ELECTRICAL POWERTRAIN HEALTH MONITORING FOR INCREASED SAFETY OF FEVs

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Current EMC standards and gaps detected regarding FEVs

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Executive Summary

This document describes the work carried out in the HEMIS project relating to the analysis of existing automotive EMC standards.

The deliverable has been split into Electromagnetic Compatibility (EMC) considerations and Electromagnetic Field (EMF) considerations. The current situation regarding the applicability of automotive EMC standards is lacking in test limits and methodology to fully account for the different electromagnetic environment generated by a fully electric vehicle (FEV). A summary of the identified areas where the range of available standards is lacking is shown in Appendix A.

The movement from the use Automotive EMC directive 2007/46/EC to the widespread introduction of UNECE regulation 10 results in this report concentrating on Regulation 10. As UNECE regulation 10 is more recent, it makes reference to tests to be carried out when a vehicle is in a charging state, however component EMC testing and whole vehicle testing are less well covered. UNECE regulation 10 calls on a range of CISPR and ISO standards (CISPR 12, CISPR 25 and ISO 11452) which do not fully define the tests needed to reflect the features of an electric powertrain. Although the versions of CISPR 12 that are referenced by the Automotive EMC Directive and UNECE Regulation 10 are different, both include specific requirements for measuring emissions from the electrical powertrain. However, further adaptations involving the way the vehicle is operated during a whole vehicle test will need to be applied, due to the differing characteristics of the electric powertrain from the more traditional internal combustion engine (ICE).

Component level EMC is also currently aimed at internal combustion engines, with UNECE Regulation 10 referencing the 2nd Edition (2002 plus 2004 corrigendum [42]) version of CISPR 25. There is a currently a 3rd Edition available and a 4th Edition under development. The 4th Edition of CISPR 25 may need more adaptation to cope with electric propulsion systems, due to the fact that the emissions are highly influenced by the load on the systems. Another consideration is related to the component testing is the definition of the ground plane in the case when the bodyshell is made from a composite material.

Regarding human exposure to electromagnetic fields, although there are generic recommendations that ought to be taken into account, there are currently no relevant product standards that specify how to measure in-vehicle field levels and interpret the results in terms of the recommended exposure limits. The recent development of an IEC standard to try and take this into account has been proposed. For wireless inductive charging systems, however, methods for assessing electromagnetic field exposure will be required for both vehicle occupants and bystanders.

Electric vehicles are currently under represented in the EMC and EMF standards that relate to vehicles. In house standards are often more detailed, but the official standards (i.e. CISPR, BS, ISO and EN) are lacking in information, test methodology and emission limits. As part of the HEMIS project it is hoped that some of the gaps present in the existing standards can be closed, and that this will result in a more robust base to ensure EMC across the full electric vehicle range.

Contents

Acronyms

ABS	Anti-lock Braking System
AC	Alternating Current
ADAS	Advanced Driver Assistance Systems
ALSE	Absorber Lined Shielded Enclosure
AM	Amplitude Modulation
AN	Artificial Network (to represent the impedance of the vehicle wiring harness)
BCI	Bulk Current Injection
BS	British Standard
C2X	Car-car/infrastructure communications
CAN	Controller Area Network
CARS	Competitive Automotive Regulatory System
CISPR	Comité International Spécial des Perturbations Radioélectriques
CNS	Central Nervous System
DC	Direct Current
DSRC	Dedicated Short Range Communications
FEV	Fully Electric Vehicle
EAS	Electronic Article Surveillance
EC	European Commission
EC WVTA	EC Whole Vehicle Type Approval
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EN	European Committee for Standardisation
ESA	Electrical/electronic sub-assembly
ESD	Electrostatic Discharge
EU	European Union
EV	Electric Vehicle
FM	Frequency Modulated

HEMIS	Electrical Powertrain **He**alth **M**onitoring for **I**ncreased **S**afety of FEVs
HEV	Hybrid Electric Vehicle
HV	High Voltage
ICE	Internal Combustion Engine
ICNIRP	International Commission for Non-Ionizing Radiation Protection
IEC	International Electro-technical Commission
I/O	Input / Output
IPT	Inductive Power Transfer
ISO	International Standards Organization
LV	Low Voltage
LVD	Low Voltage Directive
LVDWP	Low Voltage Directive Working Party
M	Category of vehicles with at least four wheels designed and constructed for the carriage of passengers
M_1	Category of passenger vehicles having no more than 8 seats in addition to the driver's seat
MEP	Member of European Parliament
MIRA	Motorsport Industry Research Agency
N	Category of vehicles designed and constructed for the carriage of goods
N_1	Category of goods vehicles having a maximum mass of 3.5 tonnes
OATS	Open Area Test Site
OFCOM	Office of Communications (UK regulatory and competition authority for the broadcasting, telecommunications and postal industries)
PHMS	Prognostic Health Monitoring System
PNS	Peripheral Nervous System
RESS	Rechargeable Energy Storage System
RF	Radio Frequency
RTTE	Radio and Telecommunications Terminal Equipment
SAE	Society of Automotive Engineers (USA)
SAR	Specific Absorption Rate

TEM	Transverse Electromagnetic
UK	United Kingdom
UNECE	United Nations Economic Commission for Europe
WPT	Wireless Power Transfer
Y-EMC	York EMC Services

1. Introduction

Electromagnetic compatibility (EMC) measurement standards for road vehicles originate from a time when the main threat posed by radio-frequency noise from vehicles was interference to broadcast transmissions from electromagnetic emissions from spark ignition systems, and the vehicles were predominantly mechanical with few potential immunity concerns. Since that time, however, on-going technological developments have resulted in changes in the nature of both the emissions from vehicles and the radio-based services under potential threat, and rapidly rising deployment of electronic sensors, actuators and control systems. Rapid changes in the technologies employed in the electrification of vehicle powertrain, in particular, raises questions as to whether the existing test methods remain appropriate for modern vehicles. The objective of this report to review current automotive EMC standards and issues detected regarding FEVs that are not covered within them [1].

Section 2 provides an overview of European vehicle type approval in general and automotive EMC requirements in particular, as well as the related issue of human exposure to electromagnetic fields.

Section 3 describes vehicle level EMC requirements, developments relating to electric vehicles, and associated limitations that have yet to be resolved.

Section 4 provides an analysis of test requirements and limitations relating to electric powertrain at the level of electrical/electronic subassemblies (ESAs).

Section 5 considers issues relating to electromagnetic fields in vehicles and human health, including and the evaluation of human exposure to electromagnetic fields and aspects relating to artificial implantable medical devices.

Section 6 addresses the issues that may arise in relation to wireless charging of electric vehicles, which is attracting considerable interest at present, and offers the potential to charge electric vehicles during operation as well as while parked.

Finally, the conclusions of this analysis are summarized in section 7.

2. Current Situation for Vehicles in Europe

2.1 Vehicle Type Approval

The importance and impact of vehicles on society are such that road vehicles have long been subject to specific certification and approval systems. In Europe there are currently two approval systems relating to vehicles:

- a system based on United Nations Economic Commission for Europe (UNECE, [2]) Regulations, which is used for type approval of automotive components and systems;
- EC Whole Vehicle Type Approval (EC WVTA), which is based on EC Directive 2007/46/EC [3] and provides for type approval of whole vehicles as well as vehicle systems and components.

Although EC WVTA initially only applied to new types of passenger cars (from 29th April 2009), and currently applies to all new types of road vehicles and trailers (from 29th October 2012), it is intended that this will be extended to cover all existing types of road vehicles and trailers by 29th October 2014. The EC WVTA Directive will also cover national schemes for small series vehicles (limited production) and individual approvals. The UNECE Regulations are part of the EC WVTA approach in the same way as the separate EC directives or regulations, which cover different aspects of vehicle functionality, including electromagnetic compatibility (EMC). The latter is addressed by the EC's Automotive EMC Directive (2004/104/EC, [4]) and by UNECE Regulation 10 [5].

2.1.1 EC WVTA Scope

The scope of 2007/46/EC includes "vehicles designed and constructed in one or more stages for use on the road, and of systems, components and separate technical units designed and constructed for such vehicles", as well as "parts and equipment intended for vehicles covered by this Directive".

Specified exclusions to 2007/46/EC include:

- agricultural or forestry tractors, which are subject to a specific framework directive [6];
- quadricycles, which are subject to a specific framework directive for two- and three-wheeled motor vehicles [7];
- tracked vehicles.

Furthermore, approval under 2007/46/EC is optional for the following classes of vehicles:

- vehicles intended exclusively for racing on roads;
- prototypes used on the road under the responsibility of a manufacturer to perform a specific test programme provided that they have been specifically designed and constructed for this purpose.

Those vehicles that are within the scope of 2007/46/EC are described in terms of a number of different categories. For example, category M encompasses "*vehicles with at least four wheels designed and constructed for the carriage of passengers*", and those vehicles with "*no more than eight* *seats in addition to the driver's seat*" (i.e. passenger cars) fall into the sub-category denoted M_1. Further sub-categories of passenger vehicles (category M) encompass those with more than eight passenger seats (i.e. busses and coaches), including M_2 (less than 5 tonnes) and M_3 (greater than 5 tonnes).

Other vehicle categories defined in 2007/46/EC include vehicles designed and constructed for the carriage of goods (category N, again with three sub-categories), trailers and semi-trailers (category O, which has four sub-categories), and off-road vehicles (category G).

2.1.2 Impending Changes

Directions for future automotive policy were investigated by the CARS 21 High Level Group, which brought together the main stakeholders (including member states, industry, non-governmental organizations and MEPs) in 2005 with the aim of examining the main policy areas impacting on the European automotive industry and making recommendations for future public policy and regulatory framework. The review conducted by CARS 21 [8] concluded that the current type-approval system was effective, that it should be maintained, and that most of the legislation was necessary and useful in the interest of protecting health, safety, consumers and the environment. Nonetheless, a total of 38 EC Directives were identified that could be repealed and replaced with the corresponding international UNECE regulations, as listed in EC Regulation 661/2009 [9], with effect from 1st November 2014.

This list includes the Automotive EMC Directive, which will be replaced by UNECE Regulation 10. Thus, EMC requirements relating to type approval of all new road vehicles and trailers will be subject to UNECE Regulation 10 from 1st November 2014. In practice there is a great deal of commonality between the Automotive EMC Directive and to UNECE Regulation 10. These documents are almost identical, and the differences between them in fact relate to detailed requirements for the testing of battery charging capabilities for FEVs. Consequently, this analysis focuses primarily on UNECE Regulation 10 as the source of automotive EMC test requirements.

2.2 Automotive EMC Requirements

2.2.1 Legislative Requirements

Both the Automotive EMC Directive and UNECE Regulation 10 describe EMC performance requirements for both whole vehicles and for "electrical/electronic subassemblies" (ESAs). An ESA is an electrical and/or electronic device or set(s) of devices that are intended to be part of a vehicle, together with any associated electrical connections and wiring, which performs one or more specialised functions. An ESA may be approved at the request of a manufacturer or their authorized representative as either a "component" (i.e. a sub-system of a vehicle) or as a "separate technical unit" (i.e. aftermarket equipment).

The performance criteria set for ESAs are somewhat higher than those that are required at full vehicle level. The aim of this is to increase confidence that ESA integration and installation aspects will not compromise vehicle level performance.

Furthermore, both vehicle and ESA EMC requirements are also divided into classes that relate to "immunity" (i.e. the ability of the system to function correctly in its intended operating environment) and "emissions" (i.e. the ability of the system to operate as intended without introducing unacceptable levels of electromagnetic disturbance into its intended operating environment).

A related requirement on vehicle manufacturers is that they must specify acceptable maximum power levels and antenna locations for after-market transmitting equipment that could be used on the vehicle, in order to ensure that the performance of the vehicle is not compromised by such transmissions.

The Automotive EMC Directive and UNECE Regulation 10 specify the performance criteria, in terms of both levels and frequencies, which are required to be satisfied in all of these areas in order to achieve type approval. However, test methods are largely described in standards that are referenced by the Automotive EMC Directive and UNECE Regulation 10. Although neither the Automotive EMC Directive nor UNECE Regulation 10 include any specific requirements relating to electric powertrain, some of the standards that they reference do take account of the potential for vehicles to be equipped with electric powertrain.

