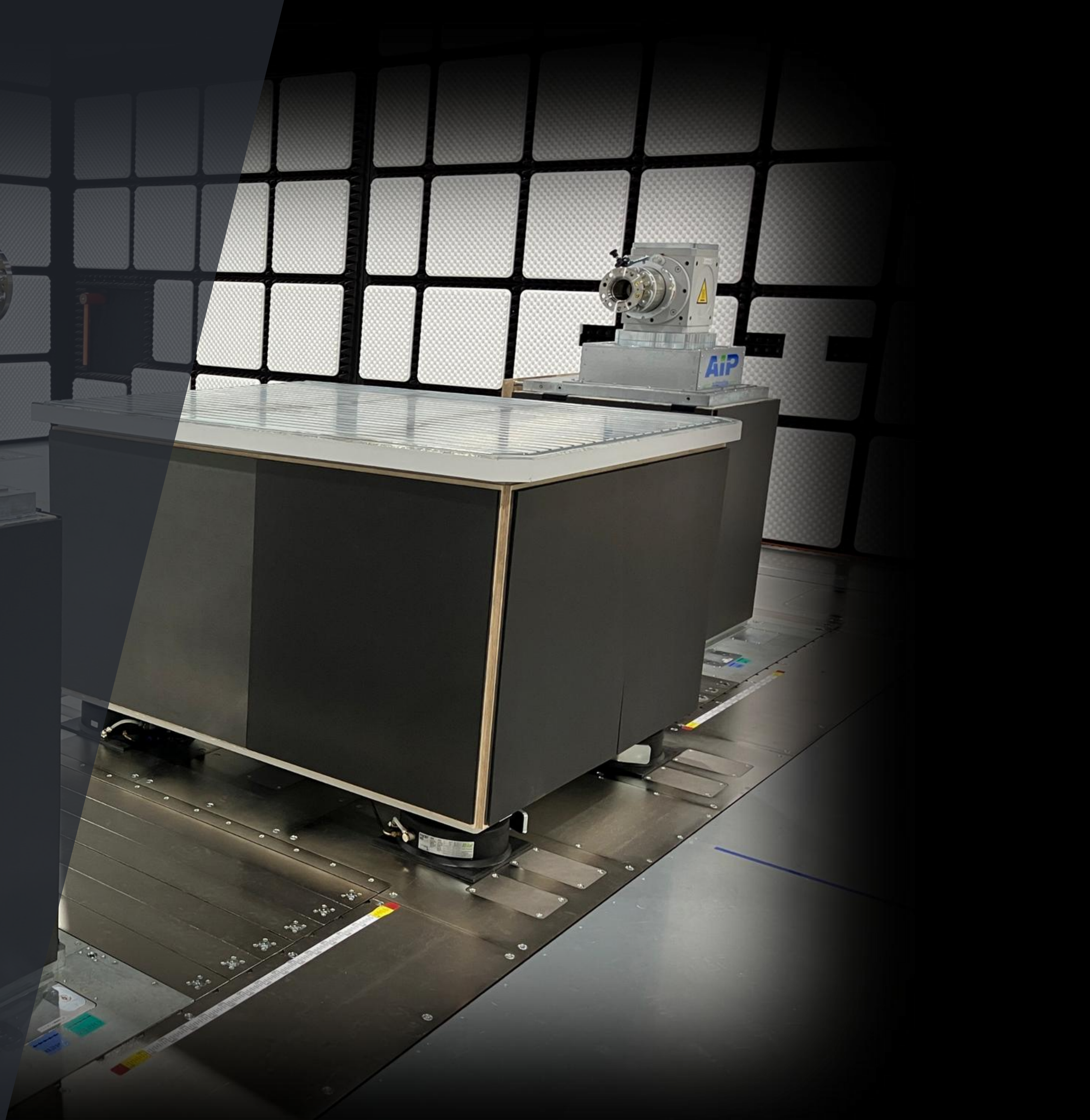
EMC Testing for E-Axles

AiP

From Norm Compliance to Real Operation

with AIP



Executive Summary

EMC as a System-Level Challenge

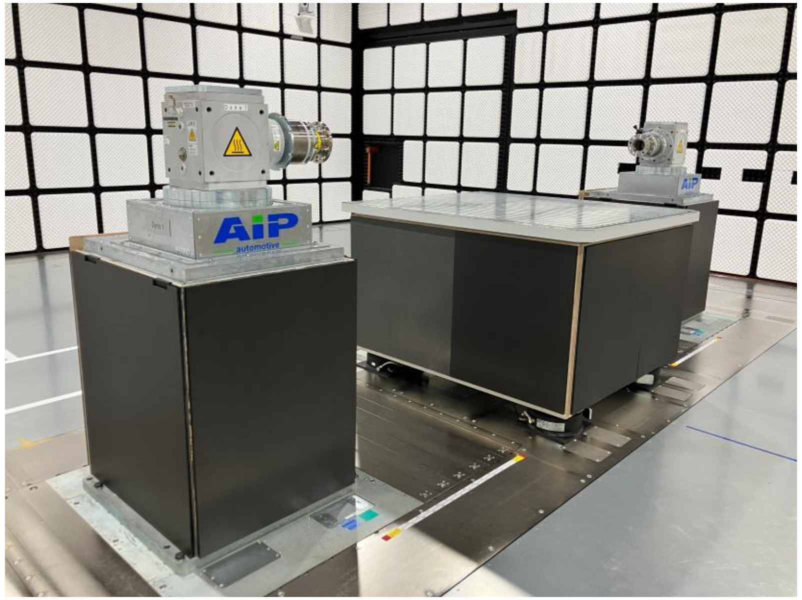
EMC has become a critical system-level challenge in the development of modern electric axles. Increasing power density, high switching frequencies, and tightly integrated inverter–motor architectures significantly amplify electromagnetic complexity, while OEM and regulatory requirements demand testing under realistic operating conditions and with high reproducibility. Conventional EMC test bench concepts struggle to reconcile these demands, particularly when high-performance load operation and norm-compliant measurement environments must be combined.

