White Paper

# The Virtual EMI/EMC Laboratory

*Enabling Earlier EMI Visibility in Electronic System Development*

This white paper introduces the concept of the Virtual EMI/EMC Laboratory, a simulation-based approach that enables engineers to investigate electromagnetic interference mechanisms earlier in the hardware development process. By replicating standardized EMC compliance test environments in simulation, engineers can analyze emission or immunity behavior, diagnose root causes, and evaluate mitigation strategies before hardware prototypes enter physical testing. This approach provides earlier EMI visibility and supports a more proactive design-for-EMC workflow.

## Contents

## 1. Introduction

Electromagnetic compatibility (EMC) remains one of the most challenging aspects of modern electronic system development. As switching frequencies increase, power densities rise, and systems become more electrically complex, predicting and controlling electromagnetic interference (EMI) has become increasingly difficult. Yet despite advances in design tools and modeling techniques, many engineering teams still discover EMI problems only during late-stage validation testing.

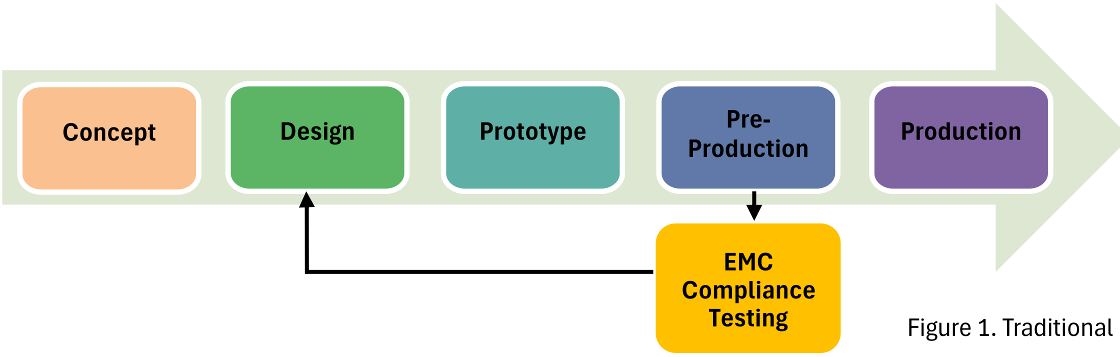


Figure 1. Traditional Design Flow

The traditional development workflow for EMC validation has remained largely unchanged for decades. Hardware is designed, prototypes are built, and compliance testing is performed in specialized EMC laboratories. When emissions exceed regulatory limits or immunity issues appear, engineers must diagnose the root cause, implement design modifications, rebuild hardware, and repeat the testing process. In many programs, this cycle occurs multiple times before a design achieves compliance.

While laboratory testing remains essential for certification and final validation, relying on physical testing as the primary method for discovering EMC issues introduces practical challenges. Engineers often have limited diagnostic visibility during compliance testing, making it difficult to determine the exact mechanisms responsible for emissions. In addition, each design iteration requires new hardware builds and laboratory scheduling, which can introduce delays and increase development risk.

Historically, simulation has not played a central role in EMC development workflows. Although electromagnetic simulation tools have existed for many years, engineers have often found them difficult to apply directly to compliance problems. Reproducing real compliance environments including the hardware assembly has traditionally required complex modeling expertise and significant setup effort. As a result, many design teams have continued to rely primarily on laboratory testing to reveal EMI behavior.

Recent advances in modeling approaches and workflow integration are beginning to change this dynamic. Modern simulation environments are now capable of replicating standardized compliance test setups with a level of fidelity that allows meaningful comparison between simulated results and laboratory measurements. As simulation-to-measurement correlation improves, engineers can begin to use these environments not only for exploratory analysis, but also to evaluate emission and immunity behavior with increasing confidence earlier in the design process.

