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## EMC for the Functional Safety of Automobiles

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## by EurIng Keith Armstrong, Cherry Clough Consultants

Electronic sub-assemblies (ESAs) are being increasingly used where they could affect vehicle safety risks, including every aspect of drivetrain control, and many aspects of body control, including lighting, displays, indicators and mirrors. Anything that could affect the direct control of a vehicle, or could confuse other road users, is of concern [2]. Indeed, there are many current developments that are safetyrelated, such as automatic parking, intelligent cruise control, automatic lane following, vision-aids, and vehicle-to-vehicle telemetry (enables vehicles to start braking when traffic ahead slows, even when hidden around bends or in fog) that would not be possible without advanced electronics and its software.

The problem is that all ESAs can suffer from errors, malfunctions and even permanent damage due to electromagnetic interference (EMI). Further, the EM environment is continually worsening due to the increasing use of electronic technologies in all areas of society, especially switch-mode power conversion and wireless communications.

Another problem is that all ESAs rely on semiconductors, either as discrete or integrated circuits (ICs), and the continuing shrinkage in their internal silicon features and reductions in operating voltages are making them more susceptible to EMI. So, for several reasons, the importance of EMI to the safety of vehicular transport is increasing.

Standards in all industry sectors, including the automotive industry, generally deal with EMI-related safety issues very poorly, if they even cover it at all [3] [4] [5]. The few that attempt to address these issues simply require the application of traditional EMC immunity tests that can never be sufficient for ensuring tolerable safety risks over the entire lifecycle, for reasons which we'll described later.

Figure 1 outlines the general situation at the time this article is being written.

Over the last ten years or so, there have been developments in applying risk management techniques to EMC to correctly address EMI-related safety issues. Specifically, there is IEC TS 61000-1-2 [7] (which is effectively the missing EMC Annex of the basic functional safety standard IEC 61508 [8]), and the IET's new guide on "EMC for Functional Safety" [9].

#### Twelve Reasons Why EMC Testing is Insufficient for Safety

(Also see references [1] [9] [10] [11] and [12].)

#### 1. Anechoic Test Chambers Do Not Simulate Real EM Environments

Traditional radiated field immunity tests specify anechoic test chambers, which are unlike all real-life EM environments experienced by road-going vehicles, so their results can differ markedly from real-life. Vehicle manufacturers overtest to address this and other shortcomings in their test methods, but over-testing cannot compensate for the deficiencies associated with anechoic chambers.



Figure 1: Increasing safety risks due to EMI

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Choose certainty. Add value. Some EMC testing experts suggest there are large and unpredictable uncertainties associated with the use of anechoic chambers [13] [14]. Reverberation chambers can provide much more realistic tests [15] [16] and, for this reason (plus their lower costs), they are used by many manufacturers of flight-critical avionics.

#### 2. RF Modulation Types and Frequencies Are Not Realistic

Traditional radio-frequency (RF) immunity tests use 1kHz sinewave modulation for ease of testing, low costs and repeatability, although some vehicle manufacturers employ pulse modulation to simulate digital cell phones and radars, at frequencies above 600MHz or so.

But real-life transmitters use a wide range of analog and digital modulation types and frequencies. References [17] and [18] show that immunity can be significantly degraded (e.g., 20dB or more) when EMI modulation corresponds with frequencies or waveforms used in internal processes, or resonates with circuits, cables, transducers or loads. Therefore, testing with 1kHz is too simple where safety issues are concerned.

Designers of military electronic warfare/countermeasures have known about the importance of modulation to immunity for many decades, but it is only now just starting to be addressed in standards (see [19] and [20]).

#### 3. DC Power Disturbance Tests Are Not Realistic or Thorough

ISO 7637 [21] specifies conducted transient tests to simulate noise on a vehicle's power supply distribution network. The tests use waveforms based on simplifications of the transients that occur in real vehicles, so they can easily and repeatably be generated by low-cost test equipment.

Reference [22] describes tests of the DC power supply on a variety of real vehicles, and shows that the use of even the highest level pulses in [21] can be insufficient for some vehicles. Reference [22] also includes examples of real-life conducted transients in vehicles for which there are, as yet, no corresponding tests.

Varying the timings used by Pulse 2b of Reference [21] can delete the firmware in some ESAs, and varying the test settings can cause some ESAs to switch on or off without command. However, most vehicle and Tier 1 manufacturers do not vary the timings. Instead, they choose settings to reduce testing cost and time, or even to achieve a pass, possibly failing to detect latent unreliabilities that could increase safety risks.