An Integrated Approach to EMC E-Axle Testing

This whitepaper presents an **integrated EMC e-axle test bench concept** developed by AIP that overcomes the classical trade-off between performance capability, EMC integrity, and reproducibility. The solution relies on the complete integration of high-performance electric load machines inside the EMC chamber, combined with an EMC-optimized mechanical, electrical, and shielding architecture. By eliminating external load machines, long mechanical feedthroughs, and undefined interference paths, the test bench establishes well-controlled and reproducible electromagnetic boundary conditions while enabling realistic, dynamic operation of the e-axle under test.

Proven EMC Compliance Under Realistic Conditions

A key contribution of the presented approach is the demonstration that integrated load machine concepts can meet and exceed EMC requirements, contradicting widespread assumptions within the EMC community. Comprehensive Normalized Site Attenuation (NSA) measurements from 150 kHz to 1 GHz, conducted by an independent accredited EMC laboratory, confirm **full norm compliance across all frequency ranges.** Despite the presence of metallic structures and operating electric machines inside the chamber, the system shows excellent and stable NSA behavior, remaining well within permissible tolerances.



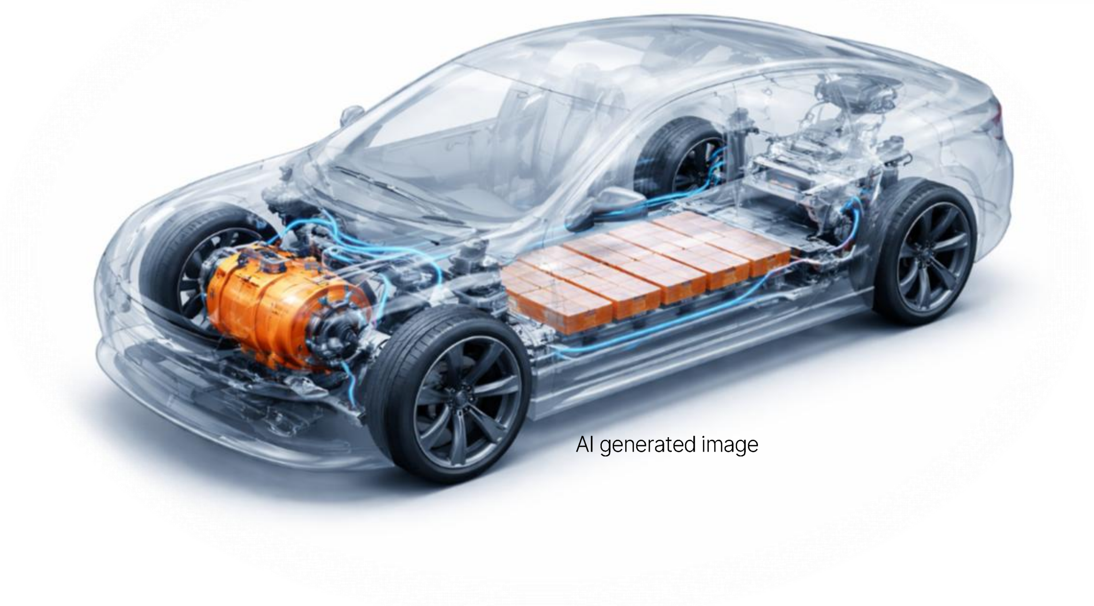
Flexible and Efficient EMC Infrastructure Utilization

Beyond EMC compliance, the test bench offers high operational flexibility. Modular mechanical adaptations, adjustable track widths, flexible antenna positioning, and rapid dismantling within approximately 30 minutes allow efficient use of valuable EMC chamber infrastructure while supporting a wide range of e-axle variants and development stages.

From Compliance to Reproducible Validation

In summary, the presented AIP EMC e-axle test bench enables realistic, dynamic, and reproducible EMC validation at component level, bridging the gap between normative requirements and real-world drivetrain operation. The concept provides OEMs and Tier-1 suppliers with a future-proof solution for early development, component acceptance, and system-level EMC validation of modern electric axles.

Introduction



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Rising EMC Challenges in Electrified Powertrains

The development of modern electric drive systems is increasingly shaped by growing electromagnetic complexity. Higher power densities, faster switching devices, wide-bandgap semiconductors, and tightly integrated inverter–motor architectures significantly increase the risk of electromagnetic interference. At the same time, electric drives are no longer isolated components but deeply embedded into highly networked vehicle architectures, where EMC behavior directly affects functional safety, communication reliability, and homologation readiness.

In this environment, electromagnetic compatibility (EMC) has evolved from a late-stage compliance topic into a critical system-level development discipline. OEMs and Tier-1 suppliers are therefore shifting EMC validation earlier into the development process, aiming to identify emission and immunity risks under realistic operating conditions before vehicle integration.

