ELECTRICAL POWERTRAIN HEALTH MONITORING FOR INCREASED SAFETY OF FEVs

DELIVERABLE D5.4–1.0

EMC Measurements and testing for FEVs

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Partner Contributions

Partner	Contribution
Y-EMC	Sections 1-4, 6-7
MIRA	Sections 2, 3, 5, 7
CEIT	Document reviewer and comments

Executive Summary

This document is a public deliverable (D5.4) of the HEMIS project. It deals in detail with the gaps in the measurement standards, the steps being done to address the gaps by the standards bodies and also provides details of additional testing that can be carried out to fill the gaps detected and previously summarized in the deliverable D5.1. It should be noted that the only additional test equipment which is required are new Artificial Networks (AN) for testing high voltage DC networks, no other additional test equipment is required to be developed to fill these gaps (existing equipment is suitable) but rather the gaps relate to frequency ranges over which testing is carried out and the number of positions at which radiated fields are measured.

It should also be noted that some of the gaps in current standards (e.g. lack of height scanning in radiated emissions testing of vehicles) do not only relate to fully electric vehicles, but also to those with an internal combustion engine. As such a summary of the main points in D5.1 has been included in this document.

Measurement results obtained as part of the HEMIS project (see D5.2 and D5.5) show that high magnetic field can be measured close to the electric powertrain. The fields take the form of low frequency radiated emissions and are generally narrow band in nature. The fields fall off rapidly with distance, and the measured field depends greatly on the cable layout. Again, suitable test equipment (3 axis field probes) already exists although the limit levels may need updating.

Contents

Acronyms

AC	Alternating Current
AN	Artificial Network
ALSE	Absorber Lined Shielded Enclosure
CEIT	Centro de Estudios e Investigaciones Técnicas
DC	Direct Current
FEV	Fully Electric Vehicle
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Field
ESA	Electrical/electronic Sub-Assembly
EUT	Equipment Under Test
FM	Frequency Modulated
HEMIS	Electrical Powertrain **He**alth **M**onitoring for **I**ncreased **S**afety of FEVs
HV	High Voltage
ICNIRP	International Commission for Non-Ionizing Radiation Protection
IEC	International Electro-technical Commission
ICE	Internal Combustion Engine
MIRA	Motor Industry Research Association
OATS	Open Area Test Site
PHMS	Prognostic Health Monitoring System
RPM	Revolutions Per Minute
RFRESS	Radio Frequency Rechargeable Energy Storage System
SAE	Society of Automotive Engineers
UK	United Kingdom
UNECE	United Nations Economic Commission for Europe
Y-EMC	York EMC Services

1. Introduction

Electromagnetic compatibility (EMC) measurements on road vehicles originate from a time when the main threat posed by radio-frequency noise from vehicles was interference to broadcast transmissions. This interference resulted primarily 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. Changes in the technologies employed in the electrification of the vehicle powertrain, in particular, raises questions as to whether the existing test methods remain appropriate for modern vehicles. The HEMIS deliverable D5.1 [1] highlighted some issues with the current set of automotive EMC standards, such as the poor treatment of low frequency electric and magnetic fields, and the lack of consideration of human electromagnetic field exposure (except for intentional transmitters). The objective of this deliverable is to recommend additional EMC tests for the vehicles with electrical powertrains.

1.1 Discussion of measured results

Measurements (reported in D5.2 [2]) made on a 75kW electric powertrain show that high magnetic fields can be generated at the motor drive frequency (and harmonics). These emissions are narrow band and the levels generated are dependent on the speed and load on the motor. The emissions relate to both human safety (levels higher than the ICNIRP guidelines were recorded) and the EMC of the overall vehicle. Due to the source type and the frequencies involved, the emissions are predominantly magnetic and fall very rapidly with distance from the source (mostly power cables connecting the motor to the controller). The rate of fall-off will depend on the cable layout. High levels relating to safety were observed at the frequencies related to the motor speed and are unlikely to be observed at frequencies higher than 1 kHz. This is below current radiated emission test frequencies and is unlikely to cause a problem to radio communications which are generally protected by radiated emissions requirements, as these frequencies are not generally used for such services and the field falls very rapidly with distance from the source. The main problem will be the internal compatibility of the vehicle in which the electric drive train is mounted, although it is possible that there may be some issues relating to road side equipment such as vehicle detectors at light controlled junctions.

2. Electromagnetic field

Regarding human exposure to electromagnetic fields (EMFs), although there are generic recommendations that ought to be taken into account, there are currently no relevant product standards that specify how to measure automotive field levels and interpret the results in terms of the recommended exposure limits. There is generic standard for the assessment of human exposure to electromagnetic fields [69], but this is not sufficiently representative of the special features of the automotive environment. Similar issues also affect other applications, which have already resulted in the development of specific standards for particular environments, such as the railways.