2.2.1.1 Emissions

Electromagnetic emissions characteristics are also described in terms of "broadband" and "narrowband" emissions. These phenomena are further subdivided into requirements relating to "radiated" and "conducted" immunity and emissions phenomena. Broadband emissions are classified as signals with bandwidths that exceed the receiver bandwidth, and have pulse repetition frequencies that are smaller than the receiver bandwidth. Narrowband emissions are classified as signals with bandwidths that are smaller than the receiver bandwidth, and have pulse repetition frequencies that are greater than the receiver bandwidth.

The emissions measurement methods referenced by the Automotive EMC Directive and UNECE Regulation 10 (although not necessarily using the same editions and amendments) include:

- **CISPR 12:** Vehicles, boats and internal combustion engine driven devices – Radio disturbance characteristics – Limits and methods of measurement for the protection of receivers except those installed in the vehicle/boat/device itself or in adjacent vehicles/boats/devices.

- **CISPR 25:** Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers

At vehicle level, CISPR 12 [10] applies, while CISPR 25 [11] is applied for ESAs. However, CISPR 25 also includes a vehicle level test for the frequency ranges of radios likely to be installed on the vehicle [12]. Applying Annex A of CISPR 25, FEVs should be tested to CISPR 25 even though there are no specific test methods in place for such vehicles.

2.2.1.2 Immunity

Electrostatic discharge (ESD) is not considered for vehicles with tyres as ESD phenomena are only expected to occur when the occupants enter or leave the vehicle, for which the vehicle must be stationary.

The immunity measurement methods referenced by the Automotive EMC Directive and UNECE Regulation 10 include:

- **ISO 11451**: Road vehicles – Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy
    - ISO 11451-1 – Part 1: General and definitions
    - ISO 11451-2 – Part 2: Off-vehicle radiation source
    - ISO 11451-3 – Part 3: On-board transmitter simulation
    - ISO 11451-4 – Part 4: Bulk current injection (BCI)
- **ISO 11452**: Road vehicles – Electrical disturbances by narrowband radiated electromagnetic energy – Component test methods
    - ISO 11452-1 – Part 1: General principles and terminology
    - ISO 11452-2 – Part 2: Absorber-lined shielded enclosure
    - ISO 11452-3 – Part 3: Transverse electromagnetic mode (TEM) cell
    - ISO 11452-4 – Part 4: Bulk current injection (BCI)
    - ISO 11452-5 – Part 5: Stripline
    - ISO 11452-6 – Part 6: Parallel plate immunity test method (now cancelled)
    - ISO 11452-7 – Part 7: Direct radio frequency (RF) power injection
    - ISO 11452-8 – Part 8: Immunity to magnetic fields (includes both Helmholtz coil and radiating loop methods to accommodate various size components)
    - ISO 11452-9 – Part 9: Portable transmitters
    - ISO 11452-10 – Part 10: Conducted Immunity in the Extended Audio Frequency Range (30 Hz to 250 kHz)
    - ISO 11452-11 – Part 11: Radiated immunity test method using a reverberation chamber
- **ISO 7637:** Road vehicles – Electrical disturbance by conduction and coupling
    - ISO 7637-1 – Part 1: Definitions and general considerations
    - ISO 7637-2 – Part 2: Electrical transient conduction along supply lines only
    - ISO 7637-3 – Part 3: Electrical transient transmission by capacitive and inductive coupling via lines other than supply lines

At vehicle level ISO 11451 and ISO 7637 (for vehicles with nominal 12 V or 24 V supply voltage) are applicable, while ISO 11452 is applied for ESAs.

2.2.2 In-house Requirements

Many vehicle manufacturers also apply in-house EMC performance requirements, at both vehicle and ESA level, which often go beyond the minimum legislative requirements. The motivations for this include such aspects as increasing confidence in customer satisfaction, ensuring resilience against age-related performance degradation, and "future-proofing" vehicles that may have a life expectancy of more than ten years in an electromagnetic environment that is expected to be constantly and rapidly evolving.

The differences between legislative and in-house requirements may include higher levels of immunity, lower levels of emission, and wider frequency ranges, as well as alternative test methods. Examples include the in-house requirements applied to ESAs by the Ford Motor Company [13], Jaguar Land Rover [14] and Daimler Chrysler [15], amongst others.

2.3 In-vehicle Electromagnetic Field Exposure

The Automotive EMC Directive does not consider human exposure issues other than for vehicle-mounted radio transmitters, through reference to the Radio and Telecommunications Terminal Equipment (RTTE) Directive 1999/5/EC [16] and its associated harmonised standards [17]. However, the RTTE Directive is only concerned with intentional transmitters, and does not address exposure from unintended transmissions and stray electromagnetic fields that may arise from electrical equipment.

Several harmonised standards relating to electromagnetic field exposure are approved [18] for use with the Low Voltage Directive (2006/95/EC, [19]). The scope of the Low Voltage Directive is defined (see Article 1) as: "*any equipment designed for use with a voltage rating of between 50 and 1000 V for alternating current and between 75 and 1500 V for direct current, other than the equipment and phenomena listed in Annex II*".

The exclusions of Annex II to 2006/95/EC are as follows:

- electrical equipment for use in an explosive atmosphere;
- electrical equipment for radiology and medical purposes;
- electrical parts for goods and passenger lifts;
- electricity meters;
- plugs and socket outlets for domestic use;
- electric fence controllers;
- radio-electrical interference;
- specialised electrical equipment, for use on ships, aircraft or railways, which complies with the safety provisions drawn up by international bodies in which the Member States participate.

Thus, conventional vehicles do not fall within the scope of Directive 2006/95/EC, since the operating voltages are below those specified in this Directive. However, voltage levels that are within the scope of Directive 2006/95/EC (values ranging from 158 V to 650 V are identified for a number of vehicles in [20]) are beginning to appear in electric vehicle applications.

Nonetheless, the most recent proposal from the Low Voltage Directive Working Party (LVDWP) concerning the legal framework for electric vehicles and related equipment [21] is as follows:

> "*(1) Member States can presume that the LVD is not applicable to both electric vehicles (i.e. notably to the electric power train of vehicle) and to on board chargers of electric vehicles. For*

> *these products, Directive 2007/46/EC (the Framework Directive on Motor Vehicles) is applicable.*
> *(2) Chargers of the batteries of electric vehicles, with the exception of on board chargers, shall always be considered as electrical equipment falling within the scope of application of the LVD.*"

The implication of this is that the off-board elements of vehicle battery charging systems are considered to be within the scope of the Low Voltage Directive 2006/95/EC, whereas the on-board elements of such systems would be within the scope of the Framework Directive on Motor Vehicles 2007/46/EC, and hence UNECE Regulation 10 for their EMC requirements.

At present, therefore, there are no specific standards relating to electromagnetic field exposures that may be associated with electric vehicle powertrain, or with unintentional sources in conventional vehicles. Nonetheless, there are general recommendations for limiting occupational and general public exposure to electromagnetic fields, such as those published by the International Commission for Non-Ionizing Radiation Protection (ICNIRP), which has produced exposure guidelines for both occupational and general public exposure in the band 0–300 GHz [22], and more recently updated the recommendations for frequencies in the range 1 Hz to 100 kHz [23]. Based on the ICNIRP guidelines, the European Union has produced a recommendation for general public exposure (1999/519/EC, [24]), while a directive concerning occupational exposure (2004/40/EC [25]) remains under discussion [26]. Thus although there are there are no specific standards relating to electromagnetic field exposure in vehicles, the available general recommendations ought to be taken into account during vehicle development.

3. Vehicle EMC Test Methods

3.1 Emissions Measurement

Current vehicle-level radiated emissions test requirements ([4]–[5]) specify broadband and narrowband emissions measurements over the band 30–1000 MHz using an antenna at a fixed point relative to the vehicle. From CISPR 12, both broadband and narrowband measurements are carried out using a receiver bandwidth of 120 kHz.

For conventional (i.e. ICE) vehicles, broadband measurements are carried out using a quasi-peak detector with the engine running at constant speed (1500 rpm), primarily to detect emissions from the spark ignition system. Narrowband measurements are carried out using an average detector with the vehicle switched on but without the engine running, in order to detect emissions from on-board electronic modules. As quasi-peak measurements require a significant dwell time, CISPR 12 permits peak measurements to be used with a 20 dB correction factor. Although this approach is questionable, due to the fact that the quasi-peak measurement is dependent on the pulse repetition rate and cannot be represented by a blanket 20 dB reduction, it is nonetheless reflected in UNECE Regulation 10 and will certainly be an issue for electric powertrain testing.

Unlike the emissions testing standards used by many other industries, such as CISPR 22 [27], there is no requirement for height scanning of the antenna and rotation of the test object in order to identify "maximum" emission levels (actually a local maximum on a cylindrical surface around the equipment under test). The approach used for vehicles is based on more restricted "snapshots" for fixed test configurations: CISPR 12 specifies that the receive antenna should be mounted 3 m high at a distance of 10 m from the car. A closer antenna configuration (1.8 m high and 3 m from the car) is also permitted by [4]–[5], with an assumed 10 dB difference in the limits based on space attenuation for a point source. The assumed relationship between the 3 m and 10 m measurements has been shown to be an over-simplification for extended sources such as vehicles [28]–[30]. Although this is also an issue for conventional vehicles, the potential for multi-motor architectures and spatially distributed electronics may make it of even greater importance for electric powertrains.

The location of the receiving antenna for traditional ICE vehicles is on a line through the engine, and therefore most commonly through the front axle, at the required distance from the surface of the vehicle. The measurements are made for both horizontal and vertical field polarizations, at points on both sides of the vehicle. Although the ICE is the main source of broadband emissions for conventional vehicles, narrowband emissions may arise from sources that are likely to be distributed throughout the vehicle. Nonetheless, the same antenna positions that are used for the measurement of broadband emissions are also used for the narrowband measurements. This approach is also questionable, although this issue is not unique to electric powertrain vehicles.

3.1.1 Adaptations for Electric Powertrain

Increasing deployment of alternative powertrain technologies (e.g. battery, hybrid and fuel cell vehicles) prompted amendments in the 5th Edition of CISPR 12 [10], which is referenced by the Automotive EMC Directive [4]. This requires vehicles with electric powertrain to be operated at 40 km/hour (or maximum speed if this is lower), either on a dynamometer under negligible load or in a free-wheeling mode with the driven wheels raised up using non-conductive axle stands, in order to ensure that emissions from the electric powertrain components are taken account of.

A further amendment to CISPR 12 [31], which includes an additional requirement for hybrid vehicles that both mechanical and electrical drive systems should be operational during the measurements where possible, is referenced by UNECE Regulation 10 [5]. Neither the Automotive EMC Directive nor UNECE Regulation 10 references the most recent edition of CISPR 12 [32]; however, this 6th Edition does not include any changes that are specific to electric powertrain. The main change introduced in the 6th Edition of CISPR 12 is to remove the differentiation between broadband and narrowband emissions [34], and instead specify the use of different detector types under different operating conditions (peak and/or average for the ignition on mode; peak and/or quasi-peak for the engine running mode). An amendment to the 6th Edition of CISPR 12 [33] was introduced to bring industrial floor cleaning machines (both battery and ICE powered), which were not previously subject to electromagnetic emissions requirements, within the scope of CISPR 12. Although BS EN 55012:2007 [35] mirrors CISPR 12, it is CISPR 12 that UNECE Regulation 10 refers to.

Amendments to UNECE Regulation 10 adopted in 2012 [5] also describe new radiated emissions test requirements relating to on-board conductively-coupled rechargeable electrical energy storage systems (RESS), which are outlined in section 6.1. Wireless inductive charging of vehicle traction batteries, which is currently of growing interest, is discussed in section 6.2.

3.1.2 Limitations for Electric Powertrain

3.1.2.1 Receive Antenna Positions

The use of electric powertrain offers considerably more architectural flexibility than can be achieved in traditional ICE vehicles. Electric vehicles could employ a single motor driving one axle, a motor on each axle, a motor driving each wheel, or perhaps even combinations of these (e.g. wheel motors at the front and a single motor driving the rear axle). Furthermore, as the definition of FEVs [36] also includes electric vehicles with range extenders, it also possible that the electric vehicle architecture could include a small ICE as well as one or more traction motors, and the location of the engine would not be necessarily tied to the vehicle axles as its role would be purely to generate electricity.