The Ford Motor Company is unique in that its EMC test specification [23] deviates in part from [21] by using chattering relay tests that should produce transient tests with waveforms closer to what is probably experienced in real life.

#### 4. Simultaneous Disturbances Are Not Tested

In real-life operation, ESAs are exposed to simultaneous EM disturbances, for example, two or more RF fields at different frequencies, a radiated field plus a conducted transient or electrostatic discharge, etc. But EMC immunity tests only apply disturbances one at a time.

Simultaneous disturbances that have different frequencies can cause EMI through intermodulation (IM), which (like demodulation) occurs naturally in non-linear devices like semiconductors. Figure 2 shows a simple example of two RF fields at different frequencies, which can cause EMI by:

- Direct interference from each frequency independently;
- Demodulation of the amplitude envelopes of either frequency, or both mixed together;
- Intermodulation, in which new frequencies are created.

Equipment that passes individual immunity tests can be much more susceptible to lower levels of the same disturbances when they are applied two at a time [24].

Vehicles have many independent sources of EM disturbances that can occur at the same time. A simple analysis, based on reasonable assumptions for a 6-cylinder engine at 2000 rpm with spark-ignition transients lasting 50ns, shows that, if there was an average of one unrelated 100ns transient per minute (e.g. due to the actuation of an electric motor or solenoid), there would be a 0.001% likelihood that the 100ns transient would overlap with a 50ns spark-ignition transient.

If this vehicle were driven for 1 hour/day, 5 days/week, 40 weeks/year, the likelihood of it experiencing an overlapping pulse event would be 12% per year. And, if the overlapping pulses caused an ESA to malfunction and caused a 1% chance of death (the official rate of death due to runaway vehicles in the United States over recent decades), the driver would have a risk of death of 0.12% per year. This might not sound much, but it is comparable with the risk of death knowingly accepted



Figure 2: Example of demodulation and intermodulation

by people working in the most hazardous occupations (e.g., oil industry divers). If there were 100,000 such vehicles on the roads for similar periods, we could expect 120 deaths from these overlapping transients every year.

In this example, to be sure of experiencing just one overlapping pulse, a test vehicle would need to be driven 24/7 for 19 weeks. The likelihood of this discovering a significant safety problem is extremely remote, and even then it would almost certainly be diagnosed as something else. Were a customer to complain to his car dealer of a malfunction (that was due to these overlapping transients), the likelihood of the dealer experiencing the problem by test-driving the vehicle for a full eight hours would be very small indeed. Most likely the dealer would assume the driver had simply made a mistake.

#### 5. Only One Port is Tested at a Time

When an ESA is subjected to a radiated RF field, all of its interconnecting cables pick up RF voltages, but with phase differences between them. But traditional EMC conducted immunity tests intended to simulate the effects of radiated fields only test one cable at a time.

Qinetiq PLC has injected RF into all of an ESA's conductors simultaneously, with phase shifts to match what would be expected in real life. They discovered that the immunity could be significantly worse than that experienced when one cable was tested at a time.

#### 6. EMC Tests Ignore the Physical Environment

ESAs that are involved in safety-related activities must maintain certain EM characteristics over their life-cycles, despite the effects of the physical environment, including the following:

- Mechanical (static forces, shock, vibration, etc.)
- Climatic (temperature, humidity, air pressure, etc. both extremes and cycling effects)
- Chemical (oxidation, galvanic corrosion, conductive dusts, condensation, drips, spray, immersion, icing, etc.)
- Biological (e.g., mould growth, etc.)
- Operational wear and tear over the lifetime (friction, fretting, repetitive cleaning, grease build-up, etc.)

Effects vary from immediate (e.g., non-flat mounting opening a gap and degrading shielding) to long-term (e.g., corrosion of a shield joint or filter ground bond). Reference [25] describes a number of real-life problems of this nature.

Reference [26] shows that a filter can suffer up to 20dB degradation in its attenuation due to a combination of ambient



temperature, supply voltage and load current that are within its specified ratings, when compared with the results of traditional immunity tests.

Highly-accelerated life tests are often used by vehicle manufacturers to verify that functionality will be maintained over the lifecycle, despite the physical environment. But the resulting aged units are rarely, if ever, tested to see if their EM characteristics have degraded, although this is understood to be common practice for Russian military equipment.

