The Evolution of EMC Testing for Electrified Powertrains in Automotive Vehicles

A brief history of automotive EMC testing and standards development

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From the time when automotive vehicles were essentially mechanical with spark ignition the only electrical system, through the many decades that brought the development of electrical, electronic and computer controlled automotive systems, the need for and methods of automotive testing have evolved along with the vehicles. At one time, electrical testing was sufficient. But with the dawn of the digital computer era, compatibility became a major issue. Those pesky clocked systems are inherently noise producers and are also subject to immunity issues. During the 70’s, industry experience included the development of advanced fuel management systems, then in progress to meet new exhaust emission standards, but the technology at the time was limited to analog controls. By the 80’s, however, the digital revolution was well underway, bringing digitally controlled fuel injection systems and many other applications that pushed the envelope of EMC concerns.

The automotive official equipment manufactures (OEM) recognized this challenge and began to develop EMC testing and evaluation capability. Initially, there were no applicable standards tailored for vehicle EMC, so the OEMs developed internal procedures that eventually became published as EMC requirements for both vehicle and component validation. Vehicles present a particularly challenging EMC immunity profile as they are numerous and versatile, being able to reach radio frequency (RF) exposure locations not accessible to most other products. Where most consumer electronics may be exposed to RF fields of a few volts per meter, vehicles face much greater threats and
must be validated accordingly. Over the years, automotive OEMs have made extensive use of road trips to RF transmitter and other high RF field sites to map the vehicle EMC environment, and have adapted their requirements and test methods to effectively protect vehicle electronics from these environmental threats.

One key example to illustrate this point is the introduction of vehicle passive restraint systems in the 80’s. At that time, not all automotive OEMs had full vehicle EMC test facilities, however, they were aware of the potential immunity risks that electro-explosive systems presented and were fully committed to an exhaustive evaluation for EMC at both the component and vehicle levels. In past experience, in order to adequately validate this new technology, the standard component test methodologies were implemented and several new ones were developed in order to provide a greater diagnostic capability to predict system performance before the system was fully integrated. To evaluate the vehicle immunity profile, use was made of the military facilities at White Sands Missile Range, NM, which had the capability of generating high-level RF fields over the electromagnetic spectrum from long wave to microwave. On the test vehicles, the electro-explosive devices that trigger the passive restraint system deployment were instrumented with state-of-the-art monitoring capability so the amount of coupled RF current at each test frequency could be monitored. Due to this exhaustive evaluation and the experience gained, it was possible to establish good correlation between vehicle test validation methods and corresponding component validation procedures. This thorough analysis and evaluation led to a successful launch of this new technology without the adverse reactions that might have otherwise occurred. The EMC test methodologies that were put in place by vehicle OEMs became the basis for future EMC standards. Over the years, the automotive OEMs have worked with SAE, ISO, CISPR and IEC to develop workable EMC standards that reflect the real world EMC environment and the need to provide vehicles that can operate reliably in this environment. These cooperative efforts are ongoing.

**VEHICLE EMC TESTING**

An important element in the design and development of today’s complex vehicles is assuring the compatibility of the electrical system and its numerous subsystems with itself and the environment in which it is used. To assure electrical system compatibility, we must understand and control the (RF) emission and immunity characteristics of all components and systems in the vehicle. This also includes fully characterizing these systems with regard to their immunity
to electrostatic discharge (ESD) and other transient voltages. Furthermore, inductive components, such as motors and solenoids, must be evaluated to determine their potential to generate transient voltages within the vehicle’s electrical system.

Vehicle EMC testing can be broken down to three major categories: immunity, emissions, and ESD/transients. In the following sections, we will describe in more detail how each is tested and the types of facilities required.

**RF Immunity**

In the presence of high electromagnetic fields created by radio transmitters (whether portable, mounted on the vehicle or roadside installations), the electronic subsystems on the vehicle could malfunction, cease to function temporarily, or experience a catastrophic failure. Furthermore, as electronics in general increase in complexity and the threat of interference increases, today we have much more spectral content generated with respect to cell phone use, radio/television broadcast, aftermarket electronics and the standard electrical content of vehicles. Testing for RF immunity not only covers external sources or devices, but also the actual in-vehicle electronics interfering with each other.