Thus, in FEVs there may no longer be a single dominant source for broadband emissions that can be used as a reference point for defining two off-board emissions measurement points as has historically been the case. Possible options could therefore include measurements at the required distances under the following conditions:

- to the side of the vehicle, in line with the wheel, for each in-wheel motor;
- on both sides of the vehicle in line with the axle, for each axle mounted motor;
- on both sides of the vehicle, in line with the ICE, for vehicles with this type of range extender.

Whilst these measures would increase the number of emissions measurements required, they could also be beneficial for obtaining a more reliable indication of narrowband emissions from the more widely distributed electronic sub-systems of the vehicle. Furthermore, time-domain emissions measurement techniques, which are expected to be permitted in the proposed 7th Edition of CISPR 12 [37], could perhaps help to limit the potential for longer test time associated with these additional antenna positions.

However, a simpler alternative that would avoid increasing the test requirements for more complex electric powertrain architectures could be to make measurements at the required distance on both sides at the mid-point of the vehicle. It is reported [37] that in the draft 7th Edition of CISPR 12 it is proposed to define the centre of the vehicle as the reference point if the 3 dB beam-width of the antenna covers the entire vehicle (otherwise multiple antenna positions would be required). Although making for a quicker measurement, not using a height scan may not be scientifically correct for a complex source such as an FEV. A similar issue is encountered when measuring emissions from equipment enclosures.

A further proposed change [37] to 7th Edition of CISPR 12 is to permit the use of test sites (e.g. OATS and ALSE) with ground conditions that more closely simulate roads (e.g. asphalt) for the frequency range 30 MHz to 1 GHz. Although not specific to electric powertrain, this change would perhaps be more representative of real world operating conditions for road vehicles.

3.1.2.2 Vehicle Operating Mode

It is noted in [37] that further clarification on conducted and radiated emission measurements on electric vehicles is necessary in the draft 7th Edition of CISPR 12, particularly on the high voltage propulsion system, as the load has a significant influence on the emission result. The operation of an electric drive under a negligible load is not necessarily representative of the worst case emissions that occur when the vehicle is in use. Depending on the operation modes and design of the powertrain it is possible that the worst case scenario for emissions could be under high or partial load conditions. In the standards that deal with EMC in the railway (the EN 50121-X series) a solution to this is partly achieved during the whole train emissions test (part 3-2 [38]) by the application of stationary and slow moving tests, with the train specified as running with 1/3 of maximum effort for the moving test. The test is designed so that the train passes a fixed antenna position, either accelerating at 1/3 maximum tractive effort or decelerating at 1/3 regenerative braking effort. This allows the regenerative braking circuits to be tested, as well as the traction propulsion system under load.

It has been observed [39] that radiated emissions from road vehicles with electric powertrain under acceleration and deceleration conditions differ from those observed in steady-state dynamic modes (i.e. at constant speed). However, there would be significant practical difficulties in making reliable measurements under such conditions, and conventional vehicles would also need to be tested in a similar manner, if this different measurement technique was to be used throughout the automotive EMC world.

In [40] it is suggested that as the higher emissions during acceleration are likely to be caused by the higher power used or by the higher motor speed, rather than as a direct consequence of the acceleration, it would be more sensible to use a constant vehicle speed under load conditions that simulate the acceleration. Potential disadvantages of this approach are that it would require the use of a dynamometer (at present CISPR 12 permits the vehicle to be operated in a free-wheeling mode with the driven wheels raised on non-conductive axle stands), and that limited traction battery capacity may seriously curtail the available test time under realistic load conditions. Nonetheless, faster emissions measurement technologies developed since the work in [39] was carried out may make time constraints less of an issue.

In [39] it is recommended that vehicle manufacturers should provide test modes to eliminate switching between electrical and mechanical power sources when using parallel hybrid powertrains during emissions testing. It is further suggested in [37] that manufacturers should provide test modes to ensure that the battery and engine power modes can be tested separately or in combination, and at appropriate speeds and/or powers, as well as defined short-duration cycles that could be linked to the scanning through the frequency range of the radiated emissions detector.

The engine running test conditions of CISPR 12 (i.e. at 1,500 revs/min for multi-cylinder engines, or 2,500 revs/min for single cylinder engines) may not be appropriate for rotary engines and gas turbines that are not conventionally found in vehicles, but may be well suited for range extender applications in series hybrid architectures [40]. It may also be beneficial to test at the specific speed that such range extenders are designed to function at, rather than an ICE based speed.

3.1.2.3 Detector Type for Broadband Emissions

Some laboratories (e.g. MIRA and Y-EMC) prefer to use peak measurements to rapidly identify those frequencies that are sufficiently close to the limits to merit more detailed investigation using the slower quasi-peak measurements, rather than simply applying the questionable 20 dB “correction factor” identified in [4]–[5].

3.1.2.4 Frequency Range & Near Field Considerations

The frequency range of the vehicle emissions measurements described in the Automotive EMC Directive, UNECE Regulation 10 and CISPR 12 is 30 MHz to 1 GHz. However, lower frequencies are known to be generated by electric powertrains (e.g. [39]). The American Society of Automotive Engineers (SAE) have published a Recommended Practice J551-5 (updated in 2012 [41]), which details measurement methods and target levels for frequencies in the band 150 kHz to 30 MHz for electric vehicles. In earlier versions the lower frequency limit was 9 kHz; but this has been raised to 150 kHz to align with CISPR 25. The scope of SAE J551-5 is road vehicles and other vehicles not exclusively used in a commercial environment.

With emphasis on low frequency emissions from powertrains, the question of near field measurements arises. A 10 m measurement distance results in a far field frequency limit of around 4.8 MHz, and there is currently no mention of near field considerations in UNECE Regulation 10. It would need to be seen if near field variations were outside a set variation (for example, 4 dB, as used on an Open Area Test Site). The EN 50121-X series assumes magnetic field dominance at low frequencies and as such specifies loop antennas for measurements at these frequencies.

SAE J551-5:2012

For radiated emissions, SAE J551-5 specifies the use of a monopole antenna mounted at ground level and located 3 m from the vehicle for measuring electric field (vertical component only), using peak and average detectors. A loop antenna located at 1 m height, also 3 m from the vehicle, is specified for magnetic field measurements, which should be carried out for the radial and horizontal field components, but only for the peak detector.

The test environment can be either an open area test site or an absorber-lined shielded enclosure meeting the performance requirements of CISPR 12, provided that the measurement noise floor is at least 6 dB below the emissions limits. The test site is required to be equipped with a dynamometer capable of providing a representative road load torque for all driven wheels for speeds up to at least 95 km/hour.

Emissions measurements are typically to be carried out with the powertrain in "drive" mode under three conditions:

- brake applied (wheels held motionless by pressure on the brake pedal);
- creep mode (no pressure on pedals , usually resulting in slow but non-zero wheel speed);
- cruise mode (accelerator or cruise control set to achieve a constant 70 km/hour).

Depending on the design of the vehicle, additional steady state operating modes may be defined as necessary to ensure that the maximum emissions can be detected.

Preliminary scans are required for all four sides of the vehicle in order to identify the highest emissions direction, following which the speed is adjusted between 16 km/hour and 64 km/hour in order to maximize the emissions level. If operation of the vehicle in the unloaded state would cause damage to the propulsion system, or result in lower radiated emissions levels, measurements may be made using a dynamometer to load the vehicle at a load representative of a zero-grade (level) road.

Test procedures for transient vehicle operating conditions are under study.

3.2 Immunity Measurement

Requirements regarding the immunity to radiated and conducted disturbances are specified for designated "immunity-related functions" of the vehicle, which include [4]:

(a) functions related to the direct control of the vehicle:

- by degradation or change in engine, gear, brake, suspension, active steering, speed limitation devices,
- by affecting driver's position (e.g. seat or steering wheel positioning),
- by affecting driver's visibility (e.g. dipped beam, windscreen wiper);

(b) functions related to driver, passenger and other road-user protection (e.g. airbag and safety restraint systems);

(c) functions which, when disturbed, cause confusion to the driver or other road users:

- optical disturbances: incorrect operation of e.g. direction indicators, stop lamps, end outline marker lamps, rear position lamp, light bars for emergency system, wrong

information from warning indicators, lamps or displays related to functions in clauses (a) or (b) which might be observed in the direct view of the driver,
- acoustic disturbances (e.g. incorrect operation of anti-theft alarm or horn);

(d) functions related to vehicle data bus functionality (e.g. by blocking data transmission on vehicle data bus-systems, which are used to transmit data required to ensure the correct functioning of other immunity-related functions);

(e) functions which, when disturbed, affect vehicle statutory data (e.g. tachograph, odometer).

The vehicle is required to be tested for immunity to radiated electromagnetic fields in the frequency range 20 MHz to 2 GHz [4]–[5], and is expected to meet the functional failure criteria defined for the various immunity related functions. A minimum set of criteria are specified in [4]–[5], but other vehicle systems that could affect the immunity-related functions must be tested using a method that is to be agreed between manufacturer and the technical service.

The vehicle immunity requirements are generally just as applicable to vehicles with electric powertrain as to conventional ICE vehicles. However, the pulse criteria for conducted disturbances that are listed in 2004/104/EC and UNECE Regulation 10 only relate to 12 V and 24 V vehicles, while electric vehicles are likely to operate at rather different voltages (up to 650 V is reported in [20]). Nonetheless, the only difference introduced in UNECE Regulation so far in relation to electric vehicles [5] is a requirement for an additional vehicle immunity test mode in which the on-board RESS is charged from an external electrical supply (discussed in section 6.1).

4. Vehicle Component Level EMC

4.1 Emissions

The measurement of emissions from ESAs is covered by CISPR 25, which aims primarily to protect on-board radio receivers from interference (the most common source of complaints from end users). The Automotive EMC Directive refers to the 2nd Edition of CISPR 25 (2002), whereas UNECE Regulation 10 refers to the 2nd Edition of CISPR 25 (2002) including the 2004 corrigendum [42]. However, there is currently a 3rd Edition [43], and a 4th Edition is currently under development, with a forecast publication date of February 2013 [44]. The 3rd Edition introduced the following significant changes with respect to the earlier edition [44]:

- addition of required measurements with both an average detector and a peak or quasi-peak detector;
- addition of methods and limits for the protection of new analogue and digital radio services, which cover the frequency range up to 2.5 GHz;
- addition of a new measurement method for components (stripline) as an informative Annex G;
- addition of the contents of CISPR 21 as Annex H (CISPR 21 is now obsolete);
- deletion of narrowband/broadband determination;
- deletion of the Annex on rod antenna characterisation (this is now covered by CISPR 16-1-4);
- deletion of the Annex on characterisation of shielded enclosure (CISPR 25 will be amended when the CISPR/D/CISPR/A Joint Task Force on chamber validation finishes its work).

The contents of the corrigendum of January 2009 to the 2nd Edition have also been included in the current 3rd Edition of CISPR 25.

At present there is no intention to extend the upper frequency limit beyond the current 2.5 GHz for the planned 4th Edition of CISPR 25. However, changes that are currently proposed for the 4th Edition include the following [37]:

- The references to the basic standard series CISPR 16 will be updated to make FFT-based receivers applicable for EMI compliance measurements.
- For the limits given in CISPR 25, the appropriate average detector for measurements at frequencies above 1 GHz is the CISPR-AV detector. Below 1 GHz the alternative use of the AV detector might be deleted.
- The application of correction factors for the AN (i.e. artificial network, used to represent the impedance of the vehicle wiring harness) and the estimation of the associated uncertainty is well known and applied by the test laboratories. It is proposed to delete the last sentence in the first paragraph of Sub-clause 6.2.3: "*When using the provided limits, no correction factors for the AN shall be used*". The affected FM band limits will not be revised.

- A new informative Annex on chamber validation will be added. It will contain two alternative validation methods ("long wire" and "reference site method") which provides the CISPR 25 user with some additional flexibility.

It has also been noted [37] that the load has a significant influence on the emission levels for conducted and radiated emission measurements on the high voltage propulsion systems of electric vehicles. Thus, there will be some adaptions in the 4th Edition of CISPR 25 to take account of electrical powertrain issues.