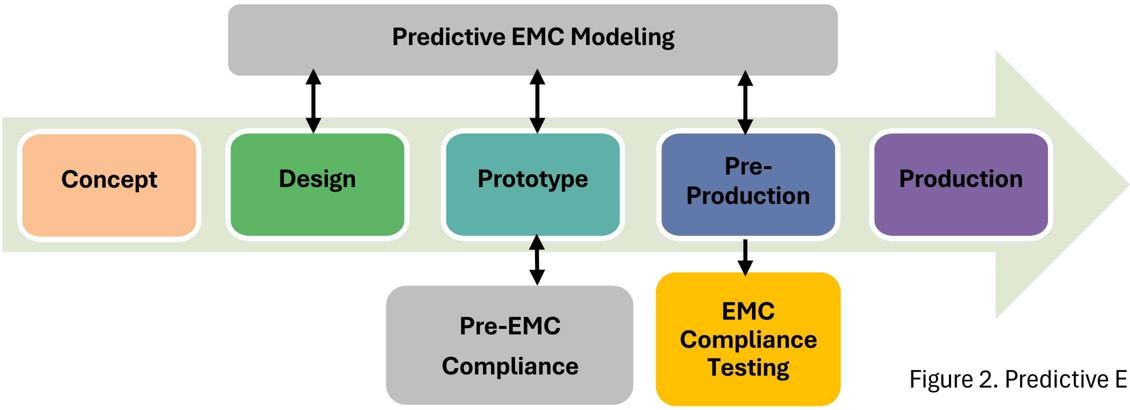


Figure 2. Predictive EMC Workflow

This capability introduces a new concept in EMC development: **the Virtual EMC Laboratory.**

Within a virtual laboratory environment, engineers can recreate standardized compliance test setups, visualize electromagnetic behavior, and evaluate potential design improvements before entering the physical test lab. This capability provides earlier EMI visibility, allowing engineering teams to diagnose potential issues, explore design alternatives, and move toward compliance with greater confidence throughout the development cycle.

**2. Traditional EMC Development Workflows**

In most electronic product development programs, EMC validation is closely tied to the availability of physical hardware. Design teams typically complete schematic development, PCB layout, and prototype fabrication before meaningful EMC evaluation begins. Once hardware becomes available, the system is brought into a pre-compliance or formal EMC laboratory where conducted and radiated emissions are measured against regulatory limits.

This process is well established and remains essential for product certification. EMC laboratories provide controlled measurement environments, standardized test setups, and calibrated instrumentation required for regulatory compliance testing. Engineers rely on these facilities to confirm that their designs meet the requirements of standards such as CISPR, ISO, and MIL specifications.

However, the role of laboratory testing within the development process often extends beyond final validation. In many cases, the first meaningful insight into a system's EMI behavior occurs during these lab measurements. Engineers observe emission levels, identify frequency peaks, and attempt to determine which parts of the design may be responsible for the observed behavior.

At this stage, diagnosing the root cause of EMI can be challenging. Compliance measurements provide accurate data about emission levels but typically offer limited visibility into the internal mechanisms that generated them. Engineers must interpret measurement results and connect them back to potential sources within the design, such as switching transitions, current loops, cable coupling, or layout parasitics.

When emission levels exceed regulatory limits, the team begins a cycle of investigation and redesign. Engineers may adjust filter networks, modify PCB layouts, alter grounding strategies, or introduce shielding and other mitigation techniques. Each design modification typically requires new hardware builds or rework, followed by additional testing to determine whether the changes were effective.

This iterative workflow can repeat several times before a design achieves compliance. Each cycle may involve laboratory scheduling constraints, prototype fabrication lead times, and coordination between design teams and EMC specialists. As a result, resolving EMI issues late in development can introduce schedule uncertainty and delays. In many cases, mitigation requires adding filters, shielding, or other suppression components not included in the original design, increasing the bill of materials (BoM) and negatively impacting product margins.