Limitations of Conventional EMC Test Setups

Despite their central role in development and certification, conventional EMC test bench concepts exhibit fundamental limitations when applied to high-performance electric drive systems. High-power test benches frequently rely on external load machines located outside the EMC chamber and coupled to the device under test via long shafts, mechanical feedthroughs, or angular gearboxes penetrating the chamber walls. While this approach enables high torque and speed capability, it introduces additional mechanical complexity, poorly defined electromagnetic boundary conditions, and potential interference paths that can significantly influence measurement results.

Alternative, compact load concepts placed inside the chamber address some of these issues but are often restricted in dynamic performance, controllability, and thermal capability. As a result, realistic operating points, transient load cases, or representative driving profiles cannot be reproduced with sufficient fidelity. This creates a fundamental conflict between performance capability, reproducibility, and EMC integrity.

Studies and practical experience show that even minor variations in cabling, grounding, mechanical alignment, or load coupling can lead to substantial deviations in measured emission levels. Consequently, the comparability of results across measurement campaigns or test locations is often limited, undermining the reliability of EMC assessments during development.

Towards Realistic and Reproducible EMC Validation

To support robust component-level EMC development, modern test environments must go beyond normative compliance and deliver system-level reproducibility under realistic operating conditions. This requires EMC test benches that provide high dynamic load capability, stable and well-defined electromagnetic boundary conditions, and minimal system-induced interference.

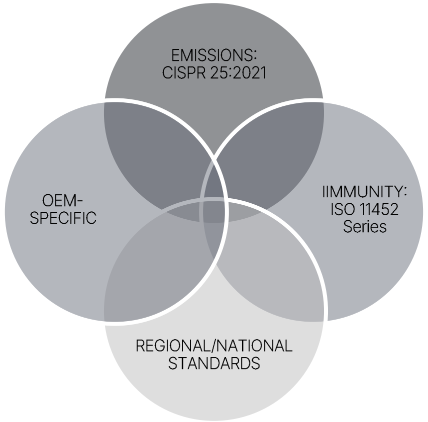
In particular, electric axles and integrated drive units demand load concepts capable of reproducing real torque and speed profiles, including transient and asymmetric operating states, without compromising the EMC measurement environment. At the same time, test bench architectures must remain flexible to accommodate different drivetrain geometries and development stages while enabling efficient use of highly valuable EMC chamber infrastructure.

Against this background, integrated EMC e-axle test benches represent a new class of validation systems. By fully embedding high-performance load machines within the EMC chamber and combining them with EMC-optimized mechanical and electrical integration concepts, these systems enable realistic, dynamic, and reproducible EMC testing without the drawbacks of classical external load configurations..

Normative Framework

EMC Requirements for Electric Drive Components

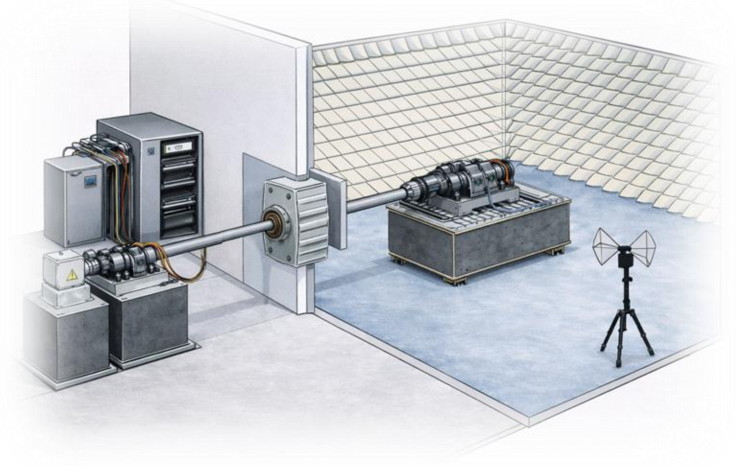
EMC Requirements for Electric Drive Components

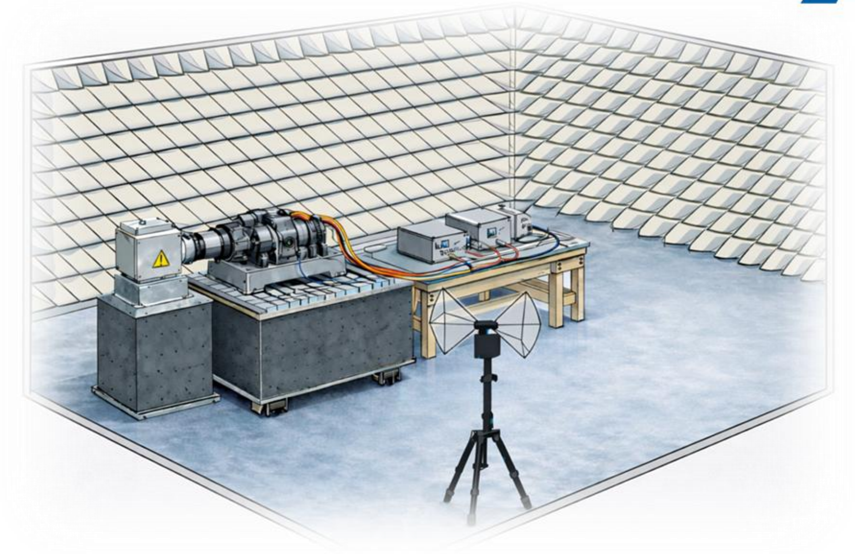


Electromagnetic compatibility requirements for automotive components are defined by a layered framework of international, regional, and OEM-specific standards. For electric drive systems and e-axles, these requirements cover both electromagnetic emissions and immunity under operating conditions, ensuring that powertrain components neither interfere with vehicle systems nor are susceptible to external electromagnetic influences.