The general frequency range covered for immunity is 10 kHz – 4 GHz, with the capability of testing to 18 GHz when known threats exist. Along with this, the capability exists to generate the various types of modulation to simulate modulation used by standard real-world devices.

For the lower frequency range of 10 kHz – 30 MHz, a transverse electromagnetic mode (TEM) cell (Figure 1) or transmission line system (TLS) is typically used. In both cases, the field is created from an overhead structure and kept uniform/homogenous around the vehicle while various functions are monitored using shielded video cameras, wheel speed sensors and fiber optics for vehicle bus traffic and diagnostics. Both test methodologies are similar in that power is created using an RF amplifier (usually 10kW power) through a transmission line acting as an antenna radiating an RF field up to 200 V/m, depending on the specification. For the vehicle in the TEM cell shown in Figure 1, the metal plate above the vehicle is the septum or radiating antenna. A RF absorber is placed in specific locations in the TEM cell to help mitigate high voltage standing wave ratio (VSWR) situations.

For the mid to upper frequency range of 30 MHz – 800 MHz, an anechoic chamber is used. The vehicle and, in some cases, the antennae are on turntables as multiple sides of the vehicle must be tested based on harness routing and module location. As with all immunity testing, monitoring such as cameras and fiber optics are used that are not affected by the RF being applied. Figure 2 shows a typical anechoic chamber with a vehicle on the turntable; note also that various antennae can be used to apply the fields. For these frequency ranges, depending on the equipment used, 1kW to 10kW is required to generate fields up to 200 V/m.

For the high frequency range of 800 MHz – 18 GHz, an anechoic or reverberation chamber is used. The advantage of a reverber chamber is that a single sweep is performed and testing is done; often with an anechoic chamber the testing takes much longer as the high frequency causes a very narrow beam width. The narrow beam width requires multiple positions of testing to cover the entire vehicle and ensure all areas are exposed to the RF field. In a reverber chamber, the field is generated and stirred with paddles to provide full exposure to the field surrounding the entire vehicle in a single sweep. Figures 3 and 4 show a typical reverber chamber with a vehicle and a closer shot of the paddles used for stirring the field. Another advantage of a reverber chamber is that much less power is required to create high field strengths of 200 V/m.

Another type of vehicle RF immunity testing is the testing of on-board transmitters. This test simulates the effect of radios being installed and used in a vehicle such as CBs, ham radios and more common devices such as cell phones or walkie-talkies. The testing consists of outfitting a vehicle with the various antennae both internal and external to the vehicle (e.g. roof top or bumper installation) and broadcasting at the various frequency and power levels while monitoring for disruption of normal vehicle operation. Figure 5 shows an example of antennae placement for on-board transmitter testing in a vehicle.

**RF Emissions**

The second major part of EMC testing is emissions; measuring the amount of noise a component and its wiring/apparatus puts out while in normal operation. This testing reveals potential interference, not only with other on-board electronics, but also with adjacent vehicles and other electronics/installations in the real world.

To protect for on-board receivers and other electronics, testing is performed per CISPR 25. The vehicle is tested in an anechoic chamber and the on-board antennae of the vehicle are used to measure their applicable fields; for other frequency bands, magnetic mount antennae are placed in the standard installation locations and used for measurement. Figure 6 shows an example of a vehicle in such an anechoic chamber.

To protect for off-board receivers and installations, testing is performed per CISPR 12; the main difference is the antennae used are set at a 3 or 10 m distance from the vehicle. This testing
is also performed either in an anechoic chamber or open area test site (OATS).

To further validate these results; especially for AM/FM radio bands, radio noise evaluation testing is performed. During this testing, levels of injected power at the various frequencies are broadcast while the different subsystems are operated to evaluate reception.