An issue with CISPR 25, which is equally true of both FEVs and conventional vehicles, is that compliance with CISPR 25 cannot guarantee compliance with vehicle level performance requirements. This is due to vehicle installation effects, which cannot be replicated in a component level measurement. Even with all components passing the EMC tests it is still possible to have a situation where radio interference is experienced. In order to try and reduce the effect of increased EMC problems once the vehicle is put together, the ESA limits are more stringent than the full vehicle test. CISPR 25 has not been written with electric drives in mind; this means that there are no charging or electric drive specific sections. This is evident in the fact that choice of instrumentation is tailored to internal combustion vehicles (see 4.4 in CISPR 25).

4.1.1 Conducted Emissions

Conducted emission measurements on components are covered in some detail in CISPR 25. CISPR 25 makes it clear that the voltage method alone is not sufficient to characterise the complete EUT emission. The voltage method uses a load simulator to provide the EUT with representative inputs, for example if the EUT is an instrument cluster the load simulator would provide rpm, speed, temperature and fuel level readings to the EUT. The load simulator location is specified throughout the tests. Applying this to the traction package of an FEV, the possible need for either a motor dynamometer or a representative electrical load arises to allow the testing of the battery pack and associated systems. This is also relevant in that the EUT is required to operate under typical loading, which is easily achievable with an instrument cluster or ignition system, but would require a much more substantial test setup to cope with a traction motor or motors. The decision whether the motor, battery and inverter drive are tested separately or as one EUT would need to be made, bearing in mind the challenge presented by using a ground plane based measurement on an FEV with four in-wheel motors, particularly if the ground plane is required to be located at 900±100 mm above the floor as specified in 6.1.1 of CISPR 25.

As CISPR 25 is designed for internal combustion engines there is a separate setup guideline for the generator/alternator class of subsystem, where an air or low emissions motor is used to drive the alternator or generator. It may be possible to replicate this in reverse (i.e. the traction motor drives an emission-free load). This would be equivalent to a motor dynamometer and separate from the whole vehicle dynamometer.

The current probe method would need to consider the same considerations regarding the test setup. In both methods, the need for identifying the load conditions under which the maximum conducted emission state occurs when using a traction package. In addition to this, section 4.1.4 states that the peripheral interface unit should be used to simulate the vehicle installation of components, to ensure correct operation. The peripheral interface only appears to be implemented when the TEM cell is used.

The AN is intended to isolate the equipment under test from power supply fluctuations, to provide a defined impedance at the power terminals of the equipment under test over the measurement frequency range, and to allow the disturbance voltage to be measured. The AN defined in CISPR 25 (and in the ISO 11452-X series) is based on measurements of the inductance presented by the electrical networks of a range of vehicles. For vehicles with electric powertrain, however, the operating voltages may be much higher (up to 650 V is reported in [20]), the HV network is isolated from the vehicle chassis, and the power cables are often shielded. Investigation of these issues [45] suggests that a new HV AN design is required for reliable conducted emissions testing on electric powertrain components.

4.1.2 Radiated Emissions

Regulation 10 Annex 7 describes the testing method for the emissions of radiated broadband emissions from ESAs, with Annex 8 covering the narrowband. Based on CISPR 25 (2005), the limits are applied from 30 MHz to 1 GHz, this is also mentioned in Section 6 of UNECE Regulation 10. As the electric drive is an ESA (stated in Annex 7 1.2) then it would seem prudent to test at the lower frequencies for broadband emissions below 30 MHz, while bearing in mind near field effects. However, it is important to keep the EMF and human health considerations separate from radio interference, which may be why the frequency range is specified as it is. In the UK, OFCOM still specify that AM radio (which in general operates lower than 30 MHz) is in a protected band, so some limits below 30 MHz would perhaps be useful in UNECE Regulation 10. CISPR 25 gives parameters for antennas and measuring equipment down to 150 kHz as part of the AM broadcast protection; limits for these frequencies are also given for radiated disturbances.

The 20 dB quasi-peak correction is also stated in UNECE Regulation 10 component emission section. An OATS can be used if there is 6 dB between the lowest measured emission and the limits of interference, other than that a screened room is to be used. In an attempt to replicate the real world situation, UNECE Regulation 10 states that the ESA should be in "*normal operating mode, preferably maximum load*". It is worth noting that maximum load may not necessarily generate the highest emissions.

It is noted in [46] that the description of how to arrange the cable harness for a CISPR 25 radiated emissions test in an ALSE is insufficiently detailed for a system as complex as the electric powertrain of a vehicle. The latter may include both AC and DC HV links, as well as communications and sensor cables. Simply bundling all of these together may not be representative of realistic vehicle installation characteristics.

4.2 Immunity

Component immunity is covered by the ISO 11452-X series of standards. UNECE Regulation 10 in Annex 9 1.21 states that ESAs may comply with the requirements of 11452-2 [47], 11452-3 [48], 11452-4 [49] or 11452-5 [50], provided that the full frequency range specified in Regulation 10 is covered. The test frequency range is 20 MHz to 2 GHz.

UNECE Regulation 10 does not distinguish between radiated and conducted as such, but instead calls on the different test methods in ISO 11452, which cover specific frequency ranges. The limits present in the various parts of ISO 11452 are not necessarily equivalent, and this, coupled with the choice of test aspect, means that tests with lower limits can be chosen by the manufacturer. The relative amounts of coupling of the EM disturbance into the ESA itself and the harness depend on the particular ESA and the frequency, for example at low frequencies the coupling into a physically small ESA will be small, and the majority of coupling will be through the wiring harness. At higher frequencies however, most of the coupling could be to the ESA itself. In addition to this, the TEM cell method provides very little coupling into the harness, whereas the 150 mm stripline provides very little coupling into the ESA, as the ESA is outside the stripline. The 800 mm stripline test method is specific to Regulation 10 (and also present in previous versions of the automotive directive) and has no ISO accredited status.

UNECE Regulation 10 specifies some specific test requirements for the immunity of ESAs, Mentioned is 4.1.2 of Annex 9 is the need to only test in an ALSE using vertical polarisation on the transmitting antenna. This is different to other standards for testing radiated immunity of non-automotive components.

ISO standard 7637-2 [51] is used to characterise test pulses to test for transient immunity. UNECE Regulation 10 simply states that supply lines and any other connectors that may be connected to supply lines are tested for transient immunity.

4.3 Ground plane issues

Both conducted and radiated emissions, and some immunity test requirements for ESAs specify that the equipment under test should be mounted above a rectangular ground plane. However, the nature of the ground reflects the requirement to test relatively small systems for use in a steel vehicle. Thus, there may be a need to adapt the ground plane requirements to the particular features of FEVs.

4.3.1 Ground Plane Geometry

A thickness of 0.5 mm and a height of 0.9±0.1 m are specified for the ground plane required for testing in both CISPR 25 and the ISO 11452-X series. The equipment under test is also to be mounted at a height of 50±5 mm above the ground plane using a non-conductive, low-permittivity material with a dielectric constant of 1.4 or less. However, the load simulator, the power supply and the AN are both to be placed on the ground plane and electrically bonded to it.

For conducted emissions measurements, CISPR 25 requires the ground plane to be 1 m x 0.4 m as a minimum. For CISPR radiated emissions, and for ISO 11452 radiated immunity [47] and BCI [49], the ground plane is required to be at least 1 m wide and 2 m long, or to extend at least 0.2 m beyond the boundaries of the equipment under test, whichever is the larger.

It is probably impracticable to test many ESAs associated with the RESS of FEVs, such as battery management and power conditioning electronics, without the other parts of the RESS. Thus, the equipment under test can be extremely large and heavy, requiring special ground planes of appropriate size and load bearing capability to be constructed. Although such tests are beginning to be undertaken [52], further development of standards to accommodate these scenarios is required.

4.3.2 Ground Plane Materials

There is increasing interest in exploiting lightweight materials for FEV bodyshells in order to maximize driving range and minimize fuel consumption for vehicles with on-board energy generation systems (e.g. hybrid and fuel cell vehicles). Thus, materials such as aluminium, plastics and carbon fibre are being used as an alternative to traditional steel panels, although a steel supporting framework may still be required in order to ensure sufficient structural rigidity.

At present CISPR 25 permits the ground plane used for emissions measurements on ESAs to be constructed from copper, brass, bronze and galvanized steel. The options are only slightly more restricted in ISO 11452, which does not include bronze. The conductivity of aluminium body panels is probably within the range already represented by these materials. For metallic ground planes the conductivity is isotropic, with values are of the order of 10^6–10^7 S/m. Carbon-fibre, however, is different in that the conductivity is anisotropic and typically much smaller than for metals. Reported conductivities for carbon-fibre samples for spacecraft applications are of the order of 10^4 S/m in the plane of the sheet and in the range 10^1–10^3 S/m normal to the sheet [53].

Copper is probably the most commonly used material in this type of application, but the steel traditionally used in vehicles has significant permeability, unlike copper, aluminium and bronze. Furthermore, a small number of vehicles have historically been constructed from glass-fibre composites (ranging from a few panels through to the entire skin) with negligible conductivity. Thus, the existing situation is already not fully representative of the electrical properties of vehicle bodyshells.

In CISPR 25 and ISO 11452 it is noted that the equipment under test “shall not be grounded to the ground plane unless it is intended to simulate the actual vehicle configuration”. This statement in CISPR 25 and ISO 11452 is ambiguous as the test should be to always attempt to simulate the actual installation in the vehicle, in which case then the equipment should be grounded if that is intended to be the case in the vehicle. This also raises questions with body ground definition in a vehicle with a composite bodyshell.

5. Human Exposure to Electromagnetic Fields

5.1 Field Reference Levels

The exposure limits identified in [22]–[25] include in-body parameters such as specific absorption rate (SAR) for frequencies in the range 100 kHz to 10 GHz, and induced current density in the band 1 Hz to 10 MHz [22], [24]–[25]. More recently, induced internal electric field has been proposed as the low frequency measure [23]. However, these in-body quantities are not easy to determine for comparison with the associated "basic restrictions". Consequently, "field reference levels" are also specified in [22]–[25], so that the more readily measured electromagnetic environment can be assessed with less difficulty for non-localized exposures (i.e. this approach is not considered to be applicable to body-worn and hand-held transmitters, such as mobile telephone handsets, for which it is necessary to establish compliance with the basic restrictions).

Numerical modelling has been used to establish the relationships between the basic restrictions and the field reference levels, such that fields complying with the reference levels can be assumed to guarantee compliance with the basic restrictions. Fields exceeding the reference levels do not necessarily imply that the basic restrictions are breached, but are considered to be sufficiently high that more detailed investigation is needed in order to establish compliance with the basic restrictions.

Different basic restrictions and field reference levels have been set for "occupational" and "general public" exposure to electromagnetic fields, with the occupational requirements set at higher levels (generally by a factor of ~5) than for the general public. The reason for this difference is that it is assumed that workers will be drawn from a more restricted sub-set of the population (in terms of age and health), and will be routinely monitored if working in a high-field environment. It can also be assumed that workers are aware of their working environments and will use defined mitigation methods. The general public, however, may be of any age and/or health condition and will not be routinely monitored for health issues relating to field exposure, or even aware that they may have been exposed to electromagnetic fields.

Various practical complications associated with real-world conditions make field exposure evaluation less straightforward. These include spatially non-uniform exposures, which make the exposure environment more difficult to characterize, and broadband and non-sinusoidal sources, for which additive effects must be taken into account.

5.2 Broadband and Non-sinusoidal Exposures

A significant difference from the assessment of electromagnetic emissions in EMC standards is that for human exposure evaluation the additive effects of multiple frequency exposure must be considered. Thus, simply comparing the field intensity with the selected reference level at each frequency is not sufficient to establish compliance with the reference levels.

Furthermore, it should be noted that the field reference levels as detailed in the tables of [22]–[25] are specified only for monochromatic sinusoidal sources, and if multiple frequencies and or non-sinusoidal fields are present in the environment then slightly different criteria are specified to assess the exposure.

