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EMC for the Functional Safety of Automobiles Why EMC Testing is Insufficient, and What is Necessary

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EMC for the Functional Safety of Automobiles
Why EMC Testing is Insufficient, and What is Necessary

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***Abstract* – 'Functional safety' means the achievement of acceptable risks due to operational (functional) errors or malfunctions over the anticipated lifetime of a product.**

Electromagnetic Compatibility (EMC) is validated by testing product characteristics using standardised test methods in an EMC laboratory. There have long been concerns [1] that this is inadequate for functional safety.

In all safety-engineering disciplines it is considered insufficient to rely totally on product testing. Instead, acceptable safety risks are validated using a variety of methods (including, but not limited to testing) to verify the safety design.

Part II of this paper describes twelve reasons why traditional EMC testing is insufficient as the sole means of demonstrating the necessary EM characteristics for functional safety.

Part III describes what EM engineering and verification techniques are required, where errors or malfunctions in electronics (hardware and firmware) could impact functional safety.

I. Introduction

Vehicles are increasingly using electronic sub-assemblies (ESAs) where they could affect functional safety, for example in every aspect of drive-chain control, and in 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].

All ESAs can suffer from errors, malfunctions and even permanent damage due to EM interference (EMI). The totality of all EM phenomena occurring at a given location (its 'EM environment') is continually worsening due to the increasing use of electronic technologies in all areas of society.

All ESAs rely on semiconductors, as discrete devices and/or integrated circuits (ICs), and the continuing shrinking in silicon feature sizes, and reductions in operating voltages, make them more susceptible to EMI. So, for several reasons, the importance of EMI to functional safety is increasing.

In the automobile industry, as in all other areas of product manufacturing, safety standards generally deal with EMI-related issues very poorly, if they even cover it at all [3] [4] [5]. The few safety standards that do cover EMI simply require the application of traditional EMC immunity tests that can never be sufficient, for the reasons described in Part II.

The result is that vehicle manufacturers who comply with the minimum regulatory requirements (e.g. [2]) and/or with their in-house or internationally standardised EMC or safety standards (e.g. [6]), will not adequately control EMC for functional safety – and so fail to control the risks for their customers, third parties and themselves, see Figure 1.

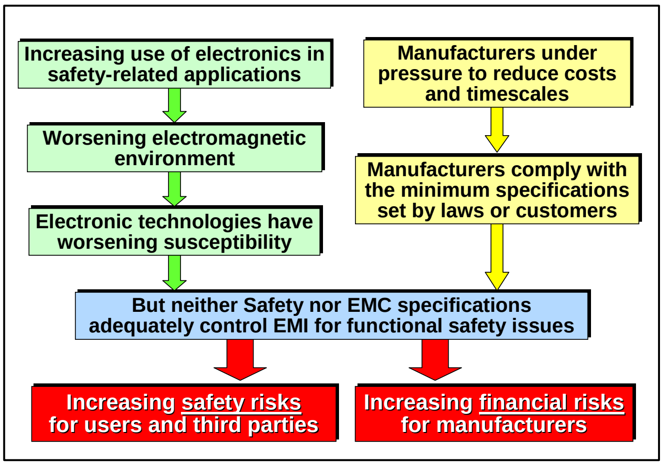

Figure 1 Increasing safety risks due to EMI

There are some recent developments that correctly address this issue, including [7], which is effectively the 'missing EMC Section' of [8], and the IET's 2000 guidance [9], a more practically useful revision of which is due in 2008.

II Why EMC testing is insufficient for safety

Also see [1] [10] [11] and [12].

Foreseeable faults are ignored

Faults can significantly affect immunity, for example:

- 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
- Intermittent electrical connections

But traditional automotive EMC tests ignore all faults – only perfect specimens of ESAs and vehicles are tested.

Foreseeable use and misuse are ignored

It is generally accepted in safety engineering that acceptable safety risk levels must be maintained despite reasonably foreseeable use or misuse. 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.