At component level, CISPR 25 represents the globally established reference for conducted and radiated emission measurements in vehicles. In parallel, the ISO 11452 series defines immunity test methods for electrical and electronic components exposed to radiated and conducted electromagnetic fields. Together, these standards form the backbone for EMC validation of electric drive systems prior to vehicle integration.

However, as electrified powertrains continue to increase in power density and functional complexity, the application of these standards, originally developed for conventional components, requires careful interpretation when applied to high-performance electric axles operating under load.





Emissions according to CISPR 25

CISPR 25 specifies limits and measurement setups for conducted and radiated emissions in the frequency range from 150 kHz to 2.5 GHz. While the standard defines boundary conditions for automotive component testing, it intentionally leaves degrees of freedom in the mechanical and electrical realization of test setups, particularly for complex devices such as electric drives.

In practice, this leaves open questions regarding:

- the mechanical coupling of load machines,
- acceptable routing and length of shafts and cabling,
- grounding concepts and reference planes,
- and the influence of auxiliary components such as inverters, cooling systems, and power supplies.

For electric axles, these aspects directly influence emission behavior. Long mechanical feedthroughs or external load machines can effectively act as unintended antennas, introducing additional radiation paths that are not inherent to the device under test. As a result, measured emissions may be dominated by test-bench-induced effects rather than the intrinsic EMC properties of the e-axle itself.

To obtain meaningful and reproducible results, CISPR 25 testing of electric drives must therefore be interpreted as a system-level validation task, requiring carefully controlled and well-defined boundary conditions rather than a purely component-centric view.

Normative Framework

Operational EMC Reality and Design Consequences

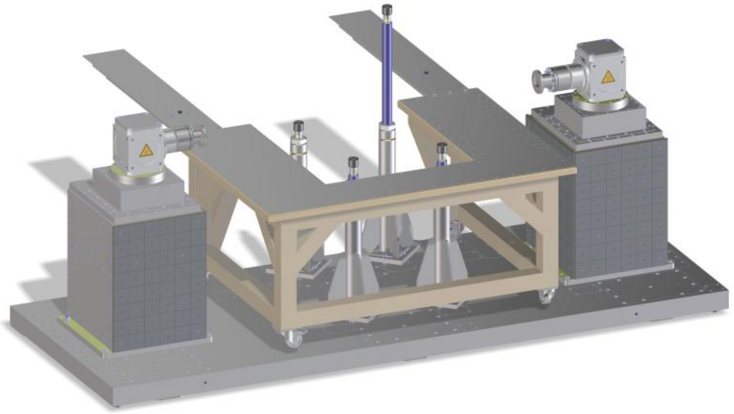
Immunity Testing Under Operating Conditions

Immunity requirements for automotive components are addressed by the ISO 11452 standard series, covering a wide range of test methods, including:

- anechoic and semi-anechoic chambers,
- stripline and TEM cell methods,
- conducted RF injection,
- magnetic field immunity,
- and portable transmitter exposure.

For electric drive systems, immunity testing under real operating conditions is particularly critical. High currents, fast switching edges, and dynamic load changes increase susceptibility to interference that may not be observable under static or no-load conditions. Functions such as torque control, communication interfaces, resolver or encoder signals, and safety-relevant supervision mechanisms can be affected by electromagnetic stress, leading to degraded performance or latent faults.

Consequently, EMC standards increasingly emphasize immunity under operation, requiring that electric drives remain fully functional during exposure to electromagnetic disturbances. This necessitates test environments capable of maintaining stable mechanical loading and dynamic operation while performing EMC measurements—without introducing additional interference sources.



Regional and OEM-Specific Requirements

Beyond international standards, regional regulations such as GB/T standards in China, AIS standards in India, and SAE-related specifications in North America further refine EMC requirements based on local homologation procedures. In addition, virtually all major OEMs define proprietary EMC specifications that extend or tighten the limits and test conditions defined in CISPR and ISO standards.

OEM-specific requirements frequently introduce:

- stricter emission limits,
- additional operating points and load cases,
- combined emission and immunity evaluations,
- and increased expectations regarding reproducibility and traceability of results.

For suppliers developing electric axles for global vehicle platforms, this results in a highly demanding validation landscape. Test benches must not only be norm-compliant but also flexible enough to accommodate varying interpretations, operating scenarios, and test philosophies across OEMs and markets.

Implications for EMC Test Bench Design

The increasing gap between normative descriptions and realistic operating behavior has significant implications for EMC test bench design. To support credible and transferable EMC validation of electric axles, test environments must provide:

- well-defined and reproducible electromagnetic boundary conditions,
- realistic mechanical loading aligned with real drive operation,
- minimal system-induced interference,
- and compatibility with international and OEM-specific EMC standards.

Rather than adapting the device under test to the limitations of conventional EMC benches, modern test setups must be engineered specifically around the requirements of high-performance electric drives. This shift from normative compliance toward engineering-driven EMC validation lays the foundation for integrated EMC e-axle test benches capable of bridging the gap between standards and real-world drivetrain operation.

AIP-Solution

Setup

To overcome the inherent conflicts of conventional EMC test setups, AIP has developed an integrated EMC e-axle test bench concept specifically engineered for high-performance electric drive systems. The core design principle is the complete integration of the load machines inside the chamber, combined with an EMC-optimized mechanical and electrical architecture.