5.2.1 Frequency range 100 kHz to 300 GHz

If fields at frequencies above 100 kHz are present then the following criteria, involving the squares of the ratios of the fields to the reference levels (see [22], [24]), must be satisfied in order to ensure that basic restrictions relating to tissue heating effects are not exceeded:

$$\sum_{f_i=100\ \text{kHz}}^{1\ \text{MHz}} \left\langle \left(\frac{E_{RMS}(f_i)}{c} \right)^2 \right\rangle + \sum_{f_i \geq 1\ \text{MHz}}^{300\ \text{GHz}} \left\langle \left(\frac{E_{RMS}(f_i)}{E_{RL}(f_i)} \right)^2 \right\rangle \leq 1 \tag{5.1}$$

$$\sum_{f_i=100\ \text{kHz}}^{1\ \text{MHz}} \left\langle \left(\frac{H_{RMS}(f_i)}{d} \right)^2 \right\rangle + \sum_{f_i \geq 1\ \text{MHz}}^{300\ \text{GHz}} \left\langle \left(\frac{H_{RMS}(f_i)}{H_{RL}(f_i)} \right)^2 \right\rangle \leq 1 \tag{5.2}$$

where $E_{RMS}(f_i)$ and $H_{RMS}(f_i)$ are the maximum RMS electric and magnetic field strengths (respectively) at frequency f_i in the exposure environment, and $E_{RL}(f_i)$ and $H_{RL}(f_i)$ represent the relevant field reference levels (for either occupational or general public exposure, as appropriate). For general public exposures, the constants applied below 1 MHz are $c = 87/f^{½}$ V/m and $d = 0.73/f$ A/m (equivalent to $d = 0.92/f$ μT if using magnetic flux density). For occupational exposures, ICNIRP currently indicates [22] values of $c = 610/f$ V/m and $d = 1.6/f$ A/m (the corresponding parameter would be $2/f$ μT for magnetic flux density).

Thus, for heating effects the fields for broadband exposures below 1 MHz are not simply compared with the reference levels. It should also be noted that the squares of the field ratios in (5.1)–(5.2) are to be averaged over a 6-minute period.

At present, the ICNIRP guidance relating to tissue heating effects, which is relevant at frequencies from 100 kHz to 300 GHz, as well as for exposure to frequencies below 1 Hz, are under review [23].

5.2.2 Frequency range 1 Hz to 10 MHz

At low frequencies, the field exposure guidelines aim to protect against undesirable electro-stimulation effects. Thus, for low frequency magnetic fields it is the rate of change of field that is important, rather than the field magnitude, since changing magnetic fields induce currents in nearby conducting materials, including human tissues. Furthermore, as electro-stimulation is an instantaneous phenomenon it is considered that there is no scientific justification to modify the basic restrictions for exposures of short duration. Thus, assessment of these effects must consider the worst-case values, rather than a time average such as is used for SAR (where the exposure restrictions are based on a 6-minute time average). Consequently, current transients on vehicle power networks, including the powertrain, are potentially important for low frequency magnetic field exposure considerations.

The field reference levels are specified as a function of frequency for monochromatic, sinusoidal fields and therefore contain implicit assumptions about the rate of change of magnetic field for sinusoidal waveforms (i.e. a multiplying factor of $2\pi f$, where f is the frequency). For exposures involving separate sinusoidal sources at multiple frequencies up to 10 MHz, the sum of the spectral components divided by their corresponding field reference levels should not exceed unity (see [22]–[24]).

In the recent ICNIRP statement concerning fields in the range 1 Hz to 100 kHz [23] (which also includes guidance for electro-stimulation effects at frequencies in the range 100 kHz to 10 MHz) the field levels are required to meet the following criteria:

$$\sum_{f_i=1\text{ Hz}}^{10\text{ MHz}} \frac{E_{RMS}(f_i)}{E_{RL}(f_i)} \leq 1 \tag{5.3}$$

$$\sum_{f_i=1\text{ Hz}}^{10\text{ MHz}} \frac{H_{RMS}(f_i)}{H_{RL}(f_i)} \leq 1 \tag{5.4}$$

where $E_{RMS}(f_i)$ and $H_{RMS}(f_i)$ are the net RMS electric and magnetic field strengths (respectively) at frequency f_i in the exposure environment, and $E_{RL}(f_i)$ and $H_{RL}(f_i)$ represent the relevant field reference levels (for either occupational or general public exposure, as appropriate). The magnetic flux density (denoted by B) could also be used for evaluation in this way, as reference levels are also provided for this parameter in [22]–[24] and it is more usual to measure magnetic flux density at low frequencies.

Thus, while a single frequency reaching 99.5% of the reference level would be compliant in isolation, the presence of a second frequency at only 1% of the corresponding reference level would put the total exposure at 100.5%, meaning that the reference levels are exceeded. If four frequencies of equal intensity were present then they would need to be at no more than 25% of the corresponding reference levels in order to achieve compliance.

It should be noted that the corresponding criteria that are specified in the EU recommendation concerning exposure of the general public [24] are slightly different to equations (5.3)–(5.4), as they still reflect the original ICNIRP 1998 statements [22]:

$$\sum_{f_i=1\text{ Hz}}^{1\text{ MHz}} \frac{E_{RMS}(f_i)}{E_{GP}(f_i)} + \sum_{f_i \geq 1\text{ MHz}}^{10\text{ MHz}} \frac{E_{RMS}(f_i)}{a} \leq 1 \tag{5.5}$$

$$\sum_{f_i=1\text{ Hz}}^{150\text{ kHz}} \frac{H_{RMS}(f_i)}{H_{GP}(f_i)} + \sum_{f_i \geq 150\text{ kHz}}^{10\text{ MHz}} \frac{H_{RMS}(f_i)}{b} \leq 1 \tag{5.6}$$

where $E_{GP}(f_i)$ and $H_{GP}(f_i)$ represent the general public reference levels for electric and magnetic field strengths (respectively) at frequency f_i as specified in [24], and the constants a and b are equal to 87 V/m and 5 A/m, respectively.

Thus, for assessing electro-stimulation risks for broadband exposures using [24], the fields are not simply compared with the reference levels detailed in the tables of [24], which are for specified for single frequency exposures only. The parameter *a* is used as a reference level for broadband magnetic field exposure from 150 kHz to 10 MHz and the parameter *b* is used for broadband electric field exposure in the band 1–10 MHz.

As reference levels are also quoted for magnetic flux density in [22]–[24], the multiple frequency exposure criteria can also be adapted accordingly. Based on 1999/519/EC [24], the magnetic flux density criterion would be:

$$\sum_{f_i=1\text{ Hz}}^{150\text{ kHz}} \frac{B_{RMS}(f_i)}{B_{GP}(f_i)} + \sum_{f_i \geq 150\text{ kHz}}^{10\text{ MHz}} \frac{B_{RMS}(f_i)}{e} \leq 1 \quad (5.7)$$

where the constant *e,* which is derived from *b* assuming free space permeability, is 6.25, for fields in μT [55].

Based on ICNIRP 2010 [23], the corresponding magnetic flux density criterion would be:

$$\sum_{f_i=1\text{ Hz}}^{10\text{ MHz}} \frac{B_{RMS}(f_i)}{B_{RL}(f_i)} \leq 1 \quad (5.8)$$

The general public reference levels for magnetic flux density ICNIRP 2010 [23] are illustrated in Fig. 5.1, which also shows the equivalent parameters relating to electro-stimulation effects under broadband exposure from 1 Hz to 10 MHz (i.e. including the parameter *e* for frequencies from 150 kHz). For frequencies above 25 Hz the ICNIRP 2010 reference levels are higher than the corresponding ICNIRP 1998 [22] general public reference levels that are reflected in 1999/519/EC [24].

The reference levels for magnetic flux density relating to electro-stimulation effects under broadband exposure are illustrated in Fig. 5.1 below, which also shows the equivalent ICNIRP 2010 [23] parameters relating to electro-stimulation effects under broadband exposure from 1 Hz to 10 MHz, which are higher than the corresponding 1998 ICNIRP levels that are reflected in 1999/519/EC [24].

Neither the latest proposal for the intended EU occupational exposure directive [26], nor the existing text [25], identify specific measures relating to multiple frequency or non-sinusoidal exposures, but instead refer to "*available harmonised European standards*" or "*other scientifically-based standards or guidelines*". However, the implication from ICNIRP 1998 [22] seems to be that the same approach described for general public exposure is also to be applied for occupational exposures involving multiple frequencies.

A similar approach can also be adopted for non-sinusoidal magnetic field waveforms, by simply extracting the spectral components, but assuming that all frequency components add in phase may lead to unnecessarily pessimistic results. In fact, it is reported in [54] that summing the measurement noise floor for a sufficiently large number of frequencies can result in criteria of the nature of equations (5.3)–(5.8) being exceeded.

An alternative approach, giving a less conservative assessment, is to weight the field values with a filter function that reflects the frequency dependence of the reference levels ([23], [55]). In this scheme the phase of the spectral components is also taken into account, allowing a time-varying, broad-band field exposure metric to be reconstructed via an inverse Fourier transform.

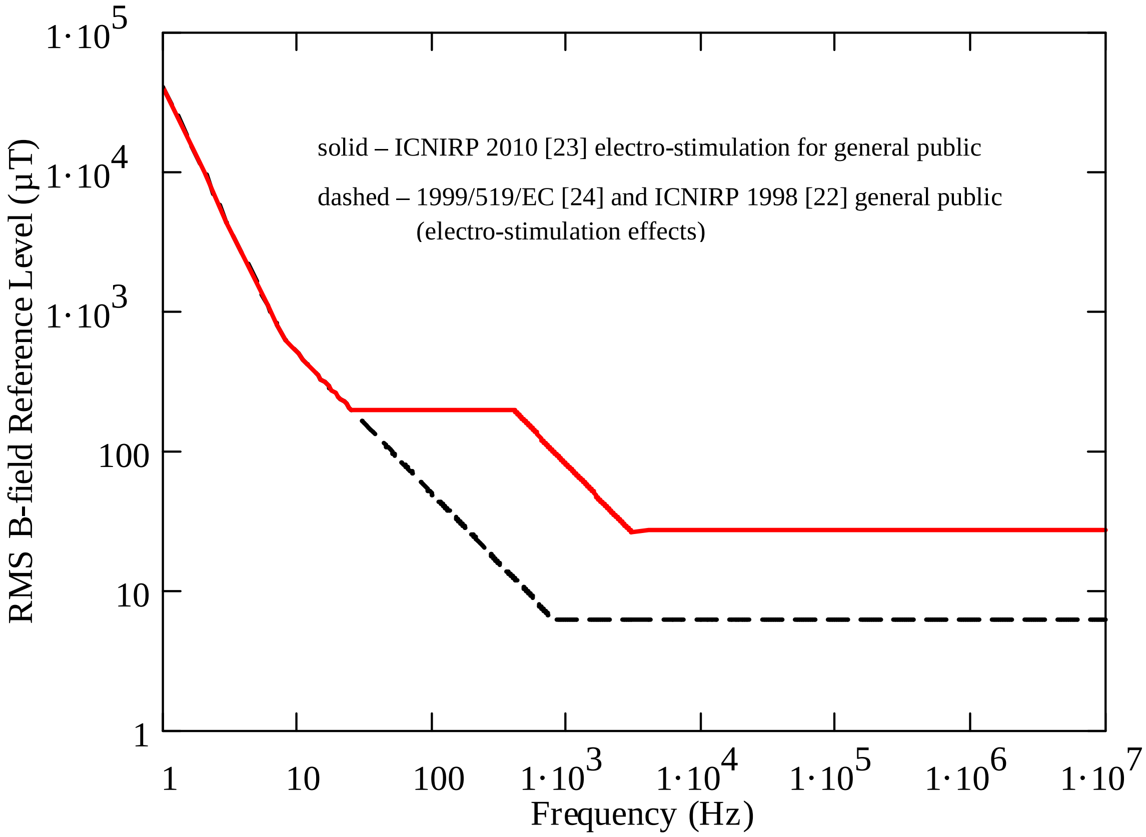

Fig. 5.1: Reference levels for RMS magnetic flux density to protect the general public against electro-stimulation effects due to broadband field exposures (1 Hz to 10 MHz)

5.2.3 Non-sinusoidal Exposures, 1 Hz to 100 kHz

An alternative approach, giving a less conservative assessment, is to weight the field values with a filter function that reflects the frequency dependence of the reference levels ([23], [55]). In this scheme the phase of the spectral components is also taken into account, allowing a time-varying, broad-band field exposure metric to be reconstructed via an inverse Fourier transform.