In addition to RF emissions and as a result of new electrified powertrain vehicles, magnetic field emissions testing is also required. This testing is performed using special magnetic field probes and tested per International Commission on Non-ionizing Radiation Protection (ICNIRP) to limit human exposure to such fields. The testing is performed in various locations, mainly throughout the interior of the vehicle where a human being would be. Figure 7 shows an example of a probe measuring magnetic fields in the engine compartment of a vehicle.

**Other Types of Vehicle EMC Testing**

There are other various types of EMC testing that occur on a vehicle such as (ESD), conducted transient emissions (CTE) and electrical tests. ESD is the simulation of discharge that occurs normally between a human and some part of the vehicle; this can be from entry, exit, or simply attempting to push a button or reach for the door handle.
CTE is a measurement of the voltage transient that occurs when an inductive load such as a motor, solenoid or actuator is switched. Finally, various electrical tests are performed, such as load dump and reverse battery, to simulate these potential events.

As can be seen, vehicle EMC testing is very in-depth and costly. The photos provided here are from the Chrysler EMC Facility which is valued at over 30 Million USD. With electrified powertrain emerging as a new technology in vehicles, the challenges for EMC increase. With such vehicles, new considerations such as testing while the vehicle is plugged into its charger, regenerative braking and, finally, operation cycles on a charged battery versus test time (some test runs can take in excess of five hours) are part of the validation process. The specifications are evolving as well; Figure 8 shows a set-up diagram for an electric vehicle to be tested while charging. As the specifications continue to be established and evolve to meet changing product requirements, the industry will adapt and evolve as well, as it always has in the past.

**AUTOMOTIVE COMPONENT/MODULE TESTING**

Similar to vehicle EMC testing, automotive component testing is categorically broken down into three types: emissions, immunity and ESD/transients. EMC requirements and test set-ups for automotive components are established by International Standards and OEM specifications that have been derived directly from vehicle testing and real-world experiences/measurements. Components that undergo EMC testing to established OEM component requirements provide a high confidence level of EMC (emissions, immunity and ESD/transients) performance when integrated into a vehicle or into a vehicle system. This is a significant distinction from other industries for several reasons:

1. All electronic products sold in the United States are required by law to be compliant to FCC Part 15. However, FCC Part 15 only addresses RF emission levels of an electronic product. Automotive OEMs at both the vehicle and component level require immunity and ESD/transient testing, as well as emissions. It should also be noted that automotive OEM emissions levels are much more severe than FCC requirements.

2. Vehicle operating environments, thus their requirements, are generally much harsher for automotive components than other electronic products sold in other industries. For example, vehicles are expected to operate safely in a wide range of operating temperatures and different weather conditions, as well as under exposure to varying sources of electromagnetic fields (natural and manmade), all of which impact electric components and design.

3. Automotive component EMC tests, conditions, set-ups and facilities have been developed specifically for correlation to vehicle environments. Compliance to automotive OEM component EMC requirements is considered as a pre-qualification. Components must also comply with vehicle EMC requirements when installed in a vehicle. As such, automotive components are given a

![Figure 8: Example of a vehicle set-up while plugged in for charging](image)
The EMC systems engineering methodology integrates all requirements and objectives; additionally it facilitates the identification and specification of unknown or hidden requirements leaving behind a traceable, repeatable, documented path of engineering effort and decisions.

The EMC system engineering process starts with OEMs and tier suppliers defining the following concepts for components, system architecture and vehicle integration:

- **System** – a set of components acting together to achieve a set of common objectives via the accomplishment of a set of tasks.

- **System behavior** – a sequence of functions or tasks, with inputs and outputs, which must be performed to achieve a specific objective.

- **Requirements** – mandates that something must be accomplished, transformed, produced or provided. The attributes of a good requirement are that it is unambiguous, understandable, traceable, correct, concise, unique and verifiable.

- **Traceability** – in reference to requirements; a requirement is said to be traceable if one can identify its source. The source may be a higher-level requirement or a source document defining its existence. An example would be if a component-level requirement (weight, reliability) is traceable back to a vehicle-level requirement

- **Operational concept** – an operational concept is a shared vision from the perspective of the users and development participants of how the system will be developed, produced, deployed, trained, operated, maintained, refined and retired to meet the operational needs and objectives.