Unlike classical solutions that rely on external load machines and mechanical feedthroughs, the AIP concept ensures that all mechanically and electromagnetically relevant components remain within a well-defined, closed measurement environment. This eliminates additional interference paths and establishes reproducible boundary conditions essential for meaningful EMC evaluation of electric axles under realistic operating conditions.

High-Performance Load Machines Fully Integrated into the EMC Chamber

The test bench architecture is based on two load machines directly coupled to the DUT. Each machine provides high torque capability, wide speed range, and fast dynamic response, enabling the reproduction of real operating points and transient load scenarios typical for modern electric drives.
By positioning the load machines entirely within the EMC chamber:

- mechanical feedthroughs through chamber walls are avoided,
- long shafts and gear trains acting as unintended antennas are eliminated,
- electromagnetic coupling paths are clearly defined and minimized.

Different antenna positions
The antennas can be placed flexibly around the setup

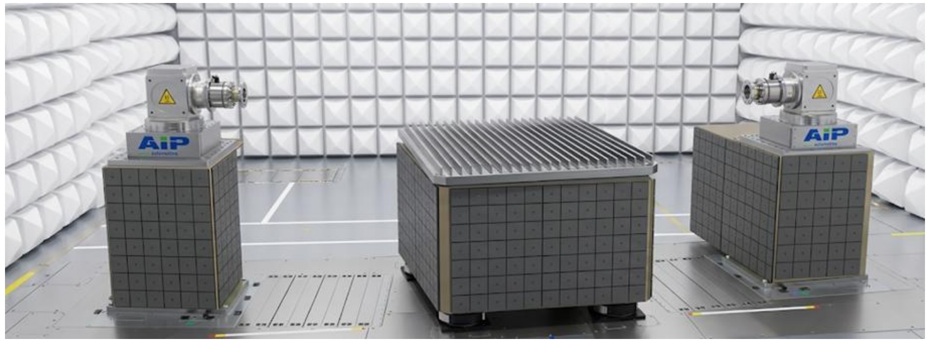
Maximum flexibility
Completely dismantled and removed from the chamber within 30 minutes. Additional track widths possible.

Customized adaptations
Various structures and customizations

Complete shielding
Shielded dynos prevent unwanted interference emissions

Small space required
External brake machines require a lot of space outside the chamber.

Real-time collection
Built-in measurement technology allows real-time monitoring of speed and torque



EMC-Optimized Mechanical and Electrical Integration

A key challenge of integrated concepts lies in preventing the load machines themselves from influencing EMC measurements. To address this, AIP has implemented a dedicated EMC design strategy covering mechanical layout, shielding, grounding, and cabling.

The load machines and their power electronics are encapsulated using an optimized shielding concept that significantly suppresses emissions. Targeted grounding and reference plane design further ensure that electromagnetic fields remain below the sensitivity thresholds of the measurement setup. As a result, the load machines operate min. 6 dB below CISPR 25 Class 5 limits and are effectively indistinguishable from background noise during emission measurements.

From a mechanical perspective, the test bench avoids unnecessary structural complexity. Compact coupling interfaces, defined mounting positions, and vibration-isolated foundations minimize both mechanical excitation and unintended electromagnetic effects. This holistic integration ensures that the measured EMC behavior reflects the intrinsic properties of the device under test, not artifacts introduced by the test environment.

AIP-Solution

Setup

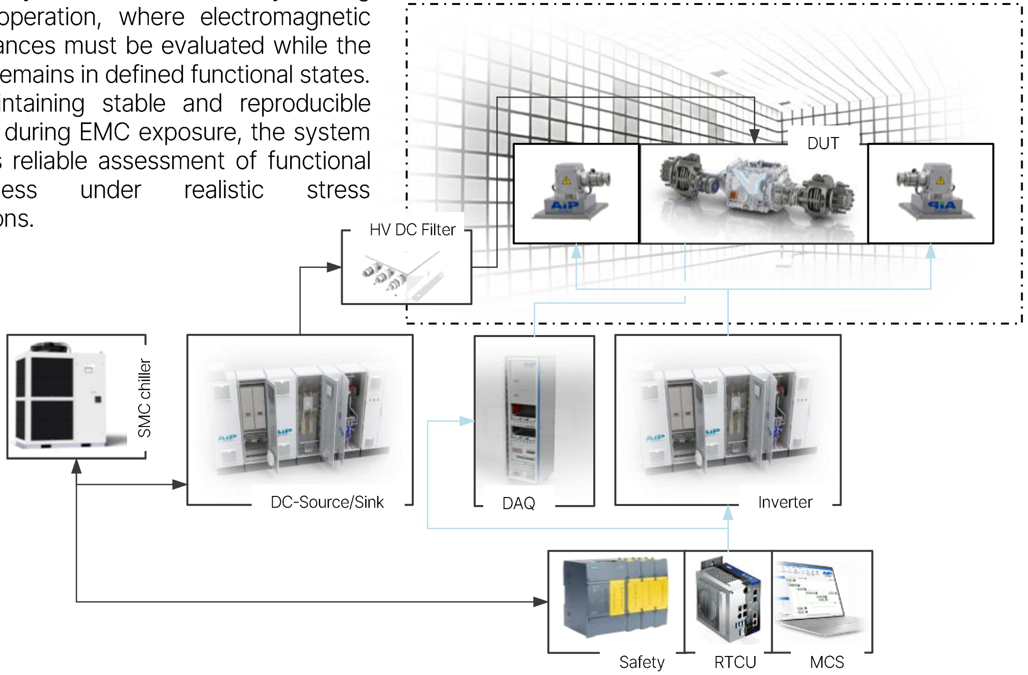
Dynamic Load Control and Realistic Operating Profiles

Beyond mechanical integration, the AIP solution places strong emphasis on dynamic load control. A specially developed control model enables high-bandwidth, stable operation of the load machines across a wide range of operating conditions. This allows:

- transient torque and speed changes,
- realistic driving-related load profiles,
- asymmetric or dynamic operating points,
- to be applied reproducibly during EMC measurements.