In addition to schedule impacts, late discovery of EMI issues can make root-cause diagnosis more difficult. Once hardware is built and integrated into larger systems, multiple electrical and mechanical factors may contribute to observed emissions. Engineers must often rely on measurement experiments, incremental design modifications, and repeated testing to isolate the dominant mechanisms responsible for the problem.

For these reasons, many engineering teams seek ways to gain earlier visibility into EMI behavior during the design process. Understanding how emission mechanisms develop before hardware is fabricated can significantly reduce the risk of late-stage redesign and improve confidence as products move toward compliance testing.

**3. EMC Challenges in Power Electronics Design**

Power electronics systems are among the most common sources of electromagnetic interference in modern electronic products. Applications such as DC-DC converters, onboard chargers, motor drives, LED lighting systems, and industrial power supplies rely on high-frequency switching devices to achieve efficient energy conversion. While these switching architectures enable significant performance improvements, they also introduce electrical behaviors that can generate substantial electromagnetic emissions.

The fundamental challenge arises from the rapid voltage and current transitions inherent in switching power circuits. Modern power devices can produce extremely fast switching edges, resulting in high dv/dt and di/dt conditions. These transitions excite parasitic elements throughout the system, including PCB trace inductance, device capacitances, cable harnesses, and chassis structures. Once these parasitic elements are excited, they can create both conducted and radiated emission paths that extend well beyond the immediate power stage.

Unlike many other electrical design challenges, EMI behavior is rarely caused by a single mechanism. Instead, it typically results from the interaction of multiple physical effects within the system. The switching node of a converter, for example, may couple noise into nearby structures through parasitic capacitance while high current loops simultaneously generate magnetic fields that can radiate or couple into cable harnesses. These effects are often strongly influenced by PCB layout, grounding strategy, enclosure geometry, and cable configuration.

As a result, relatively small design changes can significantly alter the EMI behavior of a system. Adjustments to component placement, return path routing, switching edge rates, or filtering networks may improve one emission mechanism while unintentionally increasing another. This complex interaction between switching behavior, layout parasitics, and system interconnections makes EMI behavior difficult to predict through schematic analysis or design rules alone.

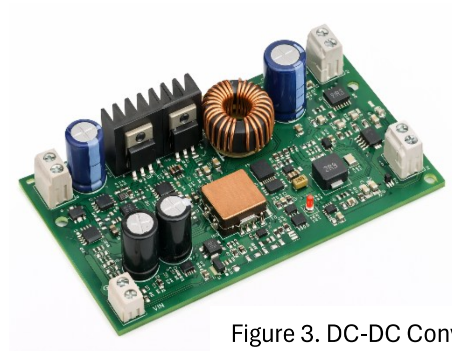

Figure 3. DC-DC Converter

Common sources of EMI in switching power electronics include:

- High dv/dt switching transitions at power switching nodes
- Large di/dt current loops within the power stage
- Parasitic capacitances between switching nodes and chassis structures
- PCB layout inductance and return path discontinuities
- Cable harness coupling and radiation paths
- Resonances formed by parasitic inductance and capacitance within the system

These mechanisms are often distributed across the design rather than confined to a single component or circuit block. As a result, diagnosing EMI issues after hardware is built can require extensive measurement and experimentation to identify the dominant sources.

For many engineering teams, the challenge is not only resolving EMI problems once they appear but understanding the physical mechanisms responsible for those problems. Without sufficient visibility into how electromagnetic fields and current paths behave within the system, engineers may rely on trial-and-error modifications such as adding filters, shielding, or layout changes until emission levels fall below regulatory limits.

This difficulty in diagnosing root causes is one of the reasons EMI issues are often discovered and resolved late in the development process. When visibility into emission mechanisms is limited until hardware testing begins, engineers must rely on laboratory measurements to reveal behaviors that could otherwise have been explored earlier during design.

**4. The Virtual EMC Laboratory Concept**

Advances in modeling technology are enabling a new approach to EMC investigation: the ability to replicate compliance test environments within simulation. Instead of relying exclusively on laboratory measurements to observe EMI behavior, engineers can now evaluate emission mechanisms earlier in the design process by recreating standardized test setups in a virtual environment.