It is recommended that a background study based on the following questions should be considered in preparation for the systems engineering process:

**System requirements**

- Has the need for the system or product been established and justified?

- Has the overall system technical design approach been justified through a feasibility analysis?

- Has the mission for the system been defined through scenarios or profiles?

- Have all basis system performance parameters been defined (technical performance measures)?

- Has the system or product lifecycle been defined (design, development, test and evaluation, production and/or construction, distribution, operational use, sustaining support, retirement and disposal)?

- Has the planned operational deployment and distribution been defined (customer requirements, quantity, distribution schedule)?

- Has the operational environment been defined in terms of temperature extremes, humidity, vibration and shock, storage, transportation, and handling? A dynamic scenario is desired.

**System trade-off studies**

- Have trade-off evaluations and analyses been accomplished to support major design decisions?

- Have all feasible alternatives been considered in trade-off studies?

- Have such analyses been accomplished with lifecycle...
considerations in mind (decisions based on lifecycle impacts)?

• Have system trade-off studies been adequately documented?

Once the above concepts have been defined and the background study performed, the six-step design process is applied as illustrated in Figures 9, 10, 11 and 12.

**Step 1 - Bound the system for EMC**

• Identify all external items.
• Establish interactions.
• Create system context diagram.

**Step 2 - Identify the source of requirements**

• Collect requirements.
• Sort requirements by classification.

**Step 3 - Discover and understand requirements**

• Discover system-, subsystem- and component-level requirements.
• Brainstorm scenarios.
• Benchmark competition.
• Use behavior models to:
  o discover “hidden” interface requirements.
  o resolve conflicts between models and scenarios.

**Step 4 - Create alternatives**

• List performance and operational objectives.
• Prioritize requirements with weighting factors.
• Synthesize physical architecture to support each alternative.
• Perform trade-off between candidate architectural solutions that satisfy the requirements.
• Collect the results in a derived set of requirements based on the chosen solution.
• Compare the various alternatives, rank them and select the best approach.
• Evaluate candidate architectures using measures of effectiveness.

**Step 5 - Select the best solution**

• Compare proposed systems implementation.
• Select the best solution.

**Step 6 - Validate best solution**

• Define validation plan
• Link to design requirements at each level (vehicle, system, component)
• Verify all requirements. (mandatory)
• Plan for verification starting early and continuosly at the system level.
• Requirements Trace requirements forward to verification and link verification back to the requirements at all levels.

**Verification methods are:**

• inspection
• test
• demonstration
• analysis, which may include simulation

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**Figure 9: Six step system engineering process for EMC**

**Figure 10: Data is generated and linked throughout the process**
System engineering process summary

- The EMC systems engineering process methodology integrates all requirements and objectives, and facilitates the identification and specification of unknown or hidden requirements.
- The systems engineering process leaves behind a traceable, repeatable, documented path of engineering effort and decisions.

THE IMPORTANCE OF EMC TEST PLANS AS GOVERNING DOCUMENTATION

See References 2, 3, 4, 5 and 6.

As automotive engineers work through the six-step design process, many documents are generated. For EMC, the most important document is the EMC test plan. Most OEM in North America provide a template to follow when generating this document. When properly completed, the EMC test plan provides a traceable link of not just the EMC tests performed and test parameters, but also documentation of the operating modes/states, justification of performance criteria, component uses in vehicles and systems, a component’s mechanical and electrical interfaces, as well as any deviations and assumptions required for individual test circumstances.

