic coupling effects become more pronounced, increasing the risk of interference with nearby electronic circuits (Karim, 2025).

From a measurement perspective, these developments necessitate more sophisticated testing methodologies capable of capturing the full spectrum of electromagnetic interactions within complex electronic systems. Traditional conducted emission measurement techniques may require adaptation to address the unique characteristics of high-frequency digital communication interfaces.

Functional safety considerations further complicate the measurement landscape. The ISO 26262 standard emphasizes systematic identification and mitigation of hazards arising from electronic system failures. Within this framework, electromagnetic interference can be interpreted as an external disturbance capable of triggering unintended system behavior. Consequently, accurate measurement of electromagnetic emissions becomes an essential component of hazard analysis and risk assessment (ISO 26262, 2011).

However, integrating electromagnetic compatibility testing with functional safety engineering presents several conceptual challenges. Safety engineers typically focus on system-level behavior and risk management, whereas electromagnetic compatibility specialists concentrate on measurement accuracy and regulatory compliance. Bridging these perspectives requires interdisciplinary collaboration and shared understanding of how measurement results influence safety validation processes.

One potential approach involves incorporating electromagnetic compatibility considerations directly into safety lifecycle management. For example, emission measurements could be linked to specific safety goals or hazard scenarios identified during system design. By establishing such connections, engineers can ensure that measurement results provide meaningful input to safety analysis rather than serving solely as regulatory documentation.

Despite the progress achieved in measurement technology, several limitations remain. Many studies focus on laboratory measurement conditions that may not fully replicate the electromagnetic environment encountered in real vehicle operation. Automotive systems operate within complex environments characterized by variable load conditions, temperature fluctuations, mechanical vibrations, and interactions among numerous electronic devices.

Future research should therefore explore measurement methodologies capable of capturing these dynamic conditions more effectively. For instance, in-situ electromagnetic monitoring techniques could provide valuable insight into how emissions behave during actual vehicle operation. Such approaches would complement traditional laboratory testing by providing real-world validation of electromagnetic compatibility performance.

Another promising direction involves the integration of advanced modeling and simulation techniques with measurement data. Computational electromagnetic simulations can provide detailed insight into how electromagnetic fields propagate through complex electronic structures. When combined with accurate measurement data, these models can help engineers predict interference scenarios and optimize system design.

Conclusion

The comprehensive analysis presented in this article underscores the critical importance of measurement accuracy in conducted emission testing for automotive electronic systems. As vehicles become increasingly dependent on complex electronic architectures, ensuring electromagnetic compatibility has emerged as a fundamental requirement for system reliability and functional safety.

The Line Impedance Stabilization Network plays a central role in establishing standardized measurement environments for conducted emissions. However, practical implementations of these networks are subject to impedance imperfections and calibration challenges that may influence measurement results. Research examining the impact of imperfect impedance realization demonstrates that even small deviations can affect emission measurements, potentially leading to discrepancies across different testing facilities.

The absence of stabilization networks in measurement setups introduces even greater uncertainty because the uncontrolled impedance of power supply systems becomes part of the measurement path. Such conditions undermine the reproducibility of electromagnetic compatibility testing and highlight the necessity of standardized measurement infrastructure.

Advances in calibration methodologies, including the use of calculable adapters and modified stabilization networks, have significantly improved the precision of impedance characterization and noise source analysis. These developments enhance the reliability of conducted emission measurements and provide deeper insight into the electromagnetic behavior of electronic devices.

At the same time, the integration of electromagnetic compatibility verification with automotive functional safety frameworks requires greater interdisciplinary collaboration. Accurate emission measurements are essential for validating the reliability of safety-critical electronic systems and ensuring compliance with standards such as ISO 26262.

Looking ahead, the continued evolution of automotive technologies will demand even more sophisticated measurement methodologies. High-speed communication networks, electrified powertrains, and advanced driver assistance systems introduce complex electromagnetic interactions that challenge traditional testing approaches. Addressing these challenges will require ongoing innovation in measurement instrumentation, calibration techniques, and system-level electromagnetic modeling.

Ultimately, advancing the state of electromagnetic compatibility testing is not merely a technical endeavor but a foundational component of ensuring the safe and reliable

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operation of modern vehicles. By strengthening the accuracy and reproducibility of conducted emission measurements, engineers can build greater confidence in the electronic systems that increasingly define the functionality of contemporary automotive technology.

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