This approach introduces the concept of the **Virtual EMC Laboratory**.

In this environment, engineers can reproduce key compliance measurement configurations such as conducted emission setups, cable harness structures, and measurement instrumentation, directly within simulation. By analyzing how electromagnetic fields and current paths develop within the design, engineers gain insight into EMI behavior before hardware prototypes are built.

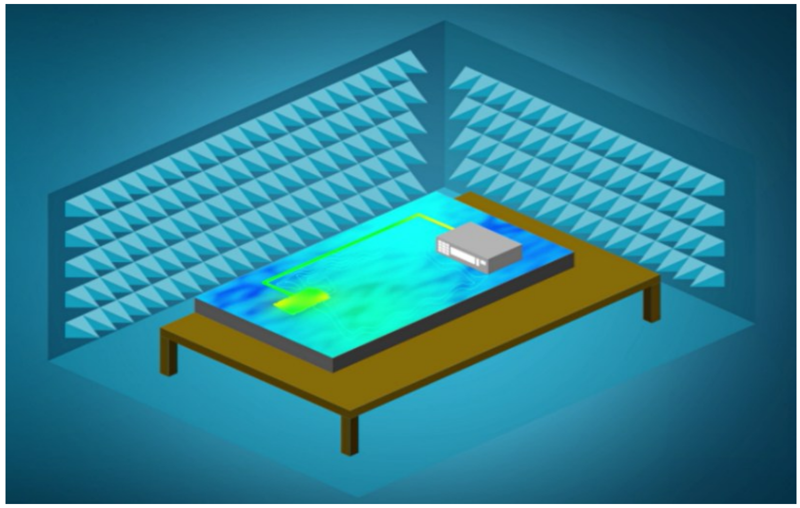

Figure 4. Compliance-Scope Instantiates the Physical Lab Environment

Unlike traditional electromagnetic simulations that often require extensive model construction and specialized expertise, virtual laboratory workflows are designed to mirror familiar compliance testing environments. Engineers interact with representations of the same measurement setups used in physical EMC laboratories, allowing them to evaluate emission behavior using workflows that closely resemble real compliance testing.

A key factor enabling this approach is the ability to achieve meaningful correlation between simulated results and laboratory measurements. When simulation environments accurately reproduce standardized compliance setups and capture the relevant electromagnetic interactions within the system, engineers can begin to use simulation results with greater confidence to guide design decisions earlier in development.