Elements of a good EMC test plan to consider for any device-under-test (DUT) (component or vehicle) should describe or answer the following information:

1. DUT part number and revision
2. DUT subassemblies such as PCB, hardware and software revision
3. DUT manufacturing/assembly location and suppliers
4. DUT customer and production release date
5. DUT releasing/program engineer
6. DUT EMC test plan revision history
7. Applicable EMC test standards (OEM or international)
8. EMC test facility, location, contact and accreditations

9. Type of EMC test report requested: engineering development, sign-off design validation or sign-off production verification

10. OEM/customer sign-off (if applicable)

11. DUT description and intended use
   a. DUT and DUT family introduction and functional description
   b. DUT description and sample selection
   c. DUT electrical and mechanical schematics, layout and diagrams
   d. DUT software functional description of operation
   e. DUT bill-of-materials (BOM)
   f. DUT operating modes
   g. DUT electrical and mechanical inputs, outputs, power requirements, loads and monitoring requirements
   h. DUT calibration procedures

12. Required loads, harness and support equipment needed to operate DUT

13. For each individual EMC test, the following should be noted or referenced:
   a. test modes
   b. environmental conditions
   c. grounding schemes and requirements
   d. harness requirements
   e. applicable loads and monitoring equipment
   f. power supply and signals
   g. functional and operational requirements
   h. test deviations
   i. pass/fail criteria
   j. instructions if an anomaly is observed
   k. any DUT safety precautions or procedures

THE EMC TEST PLAN AND ELECTRIFIED POWER-TRAIN TECHNOLOGY

See References 2, 3, 4, 5 and 6.

As test standards evolve and adapt to new technologies in the automotive industry, the overall vehicle requirement remains essentially the same. For example, the emerging electrified powertrain technology has not had a substantial impact for vehicle EMC emissions, immunity and transient requirements; however, it has increased the importance of the EMC test plan for systems such as the energy storage system (ESS) which is a large part of the electrified

Figure 13: ESS bench setup for CISPR25 Radiated Emissions/ISO 11452-2 radiated immunity

Figure 14: ESS (close-up) on a copper ground plane for CISPR25 radiated emissions/ISO 11452-2 radiated immunity testing
powertrain architecture. ESSs have come to encompass several competing electric vehicle (EV) and hybrid electric vehicle (HEV) architectures. In turn, the ESS contains multiple sub-systems in addition to just battery cells.

The ESS and its sub-systems include design variables such as high-voltage DC-to-DC power converters, battery cell charging/discharging schemes, varying numbers of battery cells, shapes and technology, cooling schemes (liquid and/or air), diagnostic sensors (thermal, voltage, current, etc.), overall ESS physical shapes, sizes and weight, as well as on-board vehicle orientations.

When writing an EMC test plan for ESS, collaboration with the EMC test facility is a good idea. The size and weight of the ESS alone can cause an issue when testing. For example, an ESS can range from 8 cubic feet to more than 64 cubic feet in size and weigh 700 to 2500 or more pounds. EMC test facility chambers and ground planes need to be able to handle the weight as well as be able to safely move the ESS in and out of the chamber. Also, thought should be given to the orientations of the ESS needed for emissions and immunity testing, with consideration given to maintaining minimum clearances per the international or OEM standards used for testing. Some examples are shown in Figures 13, 14 and 15.

Another aspect the EMC test plan should clearly specify is the monitoring requirements of the ESS. It is not uncommon that input/output requirements to monitor an ESS are double or triple that of a normal automotive component and may require special software that interfaces to software running the EMC test, so when/if an observed anomaly occurs during a test cycle, the test parameters are known.

Finally, with regards to the ESS, the EMC test plan should note the high-voltage (HV) power requirements, charging procedure and safety operation procedure for working with the HV. The goal of the EMC test plan is to provide for safe operation, reduced test down-time and a traceable document for future testing and product development.

**SUMMARY**

The authors have presented a brief history of the development of methodologies by automotive OEM to effectively validate new technologies and the cooperative role OEM have played in the generation of new EMC standards, including an overview of vehicle and component EMC testing. The advantage of the system engineering process in providing an organized and traceable method to meet the challenges of validating new technologies was presented, along with a practical approach to apply this method to a particular product. The importance of EMC test plans, particularly for complicated systems and new technologies, was stressed along with some useful guidelines for developing an effective test plan. Finally, the need for an EMC test plan to meet the particular challenges of validating electrified powertrain technology was described.

**REFERENCES**


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