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

Test chambers are not realistic

Traditional radiated field immunity tests specify test chambers that make tests more repeatable. Unfortunately, they are unlike all real-life EM environments experienced by road-going vehicles, so their results can differ markedly from immunity in real life. Vehicle manufacturers 'overtest' to address this, but cannot validate their choice of test levels.

There are also concerns about the measurement uncertainties in the test chambers, with some EMC testing experts suggesting large and unpredictable uncertainties [13], [14]. Reverberation chambers can provide much more realistic tests [15] [16], and for this reason are used by many manufacturers of flight-critical avionics.

RF modulation types and frequencies are not realistic

For ease of testing, low costs and repeatability, traditional RF immunity tests use 1kHz sinewave modulation, although some vehicle manufacturers employ pulse modulation to simulate digital cellphones and radars, above about 600MHz.

However, real-life environments contain EM disturbances with a range of modulation types and frequencies. [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.

The importance of modulation has been well known in military electronic warfare for many decades, but is only now just starting to be addressed by some, see [19] and [20].

DC power disturbance tests are not realistic or thorough

[21] specifies conducted transient tests on the vehicle's DC power supply, using 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.

[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 in some cases. [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 the ISO 7637-2 pulse 2b can delete the firmware in some ESAs, and varying the test settings can cause some ESAs to switch on or off uncommanded. However, most vehicle and Tier 1 manufacturers do not vary the timings, and 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.

Simultaneous disturbances are not tested

Traditional EMC testing applies a limited number of types of EM disturbance, one at a time. But in real life operation, safety-related systems 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.

Simultaneous disturbances with different frequencies can cause EMI through intermodulation (IM), which (like demodulation) occurs naturally in non-linear devices such as 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

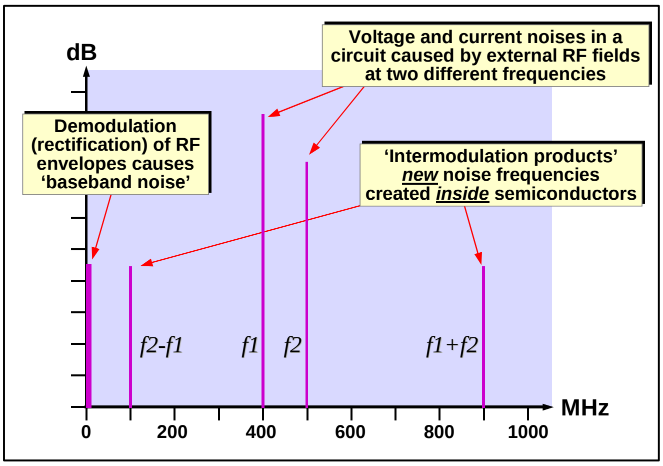

Figure 2 Example of demodulation and intermodulation

[24] shows that equipment that passes its individual immunity tests can be much more susceptible to lower levels of the same disturbances when they are applied simultaneously.

In a vehicle there are many independent 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 there in each minute there is 0.001% likelihood that a 100ns transient, that occurs once every minute on average (e.g. due to the actuation of an electric motor or solenoid), will overlap at least 50% with an ignition transient.

If the vehicle is driven for 1 hour/day, 5 days/week, 40 weeks/year, the likelihood of such an overlapping pulse event is 12% per year. And if the overlapping pulses caused an ESA to malfunction and cause a 1% chance of death, the driver would have a risk of death of 0.12% per year. This compares with a death rate of about 0.1% per year for very hazardous occupations (e.g. oil industry divers).

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

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safety problem is extremely remote, and even then it would almost certainly be diagnosed as something else.

Only one port is tested at a time

When a vehicle is subjected to a radiated EM field, all of the cables associated with its ESAs pick up RF voltages with phase differences between them. But traditional EMC conducted immunity tests only test one cable at a time.

Experiments at Qinetiq PLC injected RF energies 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 when one cable was tested at a time, in the traditional manner.

The physical environment is ignored

An appropriate level of EM performance must be maintained despite the effects of the physical environment over lifetime, 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.)

Physical 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). [25] describes a number of real-life problems of this nature.