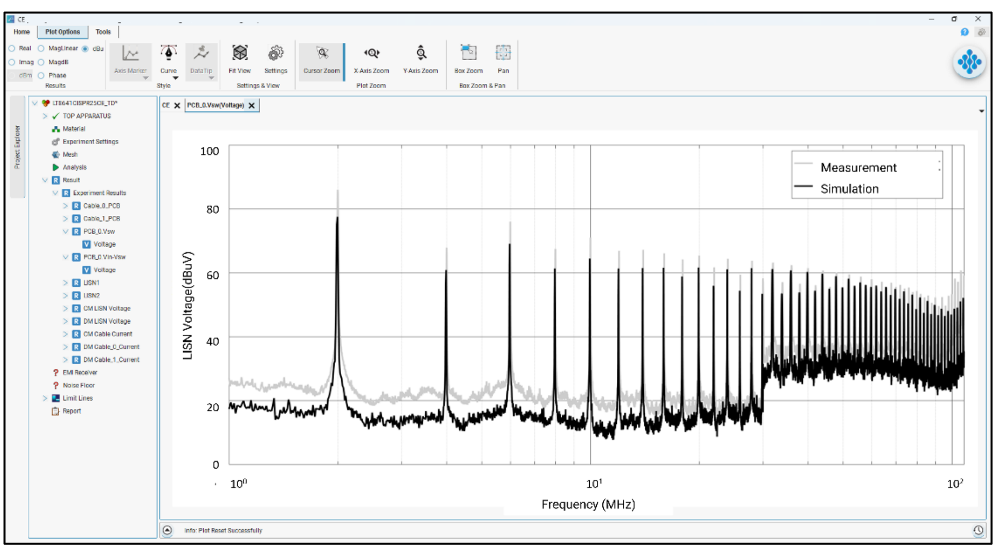


Figure 5. Compliance-Scope Correlates well with Lab Measurements

Because these environments are built around standardized test configurations, they can be used by a broader range of engineers involved in product development. Hardware design engineers, applications engineers, system architects, and design verification teams can investigate EMI behavior within the context of their designs without requiring deep expertise in electromagnetic modeling. This broader accessibility allows EMC insight to become part of the normal design workflow rather than remaining limited to specialized EMC analysis late in development.

Recent advances in IC behavioral modeling have also contributed to this progress. Modern modeling approaches can capture how device activity changes with operating conditions such as switching frequency and load current, allowing emission behavior to be evaluated across realistic operating ranges without requiring repeated characterization.

Within a **Virtual EMC Laboratory** environment, engineers can:

- Replicate standardized compliance test setups used in EMC laboratories
- Analyze conducted and radiated emission behavior during design
- Visualize electromagnetic fields and current paths within the system
- Evaluate layout changes or filtering strategies before prototype fabrication

These capabilities allow engineers to investigate emission mechanisms and evaluate potential mitigation strategies earlier in the development process, before hardware prototypes enter physical compliance testing.

**5. Engineering and Program Impact**

Electromagnetic compatibility challenges rarely affect only the engineering team responsible for resolving them. When EMI issues are discovered late in the development cycle, the consequences often extend across the broader product development program. Hardware redesign cycles, prototype rebuilds, and repeated laboratory testing can introduce delays that affect schedules, budgets, and cross-team coordination.

For engineering organizations developing complex electronic systems, the cost of late EMI discovery can be significant. Each redesign cycle may require updates to PCB layouts, component selections, or filtering strategies, followed by additional prototype fabrication and testing. These iterations consume engineering resources and can extend the time required to move from prototype validation to production readiness.

Earlier visibility into EMI behavior can significantly reduce these risks. When potential emission mechanisms are identified during the design phase, engineers can evaluate corrective strategies before committing to hardware fabrication.

This allows potential issues to be addressed while the design is still flexible, rather than after prototypes have already been built and integrated into larger systems.

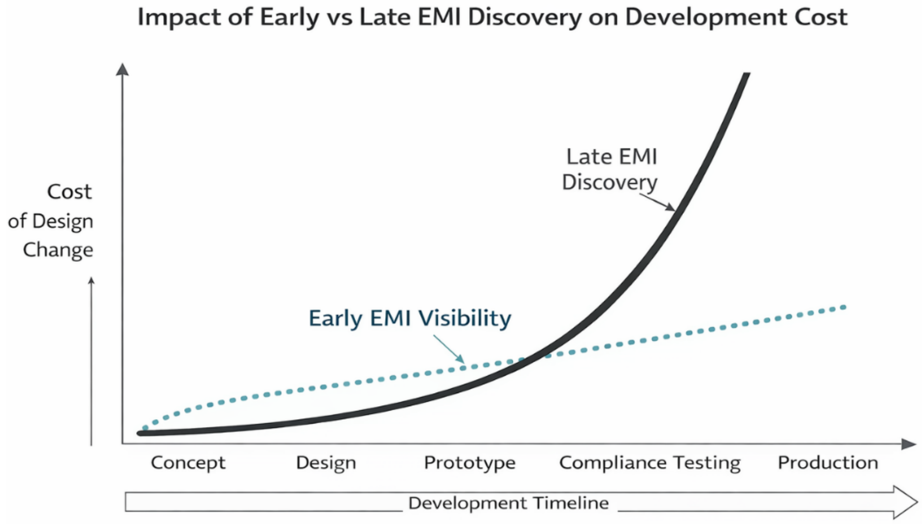


**Figure 6.** Identifying EMI issues earlier in the design process significantly reduces the cost and disruption associated with design changes later in development.