#### 7. Quality of EM Design Is Ignored

Manufacturers apply the traditional immunity tests to their products, iterating their designs until they pass. But this approach cannot distinguish between a pass that was achieved by good EM design, or by something that would not be adequately controlled in serial manufacture over the production life of a vehicle.

EMC standards ignore design issues. So, if a product's EM design does not cope with component tolerances, semiconductor die-shrinks, variations in assembly (e.g., cable harnesses, grounding, etc.), replacement of obsolete components, firmware bug fixes, etc., the fact that some samples passed EMC tests means nothing at all for the EM characteristics of the ESAs or vehicles supplied to customers.

#### 8. Assembly Errors are Ignored

Safety engineering generally requires verifying each manufactured product to make sure that assembly errors have not made it unsafe. But traditional EMC standards do not include any requirements for manufacturers to perform routine checks in serial manufacture on the EM characteristics that are necessary for achieving tolerable safety risks.

Automotive EMC test laboratories say that it is not uncommon for ESAs and vehicles that function correctly to fail EMC tests because of a misbuild. When this happens, the manufacturing errors are corrected and they are retested. Although most manufacturers employ rigorous end-of-line testing, including in-circuit test that will discover misbuilds that affect functionality, they do not generally design them to discover misbuilds that could affect EM characteristics.

So, based on type testing, a customer could receive a vehicle that includes one or more assembly errors that could prevent it from having the EM characteristics claimed by its manufacturer.

#### 9. The Maximum Test Level is Not Necessarily the Worst

Electronic devices are non-linear, and circuits, firmware and software can be very complex. So ESAs can fail when tested with EM disturbances at a low level, but fail in a different way, or even pass, when tested at the specified levels. But most EM tests only expose equipment at the highest specified level to save testing time and cost. The likelihood of lower disturbance levels occurring is usually much higher than that of higher levels, so the immunity to low level disturbances could be much more significant for achieving tolerable safety risks.

#### 10. Reasonably Foreseeable Faults are Ignored

Immunity to EMI can be significantly affected by faults, for example:

- Intermittent electrical connections;
- Dry joints, open or short circuits;
- Out-of-tolerance or incorrect components;
- Missing or damaged conductive gaskets;
- Loose/missing fixings in enclosures or cable shielding;
- Failure of a surge protection device.

But traditional automotive EMC testing ignores all faults; only perfect specimens of ESAs and vehicles are tested.

#### 11. Reasonably Foreseeable Use and Misuse are Ignored

Tolerable safety risk levels must be maintained despite reasonably foreseeable use or misuse over the life-cycle. Of course, it is impossible to make anything perfectly safe, but people are known to behave in certain ways, so safety engineering should take this into account.

But traditional EM testing assumes vehicles are driven perfectly at all times, and are not damaged or modified.

#### 12. Systematic Effects are Ignored

Many system designers incorrectly assume that, if all the ESAs incorporated into a system pass their immunity tests, those systems will also be immune enough.

But performance degradations that are perfectly acceptable when an ESA is EMC tested, or are not even measured during the testing, could have significant implications for the functional safety of systems that use those ESAs. Agreement between the EMC test results on ESAs, and on the systems that incorporate them, is frequently found to be poor. This is often attributed to the principle known as emergence, which states that the characteristics of complex systems cannot necessarily be predicted from the characteristics of its component parts.

#### What Needs to Be Done

The IET's new guide [9] provides a comprehensive and detailed practical approach to dealing with the issues described above by applying modern risk management principles to EMC. It adopts the principles of [7], but uses an application-neutral language that makes it useful whichever functional safety standard is being applied (e.g., IEC 61508, or ISO 26262), or not. Unlike [7], it includes suggestions for how to take EMC into account when using modern risk assessment methods (e.g., FMEA, fault tree analysis, brainstorming, etc.), and adds checklists that will be useful for management,



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The approach described in [7] and [9] will require a significant learning curve for many manufacturers, functional safety assessors, and EMC test laboratories who want to develop the skills to assess a design's EMC for functional safety.

#### Manufacturers Need to be More Clever

Using only EMC testing to demonstrate due diligence in achieving tolerable safety risks over a vehicle's lifecycle, requires the twelve issues raised above – and their combinations (for example, an older vehicle with one or more faults, corroded metalwork and conductors, driven incorrectly, suffering multiple physical and EM disturbances simultaneously) – to be addressed by the test program. This would be so lengthy that no organization could possibly afford it. Manufacturers need to be cleverer, if they are to achieve tolerable functional safety risks with reasonable times and costs.