The weighted process outlined in [23] and [55] only describes a single field waveform. For more general fields this approach is presumably to be applied to the waveforms for each of the three orthogonal field components individually, and the component results then combined vectorially in order to obtain the total exposure measure.

Assuming the magnetic field exposure to be time-varying and spatially non-uniform, the total magnetic field exposure measure $ME(t_i,\mathbf{r}_j)$ at point $\mathbf{r}_j$ for time t_i is given by:

$$ME(t_i,\mathbf{r}_j)=\sqrt{\sum_{k=1}^{3}\left[me_k(t_i,\mathbf{r}_j)\right]^2}\leq 1 \tag{5.9}$$

where the terms $me_k(t_i,\mathbf{r}_j)$ represent the time-varying magnetic field exposure measures determined for each of the orthogonal components k (where $k\in\{1,2,3\}$), which are evaluated as:

$$me_k(t_i,\mathbf{r}_j)=\left|\sum_{n=N}^{M/2}\frac{|B_{jkn}|}{\sqrt{2}B_{RL}(n\Delta)}\cos\{2\pi n\Delta t_i+\arg(B_{jkn})+\phi(n\Delta)\}\right| \tag{5.10}$$

In equation (5.10) the terms B_{jkn} represent the n^{th} of M complex Fourier components obtained from the magnetic flux density waveform $B_{jk}(t_i,\mathbf{r}_j)$ for field component k at point $\mathbf{r}_j$ for time t_i, Δ is the corresponding frequency increment and $N\Delta\geq1$ Hz (the lower limit for the evaluation). The parameters $\phi(n\Delta)$ are the phase angles of the filter function, which vary according to the frequency dependence of the particular reference level. The filter phase angles are specified (see Appendix to [23]) as π, π/2, 0 and −π/2 radians where the frequency dependence of the reference level varies as f^{-2}, f^{-1}, f^{0} and f, respectively. The magnetic field reference level $B_{RL}(n\Delta)$, which is specified as an RMS value in [22]–[24], is multiplied by √2 in equation (5.10) in order to derive the corresponding peak field limit for comparison with the magnitudes of the spectral components.

Results for the position $\mathbf{r}_j$ giving the values of highest instantaneous value of the exposure measure $ME(t_i,\mathbf{r}_j)$ would provide a conservative estimate for the exposure risk in non-uniform field environments.

Instruments such as the Narda ELT-400 [56] implement this scheme using a three-axis field probe and selectable filters that approximate the frequency dependence of the field reference levels for the desired evaluation regime (e.g. ICNIRP occupational, ICNIRP general public etc.). This allows an exposure quantity to be derived that is expressed as a percentage of the selected reference level. In practical systems some deviation from the piecewise linear reference levels is unavoidable in the vicinity of those frequencies where the frequency dependence of the reference level changes, but errors of up to 3 dB in attenuation and up to π/2 radians in phase are indicated as acceptable in [23].

The summations for multiple frequency exposure relating to electro-stimulation start at 1 Hz in [22]–[24] and [55]. However, there are reference levels and basic restrictions defined for magnetic field, but not for electric field, at frequencies below 1 Hz. Thus, the assessment of exposures that include magnetic field components at frequencies below 1 Hz is not entirely clear.

5.3 Spatially Non-uniform Field Exposures

The field reference levels assume a uniform exposure over the entire body, which is unlikely to be the case for the in-vehicle environment. The spatial distribution of fields in the passenger compartment of a vehicle is expected to be highly non-uniform due to factors such as proximity of the sources and complexity of the environment. Thus, results for the position $\mathbf{r}_j$ giving the values of highest instantaneous value of the exposure measure $ME(t_i,\mathbf{r}_j)$ over the regions associated with the bodies of the occupants would provide at least provide a conservative estimate for the exposure risk.

However, it is noted in [22] that the field reference levels "*are intended to be spatially averaged values over the entire body of the exposed individual, but with the important proviso that the basic restrictions on localized exposure are not exceeded*". Similar comments are also found in [24], although neither [22] nor [24] provide any suggestions concerning acceptable levels of non-uniformity. Thus, the use of spatially averaged field values to describe non-uniform, non-localized exposures is anticipated in the exposure guidelines, but ICNIRP consider [23] that it is "*the task of standardization bodies to give further guidance on the specific exposure situations where the spatial averaging can be applied*".

Furthermore, the field reference levels have only been derived for models of standing humans in a uniform field in an open environment, whereas in a car the occupants are seated and surrounded by complex structures that are in very close proximity and are generally metallic, with the sources of exposure in relatively close proximity. It is also suggested by ICNIRP [23] that "*The standardization bodies also may derive new reference levels for special types of non-uniform exposure*". Thus, the in-vehicle environment seems a prime candidate for this.

5.4 Parts of the Body in Scope

In ICNIRP 1998 [22] there are three basic restrictions relating to tissue heating effects for the frequency band 100 kHz to 10 GHz. These include maximum local SAR in the head and trunk, maximum local SAR in the limbs, and whole body average SAR. However, this document specified only a single set of basic restrictions relating to electro-stimulation effects (1 Hz to 10 MHz), in terms of induced current density in the head and trunk, with the aim of protecting the CNS (brain and spinal column).

However, ICNIRP 2010 [23] defines two sets of basic restrictions relating to electro-stimulation (which are also now specified in terms of induced internal electric field rather than current density). The first restriction relates to the CNS tissue of the head, while the second encompasses all tissues of the head and body (although in fact the values only differ for frequencies below 3 KHz, for both occupational and general public exposure classes). The implication of this change is that, for the band 1 Hz to 10 MHz, there is also a need to consider exposure of the limbs and extremities, and therefore the field environment that the feet and legs are exposed to in vehicles, not just the head and trunk regions. This would be equally true if considering general public exposure, as ICNIRP 2010 defines basic restrictions for all body tissues for both occupational and general public exposure classes.

In the proposed text (COM(2011)348 [26]) for the occupational field exposure directive 2004/40/EC [25] the description is less clear, but similar. In Annex II (for fields up to 100 kHz) two sets of exposure limits (i.e. basic restrictions) are also defined, relating to "safety effects" and for "health effects". This document also states that "*The exposure limit value for safety effects is derived from the effect threshold for effects on the central nervous system in the head (CNS)*", and that "*The exposure limit value for health effects is derived from the effect threshold for effects on the peripheral nervous system (PNS) and it also prevents stimulation of nerve fibres in the central nervous system*". The implication of these comments is that the exposure limit for safety effects applies only to the brain and spinal column in the head, and that the exposure limit for health effects applies to the rest of the body (i.e. including the limbs, which form part of the PNS). Consequently, the COM(2011)348 position is in fact very similar to that of ICNIRP 2010.

Furthermore, COM(2011)348 Annex II describes two types of reference level for evaluating the exposure environment (field in the absence of the worker); "action values" and "orientation values". These are defined as follows:

- "*The "orientation value" referred to in point (f) of paragraph 1 corresponds to a field level where no adverse health effect should be noticed under normal working conditions and for persons not being part of a group at particular risk. As a consequence, the depth of the risk assessment procedure can be reduced to a minimum. Compliance with the orientation value will ensure compliance with the relevant exposure limit values for safety and health effects.*"
- "*The "action value" referred to in point (f) of paragraph 1 corresponds to the maximum directly measurable field for which automatic compliance with the exposure limit value is guaranteed. Any exposure level between the "orientation value" and the "action value" requires more extensive evaluations and preventive measures. Compliance with the action value will ensure compliance with the relevant exposure limit values for health effects.*"

Thus, the orientation value appears to be a reference level relating to the exposure limit value for safety effects (so applicable to the CNS in the head), while the action values appears to be a reference level relating to the exposure limit value for health effects (so applicable to the PNS, and hence the rest of the body). This is not found in ICNIRP 2010, where there is only a single set of field reference levels for each of the exposure classes (either occupational or general public).

The orientation levels of COM(2011)348 Annex II for magnetic field are the same as the occupational reference levels of ICNIRP 2010 for frequencies up to 20 kHz, beyond which there are some differences. However, the justification for these differences and the origin of the (rather higher) action levels are not detailed in COM(2011)348.

5.5 Active Implantable Medical Devices

Active implantable medical devices are devices that rely on a power source not provided by the body or gravity and are designed to be introduced into the body with the intention to remain there following the procedure. Examples include cardiac pacemakers, cochlear implants, neural and other stimulators, implantable infusion pumps and defibrillators and their accessories. The use of such devices is becoming increasingly common, and is not necessarily limited to the aged and infirm.

These devices are regulated by a Directive 90/385/EEC [57], which also references the general EMC Directive (currently 2004/108/EC [58]).

The EU Recommendation for general public exposure to electromagnetic fields [24] (see article 13) includes the following statement regarding active implantable medical devices:

> *"Adherence to the recommended restrictions and reference levels should provide a high level of protection as regards the established health effects that may result from exposure to electromagnetic fields but such adherence may not necessarily avoid interference problems with, or effects on the functioning of, medical devices such as metallic prostheses, cardiac pacemakers and defibrillators, cochlear implants and other implants; interference problems with pacemakers may occur at levels below the recommended reference levels and should therefore be the object of appropriate precautions which, however, are not within the scope of this recommendation and are dealt with in the context of legislation on electromagnetic compatibility and medical devices."*

Similar observations are also made in COM(2011)348 [26], which is unsurprising given that the action and orientation levels are much higher than the general public reference levels of 1999/519/EC [24].

Thus, compliance with field exposure reference levels cannot be assumed to ensure that active implantable medical devices will continue to function, even at the lower exposure levels recommended for the general public. The EMC requirements for these devices are specified in the EN 45502 series of standards. Electronic article surveillance systems and metal detectors (hand-held and walkthrough) are reported to have interrupted the operation of such devices [59], as have power frequency fields [60]. Some walkthrough metal detectors employ sinusoidal fields operating at single or multiple frequencies ranging from 300 Hz to 8 kHz, while others use pulsed fields with components up to 70 kHz. Pulsed fields are reported to be a much more significant threat than sinusoidal fields in both [59] and [60].

At high frequencies it is not possible to compare the exposure reference levels with the immunity test specifications for active implantable devices. The immunity test levels are specified for devices to be tested outside the body, but the in-body fields are not readily related to the external field environment due to interactions between the electromagnetic field and the body tissues.

At low frequencies, however, the magnetic field in the body is essentially the same as the external magnetic field, since the magnetic permeability of body tissues is very close to that of free space and the conductivity is sufficiently low that the magnetic fields associated with the currents induced in the body tissues can be neglected. Consequently, in the low frequency range it is possible to directly compare the magnetic field immunity requirements for such devices with the corresponding magnetic field exposure reference levels.

6. Vehicle Traction Battery Charging

6.1 Wired Charging

The amendments to UNECE Regulation No. 10 adopted in 2012 [5] include requirements relating to the EMC performance of in-vehicle charging equipment for RESS and their associated coupling systems that are not present in the Automotive EMC Directive. These tests involve application of IEC 61000-3-2 [61] and IEC 61000-3-12 [62], plus other parts of the IEC 61000-3-X series in order to measure the effect of the charging system on the mains supply.

For radiofrequency conducted disturbances CISPR 16-2-1 is to be followed, classing the apparatus as floor standing equipment. The questionable aspect of the 20 dB quasi peak correction originating in CISPR 12 is also re-quoted here.

The immunity requirements identified in the proposed amendments to UNECE Regulation No. 10 relating to on-board conductively-coupled electrical charging systems comprise the following:

- Immunity to low frequency disturbances conducted along AC and DC power lines:
    - electrical fast transient and burst;
    - surges.
- Immunity to high frequency radiated disturbances, 20 MHz to 2000 MHz.