Earlier insight into emission mechanisms can also lead to more efficient design solutions. When engineers understand the dominant sources of EMI within a system, mitigation strategies can be targeted more precisely. This often reduces the need for conservative design approaches that rely on oversized filters, additional shielding, or other components added as precautionary measures. As a result, engineering teams may be able to optimize filtering networks and reduce unnecessary components within the design

From a development perspective, **earlier EMI visibility** can provide several important benefits:

- Reduced Prototype Redesign Cycles
- Faster identification of dominant EMI mechanisms
- Improved collaboration between hardware, system, and EMC teams
- Greater predictability when entering compliance testing
- Reduced schedule risk associated with late-stage EMC failures
- Opportunities for filter optimization and BOM reduction

**Example Scenario – Diagnosing Radiated Emissions in a Buck Converter**

In a recent project with a large semiconductor company, engineers were evaluating a switching buck converter design that exhibited a strong radiated emission peak near 300 MHz during compliance testing. By recreating the compliance test environment in a virtual EMC laboratory simulation, engineers were able to reproduce the emission behavior and investigate the underlying mechanisms before hardware modifications were made.

Field visualization revealed that the dominant resonance was associated with the input power loop interacting with the cable harness. Using the virtual environment, the team evaluated several mitigation strategies, including capacitor placement and power plane geometry adjustments. These changes were able to reduce the simulated emission peak by more than 10 dB, allowing the team to identify effective design improvements before entering the physical compliance laboratory.

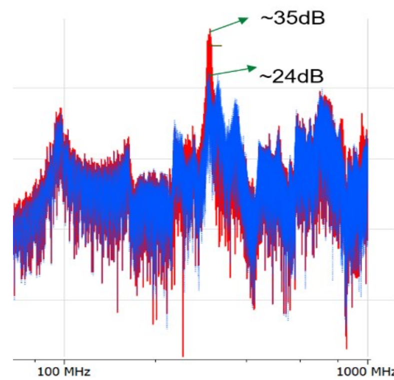


Figure 7. dB Reduction from capacitor movement

These improvements allow EMC considerations to become part of normal design decision-making rather than a late-stage troubleshooting activity. When engineers can analyze EMI behavior earlier in the development process, design teams can enter physical compliance testing with a clearer understanding of how their systems are expected to perform.

**6. Conclusion**

As electronic systems continue to increase in switching speed, power density, and overall system complexity, achieving electromagnetic compatibility remains a significant engineering challenge. Traditional development workflows often rely on physical testing to reveal EMI behavior late in the design cycle, when design changes can be costly and time-consuming.

Advances in modeling technology are enabling engineers to investigate EMI behavior earlier in the design process. By replicating standardized compliance test environments within simulation, engineers can investigate emission mechanisms earlier in the design process and virtually evaluate potential mitigation strategies before hardware prototypes are built.

This shift toward **earlier EMI visibility** allows engineering teams to move from reactive troubleshooting toward a proactive **design-for-EMC strategy**.

This modern design-for-EMC approach can reduce time to market, optimize BOM costs, improve engineering efficiency, and increase confidence as products move toward compliance certification.

## 7. Technical References and Publications

*The methodologies described in this whitepaper build on peer-reviewed research in EMC simulation, IC modeling, and simulation-to-measurement correlation published through IEEE conferences and journals.*


**Multiscale EMC Modeling, Simulation, and Validation of a Synchronous Step-Down DC-DC Converter**
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**Simulation-Based Approach for Boost Converter using Black-Box Modelling for System-Level EMC Analysis**
Adish, S. R. Rao, A. Devi, J. Sivaswamy, D. Gope, P. Shanthi
*2023 IEEE Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMC+SIPI)*
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