[26] shows that up to 20dB degradation in filter attenuation can be caused by combinations of ambient temperature, supply voltage and load current within the filter's ratings – compared with the results of traditional immunity tests.

Vehicle manufacturers perform a variety of highly-accelerated life tests to check that functionality is maintained over the lifetime, but in general the resulting 'aged' units are not tested to see if EM characteristics have been affected.

Quality of EM design ignored

Most manufacturers test their products using traditional immunity test methods, iterating the design until it passes. But this might not reveal whether the pass was achieved by good EM design, or by something that would not be adequately controlled in serial manufacture over the production life.

Traditional EMC tests do not assess EM design quality, 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 actually supplied.

Assembly errors ignored

Good safety engineering always requires testing each unit manufactured 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 on EM characteristics in serial manufacture.

Test laboratories say that it is not uncommon for ESAs and vehicles that function correctly to fail EMC tests because of 'misbuild'. Although most manufacturers employ rigorous end-of-line testing, including in-circuit test that will discover misbuilds that affect functionality, it might not discover misbuilds that affect some EMC characteristics.

Systematic effects ignored

It is generally – but incorrectly – assumed that if all the ESAs incorporated into a system pass their immunity tests, then 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 poor.

The maximum test level is not necessarily the worst

All electronic devices are non-linear, and circuits/firmware can be very complex, so products can sometimes fail when tested with low level EM disturbances – but fail in a different way – or even pass when tested with the specified levels. But some EM tests only expose equipment at the highest specified level, to save testing time and cost. Lower disturbance levels will often be much more likely, and so could be much more significant for functional safety.

III WHAT NEEDS TO BE DONE

The approach described here 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.

We need to be cleverer than just doing EMC testing

Achieving sufficient confidence in functional safety using only EMC testing, would require addressing the twelve issues raised in Part II, requiring a test program that no-one could afford, in cost or timescale. So we need to be cleverer, to achieve functional safety with reasonable times and costs.

We need to use EM design techniques that ensure safety-related systems will maintain the necessary EM characteristics over their lifetime, given the foreseeable EM and physical environments [27]. And we need to verify and validate these designs using methods that achieve the necessary confidence with acceptable risks, costs and timescales.

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)

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- 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 ageing
- Future changes to the EM and physical environments
- Component tolerances; future changes to components (e.g. obsolescence, die shrinks, etc.)

Statistical analyses would be ideal, but it is generally only possible to establish the types of EM phenomena (Figure 3), their modulations and worst-case levels, with any confidence.

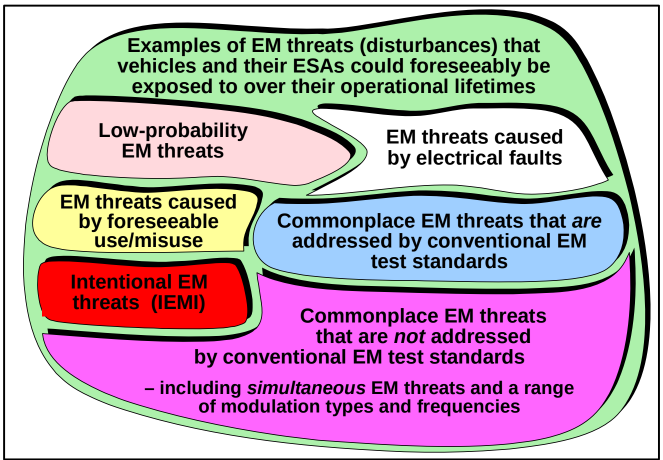

Figure 3 Examples of foreseeable EM disturbances

IEC and military standards describe a variety of physical environments, but any 'compatibility levels' (or test levels) they specify should not be applied unquestioningly.

Where a type of vehicle is to be sold into an EM or physical environment not fully covered during its original design, an assessment of the new EM and physical environment is required. This could lead to design changes, and their verification and validation, to maintain functional safety.

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 integrated circuits to cabling and vehicle structures. [27] includes a detailed discussion of well-proven good EM and physical design techniques for functional safety.