One aspect of this cleverness is to use EM design techniques that ensure safety-related systems will maintain the necessary EM characteristics over their lifetime, taking the reasonably foreseeable EM and physical environments into account [27]. Another is to verify and validate these more robust designs, using a variety of methods (generally including some EMC testing) to achieve the necessary confidence without excessive timescales or costs.

#### Assessing the Lifetime EM and Physical Environments

An assessment of the reasonably foreseeable real-life possibilities over the vehicle lifetime [28] [29] should include:

- EM disturbances in the near-field (e.g., crosstalk in cable bundles) and far-field (e.g., radio/radar transmitters);
- Intra-system interference (between ESAs in a system);
- Inter-system interference (between different systems in a vehicle, and a vehicle system and the world outside; also considering electronic devices carried by people);
- Modulation types, and their frequencies or waveshapes;
- Simultaneous EM and/or physical disturbances (including continuous, extremes, cycling and transients);
- Possibilities for use and misuse;
- Physical environment(s) (e.g., mechanical, climatic, biological, wear, etc.);
- The effects of aging;
- Future changes to the EM and physical environments;
- Component tolerances, and future changes to components (e.g., obsolescence, die shrinks, etc.)

It is usually only possible to establish the types of EM phenomena (see Figure 3), their modulations and worst-case levels, with any confidence.

Standards from the IEC and military describe a variety of physical environments, but the compatibility levels (or test levels) they specify should not be applied unquestioningly, as they may not have been created for safety purposes.

If a vehicle type is to be sold into an EM and/or physical environment not fully addressed during its original design, an assessment of the new EM and physical environments is required. To maintain tolerable risk levels could require design changes, reverification and revalidation.

#### Good EM and Physical Design Engineering

There are a great many publications on good EM design techniques that can be applied at different levels of assembly, from ICs to cabling and vehicle structures. Reference [27] discusses a number of well-proven, good EM and physical design techniques for controlling functional safety risks, which is greatly expanded upon in an Annex to [7] and Part 4 of [9].

#### Hazard Identification and Risk Assessment

A documented hazard identification and risk assessment process is required that assesses how the reasonably foreseeable EM and physical environments over the lifecycle could possibly affect the ESA or vehicle, taking into account faults, misuse, etc. It should show how any excessive risks were reduced to an acceptable degree by design, and be a living document that guides the design process throughout.

Inductive (or consequence) methods start with a low-level error or failure, and try to determine whether it could lead to a hazardous situation. They include failure mode effects analysis (FMEA) and event tree analysis [30].

Deductive (or causal) methods start with hazardous situations, and try to determine what could have caused them, and include fault tree analysis [30].

Brainstorming techniques identify any possibilities. They apply inductive methods to see if the possibilities could have hazardous consequences, and then apply deductive methods to discover what could cause them, and also their likely effects.

It is usual to employ at least one inductive and at least one deductive method to improve the coverage of the risk assessment. Brainstorming is always required to foresee faults, use, misuse, etc., overlooked by standard methods.

All of the above must take into account the EM and physical characteristics of the product and its reasonably foreseeable EM and physical environments over its lifetime. Many vehicle manufacturers and Tier 1 companies employ risk assessment methods, but they tend to do it by rote, which is not recommended by functional safety experts [31] [32].

Any risk assessment method must take into account the fact that some failure modes (e.g., latch-up) can cause some/all

of an IC's output pins to change state at the same time, and common-mode EMI causes noise on many/all circuit nodes at the same time. Also, EMI and some types of faults can create noise that can be mistaken for valid signals.

It is generally assumed that two or more independent faults are so unlikely that only single-fault issues need be considered, but this is a misunderstanding. Where the likelihood of certain faults is high enough (e.g., due to inadequate design or assembly) the possibility that two or more such independent faults could occur simultaneously should be taken into account.

When designing a vehicle so that a person can drive it safely, it is also appropriate to use task analysis and human reliability analysis.