The emissions requirements identified in the proposed amendments to UNECE Regulation No. 10 relating to on-board conductively-coupled electrical charging systems comprise the following:

- Low frequency conducted disturbances on AC power lines from the vehicle:
    - emission of harmonics;
    - emission of voltage changes, voltage fluctuations and flicker.
- Radiofrequency conducted disturbances, 150 kHz to 30 MHz
    - on AC or DC power lines from the vehicle;
    - on network and telecommunication access from vehicles.
- Radiated broadband electromagnetic fields, 30 MHz to 1000 MHz.

Radiated emissions is covered in Annex 4 of Regulation 10, but it would appear that no limits are suggested for less than 30MHz, the area of particular interest to FEVs, and the 20 dB quasi-peak correction is still present.

It is reported [37] that the draft 7th Edition of CISPR 12 proposes requirements for the following additional measurements for the charging mode of electric and plug-in hybrid vehicles, if the charger is part of the vehicle:

- conducted emission according to CISPR 14-1 in the frequency range 150 kHz to 30 MHz;
- radiated emission to be added in CISPR 12.

6.2 Wireless Charging

Work on the IEC standard for electric vehicle inductive charging systems (IEC 61980) appears to have been dormant from 2000 to 2010, presumably due to lack of interest in the industry (e.g. the California Air Resources Board decided to adopt a conductive charging interface in June 2001). More recent activity (in September 2010) resulted in draft of IEC 61980-1 [63], which described general requirements and included a chapter on EMC, but this remains unpublished at committee draft stage. The planned subsequent parts of IEC-61980 (61980-2 and 61980-3) were originally intended to be concerned with requirements for manually inserted "paddle" systems of the type described in SAE 1773 [64]. In this scheme the paddle is directly connected via a cable to the external electrical supply, and manually inserted into a charge port on the vehicle with coupling to the on-board systems achieved using a very short range inductive system rather than a direct conductive connection.

However, increasing interest in wireless charging of electric vehicles (e.g. [65]) appears to have caused a change of direction for IEC 61980, as the proposed titles for the various parts are now as follows:

- IEC61980-1: "Electric equipment for the supply of energy to electric road vehicles using an inductive coupling - Part 1: General requirements" (approved new work).
- IEC 61980-2: "Electric vehicle wireless power transfer (WPT) systems – Specific requirements for communication between electric road vehicle (EV) and infrastructure with respect to wireless power transfer (WPT) systems" (potential new work item [66]).
- IEC 61980-3: "Electric vehicle wireless power transfer (WPT) systems – Specific requirements for the magnetic field power transfer systems" (potential new work item [67]).

The SAE have also established a taskforce on wireless charging and vehicle positioning (SAE J2954 [68]). The aim is to establish minimum performance and safety criteria for wireless charging of electric and plug-in vehicles, and develop a common approach for multiple technologies (inductive, magnetic resonance, etc.). However, this document is not yet available.

6.2.1 Requirements of IEC 61980-1

The scope of the current draft of IEC 61980-1 [63] is equipment for the inductive transfer of electric power from the supply network to the electric vehicle for purposes of charging the on-vehicle energy store and/or maintaining other on-vehicle electrical systems in an operational state when connected to the supply network, at standard AC supply voltages up to 690 V.

The immunity requirements of IEC 61980-1 comprise the following:

- Low frequency conducted disturbances:
  - supply voltage harmonics (off-board inductive charging equipment directly powered by the AC supply network shall withstand the voltage harmonics of the main supply, generally caused by other non-linear loads connected to the network);

  - supply voltage dips and interruptions (off-board inductive charging equipment directly powered by the AC supply network shall withstand the voltage dips and interruptions of the main supply, generally caused by faults on the network);
  - voltage imbalance (off-board inductive charging equipment directly powered by the three-phase AC supply network shall withstand voltage imbalance of the main supply, requirements under consideration);
  - DC component (off-board inductive charging equipment directly powered by the AC network shall withstand the DC components generally caused by asymmetrical loads, requirements under consideration);
  - electrostatic discharge (the inductive charging system shall withstand electrostatic discharges with the charging systems operating at rated power and attached to a battery load).
- Immunity to high frequency conducted disturbances:
  - fast transient bursts (off-board inductive charging equipment directly powered by the AC supply network shall withstand common mode conducted disturbances, generally caused by the switching of small inductive loads, relay contacts bouncing, or switching of high voltage switch gear, for all power cables and on I/O signal and control cables, if any, normally connected to the EV supply equipment during charging);
  - voltage surges (off-board inductive charging equipment directly powered by the AC supply network shall withstand voltage surges, generally caused by switching phenomena in the power network, faults on the network or indirect lightning strikes, on all power cables).
  - immunity to radiated electromagnetic disturbances, 30–1000 MHz (the inductive charging system shall withstand radiated electromagnetic field exposure, with charging system operating at rated power and attached to a battery load).

The emissions requirements of IEC 61980-1 include:

- Low frequency conducted (input current distortion caused by operation of the inductive charging system when connected to the AC supply network shall not be excessive).
- High frequency conducted disturbances:
  - AC supply network input connections (conducted disturbances generated by the inductive charging system at the connections to the AC supply network);
  - signal I/O and control connections (conducted disturbances generated at the signal I/O and control connections of the inductive charging system).
- Radiated electromagnetic fields:
  - electric fields, 30 MHz to 1000 MHz (radiated disturbances by the inductive charging system at 10 m distance, measured under operating modes determined to cause worst case emissions);
  - magnetic fields (25 kHz to 30 MHz).

The last of these is actually concerned with human exposure issues, as well as possible fire risks associated with inductive heating of combustible debris that may be beneath the vehicle, rather than with EMC performance.

6.2.2 EMC standards relevant to IEC 61980-1

6.2.2.1 Emissions

Inductive Module
In IEC-61980-1 the limits for radiated and conducted high frequency emissions are referenced to CISPR 14-1 (equivalent to EN 55014-1 [69]), which relates to household appliances, electric tools and similar apparatus. However, the scope of EN 55014-1 is "*the conduction and the radiation of radio-frequency disturbances from appliances whose main functions are performed by motors and switching or regulating devices, unless the RF energy is intentionally generated or intended for illumination*". So although EN 55014-1 may be appropriate for conductive charging systems, where any radio-frequency emission is unintended, inductive charging systems, where radio-frequency emissions are intentionally generated, do not appear to be within the scope of EN 55014-1. The reference to a household appliance standard also suggests that IEC 61980-1 may have been developed assuming the only applications to be low-power domestic installations.

The core of the inductive charging system is an off-board coil that is energised at frequencies in the range 20–100 kHz in order to transfer energy to the vehicle via an on-board coil. The list of harmonised standards [70] for the general purpose EMC Directive 2004/108/EC [71] includes EN 55011 [72], which "*applies to industrial, scientific and medical electrical equipment operating in the frequency range 0 Hz to 400 GHz and to domestic and similar appliances designed to generate and/or use locally radio-frequency energy*". An inductively coupled electric vehicle charging system is therefore within the scope of EN 55011 as it generates and makes local use of radio-frequency energy (over a distance of a few inches). Furthermore, this standard provides emissions requirements relating to radio-frequency disturbances for frequencies in the range 9 kHz to 400 GHz, which also encompasses the anticipated resonant frequencies of inductively coupled electric vehicle charging systems.

Equipment within the scope of EN 55011 is classified in terms of two groups. Group 2 contains "*equipment in which radio-frequency energy is intentionally generated and used or only used, in the form of electromagnetic radiation, inductive and/or capacitive coupling, for the treatment of material or inspection/analysis purposes*". Examples of Group 2 equipment include dielectric heating equipment, microwave lighting apparatus, microwave ovens, electric welding equipment, industrial induction heating equipment operating at frequencies above 9 kHz, induction cookers and electro-discharge machining equipment.

Group 1 contains all equipment falling within the scope of the standard that is not classified as Group 2. Examples include scientific and laboratory equipment, semi-conductor rectifiers and inverters, industrial process measurement and control equipment, machine tools and industrial electro-heating equipment operating at frequencies below 9 kHz. In terms of EN 55011, therefore, induction chargers would be classified as Group 1 as their functions do not include inspection/analysis or treatment of material.

Equipment in Groups 1 and 2 is further categorized as either Class A ("*suitable for use in all establishments other than domestic and those directly connected to a low voltage power supply network which supplies buildings used for domestic purposes*") or Class B ("*suitable for use in domestic establishments and in establishments directly connected to a low voltage power supply network which supplies buildings used for domestic purposes*"). Different emissions limits are provided for the various group/class combinations. It should also be noted that while Class A equipment may be measured either on a qualified test site or in situ, Class B equipment must be measured on a qualified test site. Different limits are specified for Class A equipment depending on whether the test is carried out on a test site or in situ.

If the inductively coupled electric vehicle charging equipment is considered to be a fixed installation, requiring measurement in situ, it would have to be Class A. For Group 1, radiated emissions limits are specified down to 30 MHz and conducted emissions limits (mains terminal disturbances) are specified down to 150 kHz.

Radiated emissions limits for frequencies below 30 MHz are absent from EN 55011 for Group 1 equipment (and from EN 55014-1, referenced by IEC 61980-1). However, the list of harmonised standards for 1999/5/EC (see [17]) includes EN 300 330-2 [73], which is stated to have the same scope as ETSI EN 300 330-1 [74] and therefore applies to the following short range devices:

- generic short range devices including transmitters operating in the range from 9 kHz to 25 MHz;
- inductive loop transmitters operating from 9 kHz to 30 MHz including radio frequency identification (RFID) and electronic article surveillance (EAS) equipment;
- receivers operating from 9 kHz to 30 MHz.

The emissions requirements of EN 300 330-2 are also stated to be the same as EN 300 330-1, which include radiated magnetic field limits from 9 kHz to 30 MHz measured at a distance of 10 m (correction factors are also provided to allow for measurements at 3 m and 30 m distances). At 9 kHz the 10 m limit is 5 nT, falling to 96.4 pT at 148.5 kHz, for measurements made on a qualified test site.

In EN 55011 it is noted that the frequency bands 10–14 kHz and 90–110 kHz are allocated to safety-related radio services (radio-navigation). However, EN 300 330-1 identifies the range 9 kHz to 5 MHz as designated for short range inductive devices of generic use.

The inductive charging system could be considered as having some similarities with other emissions sources that are found in the road environment, such as trams and their roadside power supply infrastructure. Emission limits for trams operating in city streets (as well as for railways and substations) are detailed in EN-50121-2 [75] for frequencies from 9 kHz to 1 GHz. In the band 9–150 kHz the magnetic field limits at 10 m from city tram tracks (or from a substation boundary) fall with increasing frequency from 397.4 pT at 9 kHz down to 22.4 pT at 150 kHz.

The low frequency radiated emission limits of EN-50121-2 are therefore lower than those of EN 300 330-1, which probably reflects the fact that the EN 50121-2 measurements have to be carried out in situ. Thus, these limits are probably a better alternative for the electric vehicle inductive charging system, which is considered to be a fixed installation and will need to be measured in situ for radiated emissions.

Power supply
The EN 61000-3 series provides limits for lower frequency conducted emissions phenomena that are relevant power networks, depending on the input current levels for the system. These include harmonic currents (EN 61000-3-2 [61] if the input current is ≤16 A per phase, EN 61000-3-12 [62] if the input current is >16 A ≤75 A per phase), as well as voltage changes and fluctuations, and flicker (EN 61000-3-3 [76] if the input current is ≤16 A per phase, EN 61000-3-11 [77] if the input current is >16 A and ≤75 A per phase). These standards are approved under both 2004/108/EC (see [71]) and 1999/5/EC (see [17]), and are also referenced by the RESS amendments recently introduced in UNECE Regulation No. 10 [5].

In IEC 61980-1 the power supply emissions limits only reference EN 61000-3-2, which again suggests that IEC 61980-1 has been developed assuming the only applications to be low-power domestic installations.

Vehicle equipment (if vehicle not immobilised during charging)
If the vehicle is not immobilised during charging then the on-board equipment is required to comply with Directive 1999/5/EC (which would be covered by EN 300 330-1 as discussed above) and the emissions requirements of Directive 2004/104/EC (essentially emissions in the band 30–1000 MHz). The 2004/104/EC requirements are described in EN 50498 [78].

Radio-communications
For the communications element of the system, suitable standards for use in demonstrating compliance with Directive 1999/5/EC should be selected from the list in [17], depending on the particular technology that is used.