In contrast to simplified load concepts, the load machines are not passive elements, but actively controlled subsystems tightly synchronized with the overall test bench operation.

The dynamic control capability is particularly relevant for immunity testing under operation, where electromagnetic disturbances must be evaluated while the e-axle remains in defined functional states. By maintaining stable and reproducible loading during EMC exposure, the system enables reliable assessment of functional robustness under realistic stress conditions.



Flexibility and Efficient Use of EMC Infrastructure

In addition to performance and EMC integrity, the AIP test bench concept is designed for high operational flexibility. Adjustable track widths and adaptable mechanical interfaces allow different e-axle geometries and drivetrain configurations to be tested on the same platform.

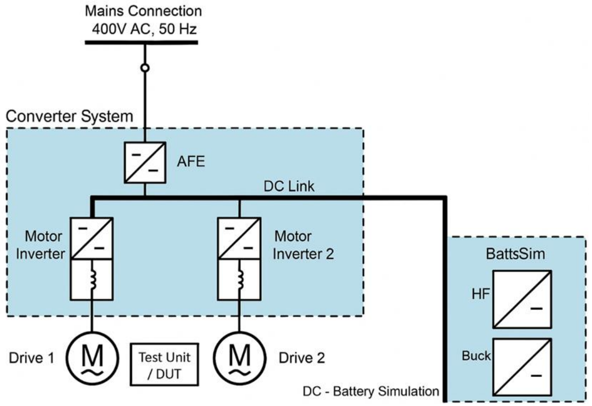
A further distinguishing feature is the efficient use of expensive EMC chamber infrastructure. The entire test bench, including load machines and device fixtures, can be dismantled and removed from the chamber within a short time. This makes it possible to reuse the EMC chamber for alternative test setups without permanent installation constraints, significantly increasing overall facility utilization.

From a development perspective, this flexibility enables OEMs and Tier-1 suppliers to adapt the test environment to different project phases, from early component validation to pre-integration acceptance testing, without compromising EMC quality or measurement reproducibility.

System-Level Integration Beyond Mechanical Hardware

The AIP EMC e-axle test bench is conceived as a fully integrated system rather than a standalone mechanical fixture. Beyond the mechanical architecture, the overall concept includes a coordinated interaction of load machines, power electronics, energy management, conditioning units, and measurement systems.

A central element of this system-level integration is the DC-DC intermediate circuit (DC link), which is implemented in the same way as in many AIP test bench solutions. The DC link couples the load machine inverters and the device under test to a shared energy bus, allowing bidirectional power flow and efficient internal energy circulation. As a result, the required grid connection power is drastically reduced, since only system losses must be compensated from the mains supply.



This approach is particularly advantageous for high-power EMC testing of electric axles, as it:

- significantly reduces required electrical infrastructure,
- improves overall energy efficiency during long test campaigns,
- minimizes grid-side disturbances that could influence EMC measurements,
- and supports stable operation even at high torque and speed levels.

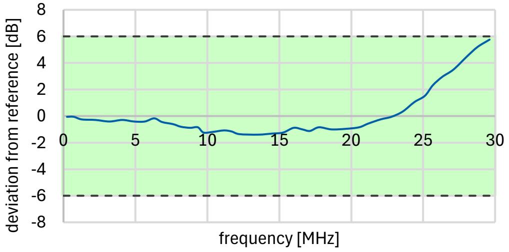
Validation
Measurements

ALSE Performance Validation from 150 kHz to 1 GHz according to CISPR 25

To verify the electromagnetic suitability of the integrated EMC e-axle test bench, comprehensive ALSE verifications according to CISPR 25 measurements were conducted over the full frequency range from 150 kHz to 1 GHz. The measurements were performed and evaluated by an independent accredited EMC laboratory (Bluetechnix Laboratories, a member of the Becom Group) under realistic test conditions and with the complete test bench installed inside the EMC chamber.

Despite the presence of large metallic structures and fully integrated electric load machines, the measurements demonstrate excellent compliance with the CISPR 25 requirements across all frequency ranges.

Rod Antenna (150 kHz – 30 MHz)

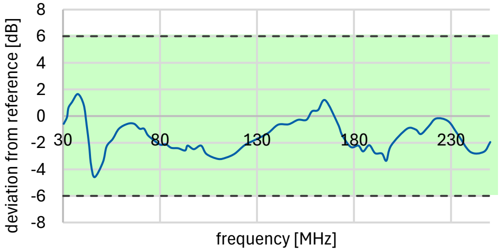


In the low-frequency range, the NSA results show very stable behavior with only minor deviations from the reference curve. Even with the large metallic setup present, the test bench exhibits nearly ideal and extremely well-controlled electromagnetic characteristics. This confirms that the integrated concept does not introduce relevant disturbances in the lower frequency domain, which is typically sensitive to grounding and structural effects.

Biconical Antenna (30 MHz to 250 MHz)

In the mid-frequency range, the measurements reveal physically expected interference patterns, while remaining continuously within the permissible tolerance limits.