Hazard identification and risk assessment

A documented hazard identification and risk assessment process is required, that assesses how its reasonably foreseeable EM and physical environments over its lifetime, taking into account faults, misuse, etc, could possibly affect the product. It should show how any excessive risks were reduced to an acceptable degree by design, and be a 'live' 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 likelihood.

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 employed 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 where the probability of a fault is quite high (e.g. due to poor design for the physical environment) two or more independent faults could cause excessive safety risks.

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

A Safety Requirement Specification (SRS) should be created for each safety-related system [8], and should include the EM and physical requirements from the above activities. The EM/physical specifications for an ESA to be incorporated in a safety-related system should be derived from its SRS, taking into account any EM or physical mitigation measures applied by the system (e.g. shielding, filtering, surge suppression, anti-vibration mountings, forced cooling, etc.).

A verification/validation plan

To achieve sufficient confidence in verification and validation of all the design activities requires a mixture of technique [33], none of which is sufficient alone, including:

- 'Calibrated' computer simulations
- Demonstrations
- Checklists

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- Inspections
- Reviews and audits
- Independent assessments
- EM tests on ESAs and complete vehicles

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 standardised test methods, expertly modified to simulate real-life.

Highly-accelerated life testing (HALT) is a powerful tool for assessing the suitability of design methods, and of EM mitigation techniques such as shielding and filtering [34]. By using appropriate test set-ups, it can be easy to detect unacceptably degraded EM performance during HALT.

Final verification/validation tests are always required on ESAs for use in safety systems, and also for the safety systems themselves when installed in the vehicle. But the tests need to be specially designed to provide the required confidence without adding high costs.

The EM characteristics of ESAs and vehicles in serial manufacture can be significantly affected by, for example:

- 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.

So, all of the build-state issues relevant for maintaining functional safety should be identified during design and controlled by Quality Control (QC) in serial manufacture.

QC can use a range of techniques; including 'EM checks' on delivered goods and finished equipment; and sample-based testing designed to maintain an acceptable quality level (AQL). EM 'checks' can be designed to need very little time or expertise. QC should employ competent personnel, backed up by appropriate testing, to assess every proposal for a design change for its EMC and functional safety implications.

The results achieved by verification and validation

Documents should show how any shortcomings in meeting the ESA's specifications, and/or the SRS, were dealt with so that each safety-related system complied with its SRS.

Measures necessary to maintain EM characteristics

Any assumptions that were originally made about real-life EM and physical environments should be checked during the lifetime of a model of vehicle, and appropriate actions taken if they turn out to be wrong.

Appropriate QC techniques are required in Maintenance, Repair, Refurbishment, Modifications and Firmware Upgrades to ensure that the required EM and physical characteristics are not compromised over the vehicle lifetime.

Regular vehicle service schedules might need to include certain checks and/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. Automated diagnosis programs might need to be modified where EMI could cause of error, malfunction or damage.

Repair instructions might need to include techniques to maintain the vehicle's EM characteristics, even EM checks or tests afterwards. User Manuals might need to recommend activities to help maintain the required EM characteristics over the vehicle's lifetime, and may need to describe, in layman's terms, how the user can identify EMI as the cause of a problem, and also perhaps how to deal with it.

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 functional safety.

The amount of work required depends on the level of risk

Where safety risks are higher, and risk-reduction more important as a consequence, all of the work described above should be more detailed, comprehensive and in-depth, and performed by people who are more knowledgeable, and more expert in the techniques required.

IV Conclusions

This paper has described a dozen reasons why – for functional safety – it is insufficient to rely solely on EM testing.

Also, it has shown that rare and untested EMI events that could cause a safety incident only once during a 10-year vehicle life, could still expose drivers to safety risks comparable with those of the world's most dangerous occupations.

EMI must be treated like any other possible generator of hazards, including firmware [35]. Appropriate techniques in assessing the EM/physical environments, and in design; verification and validation; manufacture; maintenance and repair, are required for achieving acceptable safety risks over the vehicle's anticipated operational lifetime despite EMI.

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