6.2.2.2 Immunity
Threats to be protected against at the system boundaries (described as the “enclosure port”) include electrostatic discharge (ESD), power frequency magnetic fields (if used in a high field environment) and radiated electromagnetic fields. As the on-board equipment forms part of the system during charging it is also required to comply with 2004/108/EC [70] and to withstand the same enclosure port threats.

As EN 55011 does not specify immunity limits, suitable generic immunity standards from should be applied. In IEC 61980-1 the radiated immunity requirements are referenced to EN 61000-4-3 [79], with limits based on the generic immunity standard for industrial environments EN-61000-6-2 [80]. The recent RESS amendments to UNECE Regulation No. 10 [5] also reference EN 61000-6-2. These requirements should ensure that the inductive charging system can be successfully operated in a very wide range of environments. Operation in the residential, commercial and light industry would not be covered unless EN 61000-6-1[81] and EN 61000-6-3 [82] were also considered.

Conducted threats at cable connections (e.g. at the "AC power port") include voltage dips and interruptions, electrical fast transients and bursts, surges (including the effect of indirect lightning strikes) and conducted radio frequency disturbances. Tests for these phenomena are detailed in the EN 61000-4 series of standards. Guidance on the applicability of the various parts of this standard is given in EN 61000-4-1 [83]. The EN 61000-4 series of standards are also referenced in IEC 61980-1 for conducted immunity. The proposed amendments to UNECE Regulation No. 10 also reference EN 61000-4-4 [84] and EN 61000-4-5[85].

6.2.3 Limitations of IEC 61980-1

If the charging takes place dynamically then the on-board charging system would also need to comply with UNECE Regulation 10. However, the radiated emissions requirements of the latter for ESAs intended for subsequent fitting to vehicles do not consider frequencies below 30 MHz. Consequently, the SAE recommended practice J551-5 [41], which suggests emissions limits for frequencies in the band 150 kHz to 30 MHz for electric vehicles, could be a beneficial addition for dynamic vehicle charging applications.

In addition, the immunity requirements for vehicles and associated electrical sub-assemblies are only specified for the band 20–2000 MHz in UNECE Regulation 10, so there is no legal obligation for immunity testing of vehicles or their sub-systems at lower frequencies. Nonetheless, many vehicle manufacturers do chose to test at frequencies outside the 20–2000 MHz band, as well as to higher field strengths than those specified in UNECE Regulation 10. For example, the in-house component and subsystem EMC specification of Jaguar Land Rover [14] includes tests for immunity to magnetic fields at frequencies from 50 Hz to 100 kHz for electronic modules that may have sensitivity to magnetic fields. This is intended to protect against off-board threats such as power lines, as well as on-board threats including charging systems and pulse-width modulated sources. The limits identified in this document over the band of frequencies interest for inductive charging are 8.9 μT for the band 1–10 kHz, falling thereafter with increasing frequency to reach 0.89 μT at 100 kHz. However, published data regarding the Wampfler IPT system [86] indicates magnetic field levels from a rail type system of the order of 100 μT in the vicinity of a vehicle floor (for system operating frequencies reported to be in the range 15-20 kHz). Thus, vehicle immunity to the magnetic fields generated by the inductive charger is a potential concern if the vehicle is not immobilised during the charging process.

7. Conclusions

This document has presented a review of the applicability of current EMC standards and EMF recommendations to FEVs. Concentrating mainly on UNECE Regulation 10, the various aspects of emission and immunity testing, limits and requirements have been analysed from the point of view of an electrically powered vehicle.

7.1 EMC

The current situation regarding automotive EMC standards is lacking in test limits and methodology to fully account for the different electromagnetic environment generated by an FEV. A summary of the gaps identified is given in Appendix A. UNECE Regulation 10 makes reference to immunity and emissions measurements when the vehicle is in a charging state, but component EMC and whole vehicle testing are less well covered. The testing standards that UNECE calls upon (CISPR 12, CISPR 25 and ISO 11452) still do not fully reflect the particular features of electric powertrain. Although the versions of CISPR 12 that are referenced by the Automotive EMC Directive and UNECE Regulation 10 are different, both include specific requirements for measuring emissions from the electrical powertrain. However, further adaptations involving the way the vehicle is operated during a whole vehicle test will need to be applied, due to the differing characteristics of the electric powertrain; some possibilities are suggested in section 3.1.1.

Component level EMC is also currently aimed at internal combustion engines, with UNECE Regulation 10 referencing the 2nd Edition (2002 plus 2004 corrigendum [42]) version of CISPR 25. There is a currently a 3rd Edition available and a 4th Edition under development. The 4th Edition of CISPR 25 may need more adaptation to cope with electric propulsion systems, due to the fact that the emissions are highly influenced by the load on the systems. One consideration when testing electric propulsion systems is that the physical size of the system may be much larger than those previously encountered in existing internal combustion vehicles. This becomes apparent when specifying the ground plane, originally designed to test physically small systems. Another consideration is the construction of the vehicle body, which may not be adequately represented by a copper or steel ground plane in the case of a vehicle with a composite bodyshell.

Amendments to UNECE Regulation 10 adopted in 2012 [5] include EMC requirements for RESS when using a wired charging system; these additions are not present in the Automotive EMC Directive [4], but this will be replaced by UNECE Regulation 10 from 1st November 2014 for EC WVTA [9]. Work is on-going into the EMC of wireless charging systems, as the focus up until recently has been directed largely at wired conductive approaches. As wireless charging is a popular emerging technology, addition of EMC aspects to regulations for wireless charging will be essential. Electric vehicles are currently under represented in the EMC standards that relate to vehicles. In house standards are often more detailed, but the official standards (i.e. CISPR, BS, ISO and EN) are lacking in information, test methodology and emission limits. As part of the HEMIS project it is hoped that some of the gaps present in the existing standards can be closed, and that this will result in a more robust base to ensure EMC across the full electric vehicle range.

7.2 EMF

Regarding human exposure to electromagnetic fields, although there are generic recommendations that ought to be taken into account, there are currently no relevant product standards that specify how to measure in-vehicle field levels and interpret the results in terms of the recommended exposure limits. Consequently, the development of an IEC standard relating to the measurement of low frequency magnetic fields generated by electronic and electrical equipment in the automotive environment with respect to human exposure has recently been proposed [87]. For wireless inductive charging systems, however, methods for assessing electromagnetic field exposure will be required for both vehicle occupants and bystanders.

The latter could perhaps be derived from an existing standard such as EN 62369 [88], which is concerned with short range devices operating in the band 0–300 GHz, and therefore more closely reflects the characteristics of inductive charging application than the generic exposure standard EN 62311 [89]. The measurement and calculation methods described in EN 62369 are referenced by EN 50364 [90], which is listed as a harmonised standard for the Directives 1999/5/EC [16] and 2006/95/EC [19]. The exposure conditions covered by EN 62369 are normally associated with non-uniform spatial field distributions and often with a very rapid reduction of field strength with distance. Consequently, it describes methods for deriving an average exposure value based on field measurements obtained over a grid based around the torso or head of a standard person (of height 1.75 m) for typical source positions, including in-floor sources.

7.3 Influence on emerging standards.

As can be seen by inspection of the gap analysis table in Appendix A, there are some issues that are not yet addressed with the current standards. This document (D5.1) is the first in a suite of documents that will be produced by the HEMIS project. The remaining documents will involve test methods (D5.2), simulation of in-vehicle EMF (D5.3) and limits and mitigation techniques (D5.4). This suite of documents could be used as a valuable resource for either manufacturers looking to apply EMC and EMF considerations beyond the standards that are lacking, and also could be used to inform future versions of the standards discussed here. Updates to Regulation 10 could benefit from the filling of the gaps identified here. Methods for the testing that can be applied to standards updates will be presented in D5.2. It is hoped that the development of new or improved test methods will be carried out during D5.2, and that these new or improved test methods will be applicable to future versions of the relevant standards. The same applies for D5.3 and the gaps in the EMF standards. D5.4 will establish limits and mitigation techniques, which could be incorporated into emerging standards. The limits will have had sound scientific backing with the tests and simulation presented within WP 5 and so it is hoped that the work package as a whole can influence changes to or indeed new versions of automotive EMC standards.

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Appendix A: EMC Gap Analysis Table

<table>
<tr><th rowspan="2">Task</th><th colspan="3">Emissions</th><th colspan="3">Immunity</th></tr>
<tr><th>Standard</th><th>Gaps</th><th>Future standards[1]</th><th>Standard</th><th>Gaps</th><th>Future Standards</th></tr>
<tr><td rowspan="5">Whole vehicle EMC testing</td><td rowspan="5">UNECE Regulation 10 Calls CISPR 12</td><td>Height scanning</td><td>Not addressed</td><td rowspan="5">UNECE Regulation 10 Calls ISO 11451</td><td rowspan="5">Pulse criteria for conducted disturbances Regulation 10 only relate to 12 V and 24 V vehicles</td><td rowspan="5">Further development of UNECE Regulation 10 likely to keep pace with FEV immunity</td></tr>
<tr><td>Receive antenna location</td><td>Amendments to CISPR 12 (7th Edition)</td></tr>
<tr><td>Questionable 20dB correction factor for Quasi-peak measurements</td><td>Not addressed, but test labs are avoiding use.</td></tr>
<tr><td>Vehicle operating mode</td><td>Not fully addressed – some requirements for FEVs in later issues of CISPR 12</td></tr>
<tr><td>Low frequency emissions (below 30MHz)</td><td>SAE J551-5 for 150kHz to 30MHz</td></tr>
</table>

[1] Only changes to standards are mentioned here, for further research that may inform standards please see the body of the text.

<table>
<tr><th rowspan="2">Task</th><th colspan="3">Emissions</th><th colspan="3">Immunity</th></tr>
<tr><th>Standard</th><th>Gaps</th><th>Future standards[1]</th><th>Standard</th><th>Gaps</th><th>Future Standards</th></tr>
<tr><td rowspan="10">Testing of ESAs/ Components</td><td rowspan="10">UNECE Regulation 10 Calls CISPR 25 (2002)</td><td>UNECE Regulation 10 does not call latest version</td><td>UNECE Regulation 10 needs updating to reflect advances in CISPR 25 – currently (2013) 4th Edition under development</td><td rowspan="10">UNECE Regulation 10 Calls ISO11542-X Series</td><td>Choice of test procedures can lead to manufacturers picking ‘easier’ tests with lower limits</td><td>Not addressed</td></tr>
<tr><td>Load influence on emission levels</td><td>4th Edition of CISPR 25 should be adapted</td><td>Test methods in different parts of ISO 11452 are not equivalent</td><td>Not addressed</td></tr>
<tr><td rowspan="3">Instrumentation tailored to combustion engines</td><td rowspan="3">Not addressed</td><td>Use of vertical polarisation only</td><td>Not addressed</td></tr>
<tr><td>Size of the Ground plane used: FEV RESS and powertrain packages potentially very large</td><td>Not addressed</td></tr>
<tr><td rowspan="6">Ground plane materials – not necessarily representative of composite bodyshell</td><td rowspan="6">Not addressed</td></tr>
<tr><td>Load simulator not defined for traction package</td><td>Not addressed</td></tr>
<tr><td>AN definition not applicable to high voltage networks</td><td>Not addressed</td></tr>
<tr><td>Loading of FEV drive</td><td>Not addressed</td></tr>
<tr><td>No radiated emission limits below 30MHz</td><td>Not addressed</td></tr>
<tr><td>Cable harness arrangement for traction package</td><td>Not addressed</td></tr>
</table>

Task	Emissions			Immunity		
	Standard	Gaps	Future standards[1]	Standard	Gaps	Future Standards
Testing of wired charging systems	UNECE Regulation 10 calls IEC61000-3 series and CISPR 16	20dB quasi peak correction	Not addressed	Proposed Amendments to UNECE Regulation 10		
		Low frequency radiated emission limits not present below 30MHz	CISPR 12 7th Edition extending down to 150kHz			
Testing of wireless charging systems	No consideration in current standards	No consideration in current standards	Updated versions of IEC61980-1, IEC61980-2 and IEC61980-3	No consideration in current standards	No consideration in current standards	Updated versions of IEC61980-1, IEC61980-2 and IEC61980-3