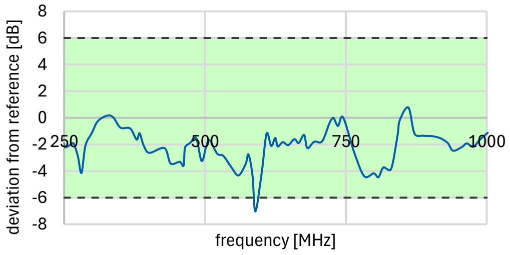
The results indicate a well-controlled electromagnetic environment, even under setup conditions representative of real e-axle testing. This confirms that reflections and coupling effects caused by the metallic structures are effectively managed.



Log-Periodic Antenna (250 MHz to 1 GHz)

Even in the highly sensitive high-frequency range, all measured deviations remain well within normative limits.

This demonstrates the effective absorption characteristics and the high overall quality of the EMC chamber and test bench integration, despite the complex metal-dominated setup.



Expert Statement

BLUETECHNIX LABORATORIES

"The realization of a load test bench for electric drive systems represents a highly complex EMC challenge. An EMC-suitable test bench must remain measurement-transparent under all operating conditions and must not dominate or distort the emission behavior of the device under test. For radiated emissions, this requires that emissions from the test bench itself are at least 20 dB below required automotive limits, for example CISPR 25 Class 5 – even at maximum speed and torque."

"Test benches designed purely for functional load testing, without systematic EMC optimization of structure, cabling, grounding, shielding, and control, are not suitable for either pre-compliance or full-compliance EMC measurements – particularly at power levels up to 400 kW."

"From the perspective of the EMC laboratory, the AIP system meets these requirements in a consistent manner. The combination of EMC behavior, usability, efficiency, flexibility, and mobility was decisive in the selection of this test bench for operation in a modern, performance-oriented EMC laboratory."

Roland Palkovich
Head of Bluetechnix Laboratories
Bluetechnix Lab GmbH
A-1230 Wien, Gutheil-Schoder-Gasse

Validation

Noise under load

Noise Level Under Load – EMC Transparency of the Test Bench

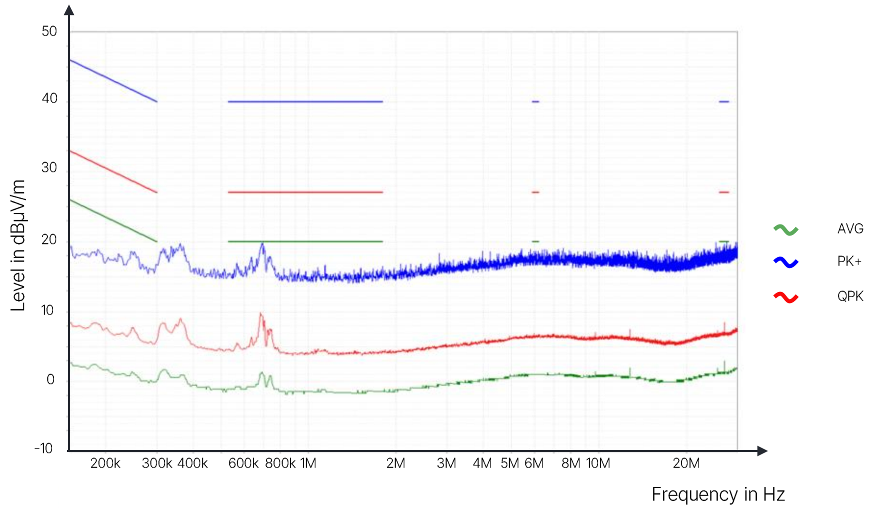
To assess the electromagnetic transparency of the integrated e-axle test bench during operation, noise level measurements under load were conducted across the relevant automotive EMC frequency ranges. The objective was to verify that the test bench itself does not introduce dominant emissions and remains sufficiently below automotive EMC limit values, even under demanding operating conditions.

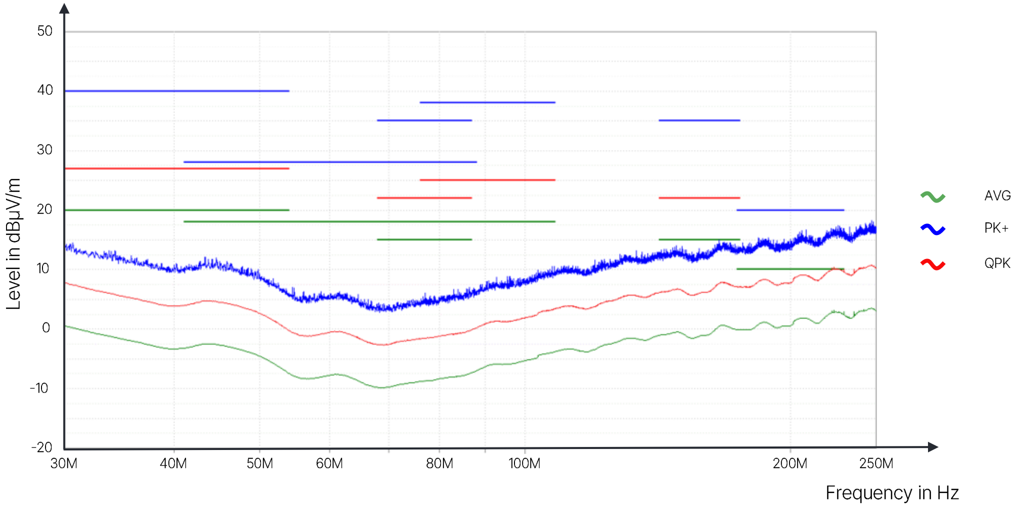
Measurements were performed in an EMC-controlled laboratory environment using two complementary antenna types to cover the full frequency spectrum relevant for pre-compliance and full-compliance investigations. Detailed measurement protocols and raw data are provided in the appendix.