#### EM and Physical Specifications

Specifications should be written for each vehicle safetyrelated system in order to control their design, manufacture, verification and validation, and the specifications should include EM and physical requirements derived from the above. Specifications for the ESAs to be incorporated in a safety-related system should then be derived from the system's specification, taking into account any EM or physical mitigation measures employed by the system (e.g., shielding, filtering, surge suppression, anti-vibration mountings, forced cooling, etc.)

#### A Verification/Validation Plan

Achieving sufficient confidence when verifying and validating the design and assembly requires a mixture of techniques [33], none of which is sufficient alone, including:

- Demonstrations
- Checklists
- Inspections
- Reviews and audits
- Independent assessments
- EM tests on ESAs and complete vehicles
- Validated computer simulations

EM tests are most useful when they closely replicate the EM/physical characteristics of the real-world environment(s). It is generally best to base such tests on the standardized test methods, competently modified to better simulate the real life EM/physical environments.

HALT (highly-accelerated life testing) is a powerful tool for assessing the lifecycle suitability of design and assembly methods, and of EM mitigation techniques such as shielding and filtering [34]. Appropriate design of test set-ups can make it possible to detect unacceptably degraded EM performance during HALT testing. ESAs for use in safety systems always require some final verification/validation tests, as do the completed vehicle safety systems themselves. These tests should be designed to provide the required confidence without high costs.

The EM characteristics of serially-manufactured ESAs and vehicles can be significantly affected by any of the following issues:

- Variations in purchased parts (e.g., IC die-shrinks);
- Alternative or replacement parts;
- Variations in plating, painting and fixing;
- Differences in assembly (e.g., wiring);
- Design changes and improvements;
- Firmware bug-fixes and upgrades, etc.

Therefore, all of the build-state issues relevant for maintaining tolerable functional safety risks should be identified during design, and controlled by quality control (QC).

QC should use a range of techniques; including quick, easy, low-cost EM checks on delivered goods, ESAs and subassemblies, plus sample-based testing designed to maintain an acceptable quality level. QC should employ competent personnel, backed up by appropriate testing, to assess every proposal for a design change for its implications for EM characteristics and functional safety risks.

#### The Results of Verification and Validation

Documents should show how any shortcomings in meeting the specifications were dealt with, and the specifications achieved.

#### Measures Necessary to Maintain EM Characteristics

Assumptions originally made about real-life EM and physical environments should be verified during the lifecycle of a model of vehicle and, if they are in error, what appropriate actions were taken.



Figure 3: Examples of foreseeable EM disturbances

Appropriate QC activities are required for maintenance, repair, refurbishment, modification and firmware upgrades to ensure that the required EM and physical characteristics are not compromised over the vehicle lifecycle.

Vehicle service schedules might need to include certain checks, tests or component replacements. EMC checks or tests might also need to be devised, and equipment provided for use by relatively unskilled technicians in dealers' service departments for use at scheduled intervals. Computerized diagnostic programs might need to be modified to detect certain EM or physical characteristics.

Repair instructions should include activities that maintain the vehicle's EM/physical characteristics, possibly followed by EM and physical verification to specification. User manuals should recommend activities that help maintain the required EM/physical characteristics over the vehicle's lifecycle, and may need to describe, in layman's terms, how the user can identify EMI as the cause of a problem, and perhaps how to deal with it (in some circumstances).

#### Documentation – the Safety Case

To help manage functional safety, and for a good defense in case of a legal challenge, a safety case should be created that documents all the activities described above and shows how they achieve tolerable safety risks over the vehicle's lifecycle.

#### The Amount of Work Required Depends on the Level of Risk

The greater the excess safety risk is above the tolerable level of risk (making increased risk-reduction necessary), the more critical the need that all of the activities described above are more detailed, comprehensive and in-depth, and that they are performed by people who are more knowledgeable and more competent in the necessary techniques.

#### Conclusions

This article has described a dozen reasons why it is generally not possible to rely solely on EM testing to help achieve tolerable functional safety risks.

We have also shown that rare and untested EMI events that could cause a safety incident only once during a 10-year vehicle life could expose drivers to safety risks comparable with those of the world's most dangerous occupations. These safety risks are most unlikely to be detected by a car dealer, even when a customer complains about the symptoms.

EMI must be treated like any other possible cause of hazards, including malfunctions in firmware [35]. Appropriate techniques in assessing the EM/physical environments, and in design, verification and validation, manufacture, maintenance, repair, modification and upgrade are required to ensure that tolerable safety risks are achieved over the vehicle's anticipated operational lifecycle. □

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