Measurement Setup and Frequency Coverage

Rod Antenna – 150 kHz to 30 MHz

The rod antenna measurements cover the low-frequency range, which is particularly sensitive to grounding concepts, power electronics, and large current loops. The measured noise levels remain well below typical automotive emission limits, even under load. This demonstrates that the test bench does not introduce low-frequency interference that could mask or distort emissions originating from the device under test.





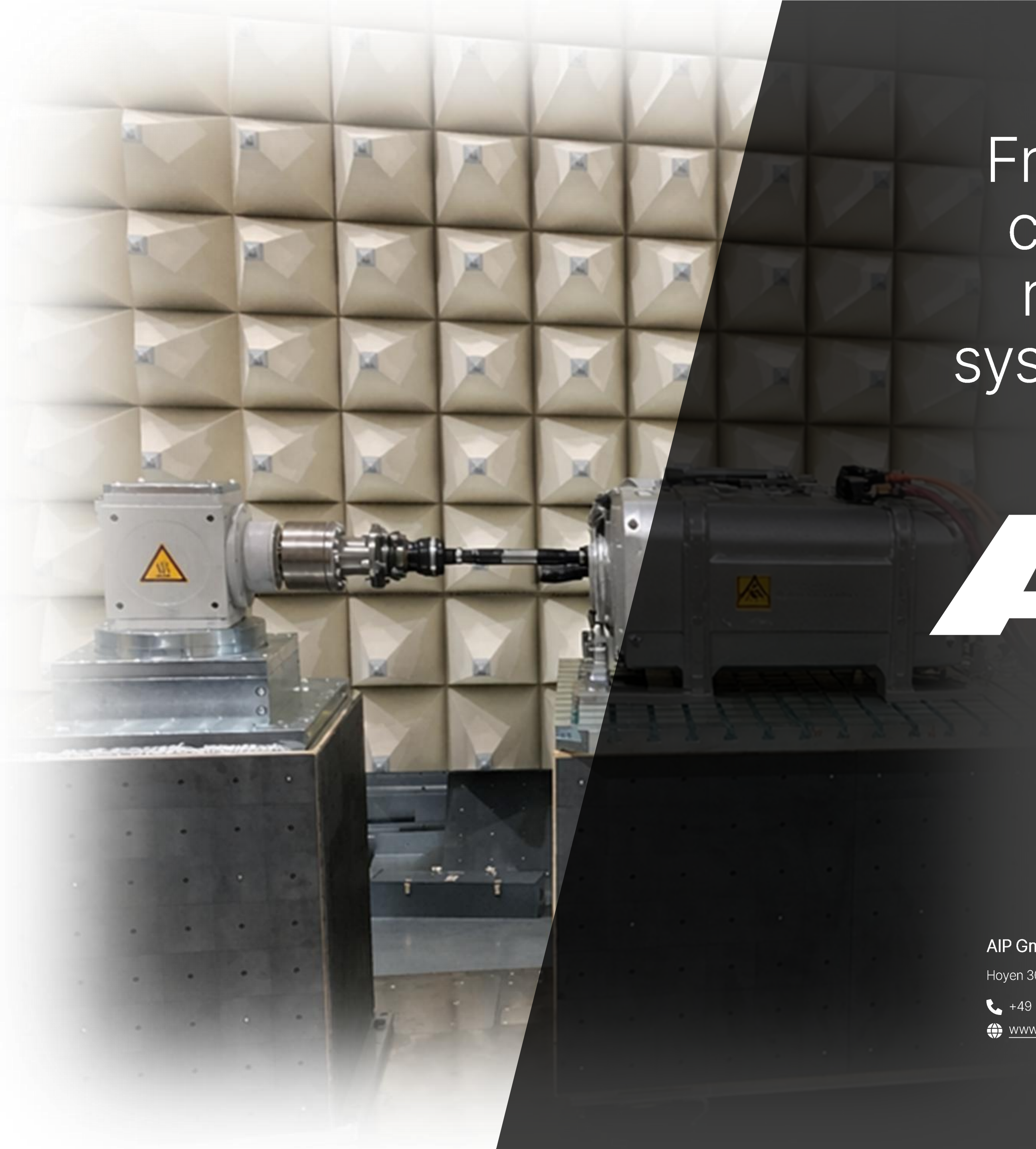
Biconical Antenna – 30 MHz to 250 MHz

In the mid-frequency range, measured using a biconical antenna, the noise spectrum remains stable and clearly separated from relevant limit values. Even under active load operation, no dominant emissions from the test bench are observed. This confirms that the EMC-optimized integration concept effectively suppresses radiated disturbances caused by switching processes and dynamic control operation.

Together, the results confirm that the test bench remains EMC-transparent under load, providing a reliable basis for both emission and immunity measurements on electric axles.

Interpretation of Results

Across both frequency ranges, the noise levels measured during operation are significantly below typical automotive emission limits. This ensures sufficient measurement margin and allows clear differentiation between test-bench-related effects and emissions caused by the device under test. As a result, reproducible and norm-compliant EMC assessments are possible even during dynamic operation at high power levels.



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