The standard for assessing human exposure in the railway environment [73] requires measurements at points located 1.5 m above the standing area in the vicinity of railway tracks, at distances of 0 m from the track axis for trams, 3 m for urban transport, and 10 m for main lines. On railway platforms, measurements are also specified at heights of 0.9 m and 1.5 m at a distance of 0.3 m from the edge. The required height probably reflects the fact that the basic restrictions of the ICNIRP 1998 guidelines [15] were focussed on the central nervous system (i.e. head and spinal column). Within public areas of rolling stock, measurements are specified at heights of 0.3 m, 0.9 m and 1.5 m above the floor in accessible areas. The 0.3 m height is presumably intended to represent children, as it is not used for areas that are only accessible to workers. For cars, however, the sources are likely to be much closer to the occupants than in the railway environment.

The results of simulation-based investigations of the relationship between the basic restrictions and magnetic field exposures that are representative of those that might arise from traction current paths in vehicles with electrical powertrain are presented in HEMIS Deliverable D5.5 [3]. Based on these results, it is considered that the field reference levels recommended in [15] and [17] may provide a more reliable source of magnetic field exposure limits for the automotive environment than the more recent recommendations from ICNIRP [16].

2.1 Field Reference Levels

The exposure limits identified in [15]–[18] 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 [15], [17]–[18]. More recently, induced internal electric field has been proposed as the low frequency measure [16]. 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 [15]–[18], 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.

Note that as the high fields from an electric vehicle are generated at the motor drive frequencies and its harmonics and are generated by the high currents (so are therefore magnetic), reference to electric fields and higher frequencies are removed from the discussions that follow.

2.1.1 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 [15]–[18] 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 (see below).

2.1.1.1 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 [15]–[17]).

In the recent ICNIRP statement concerning fields in the range 1 Hz to 100 kHz [16] the field levels are required to meet the following criteria:

$$\sum_{f_i = 1\text{ Hz}}^{10\text{ MHz}} \frac{H_{RMS}(f_i)}{H_{RL}(f_i)} \le 1 \qquad (2.1)$$

where $H_{RMS}(f_i)$ is the net RMS magnetic field strengths (respectively) at frequency f_i in the exposure environment, and $H_{RL}(f_i)$ represents the relevant field reference level (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 [15]–[17] 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 [17] are slightly different to equation (3.1), as they still reflect the original ICNIRP 1998 statements [15]:

$$\sum_{f_i = 1\text{ Hz}}^{150\text{ kHz}} \frac{H_{RMS}(f_i)}{H_{GP}(f_i)} + \sum_{f_i \ge 150\text{ kHz}}^{10\text{ MHz}} \frac{H_{RMS}(f_i)}{b} \le 1 \qquad (2.2)$$

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 [17], and the constant b is equal to 5 A/m. In practise these two sets of equations come down to the same thing when there are no frequencies above 150 kHz present (as is expected for the electric drive train).

Thus, for assessing electro-stimulation risks for broadband exposures using [17], the fields are not simply compared with the reference levels detailed in the tables of [17], which are for specified for single frequency exposures only. The parameter b is used for broadband magnetic field exposure in the band 150–10 MHz.

As reference levels are also quoted for magnetic flux density in [15]–[17], the multiple frequency exposure criteria can also be adapted accordingly. Based on 1999/519/EC [17], the magnetic flux density criterion would be:

$$\sum_{f_i = 1\text{ Hz}}^{150\text{ kHz}} \frac{B_{RMS}(f_i)}{B_{GP}(f_i)} + \sum_{f_i \ge 150\text{ kHz}}^{10\text{ MHz}} \frac{B_{RMS}(f_i)}{e} \le 1 \qquad (2.3)$$

where the constant e, which is derived from b assuming free space permeability, is 6.25, for fields in µT [48].

Based on ICNIRP 2010 [16], the corresponding magnetic flux density criterion would be:

$$\sum_{f_i = 1\text{ Hz}}^{10\text{ MHz}} \frac{B_{RMS}(f_i)}{B_{RL}(f_i)} \le 1 \qquad (2.4)$$

The general public reference levels for magnetic flux density ICNIRP 2010 [16] are illustrated in Fig. 3.1, 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 [15] general public reference levels that are reflected in 1999/519/EC [17].

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 [47] that summing the measurement noise floor for a sufficiently large number of frequencies can result in criteria of the nature of equations (3.1)–(3.4) being exceeded. For these reasons, the "weighted-peak" approach described below is recommended for non-sinusoidal exposures, as this takes account of the relative phases of the frequency components. The EU occupational exposure directive [19] also makes reference to the weighted-peak approach for combined exposure to low frequencies, as well as to the simple summations described above for higher frequencies.

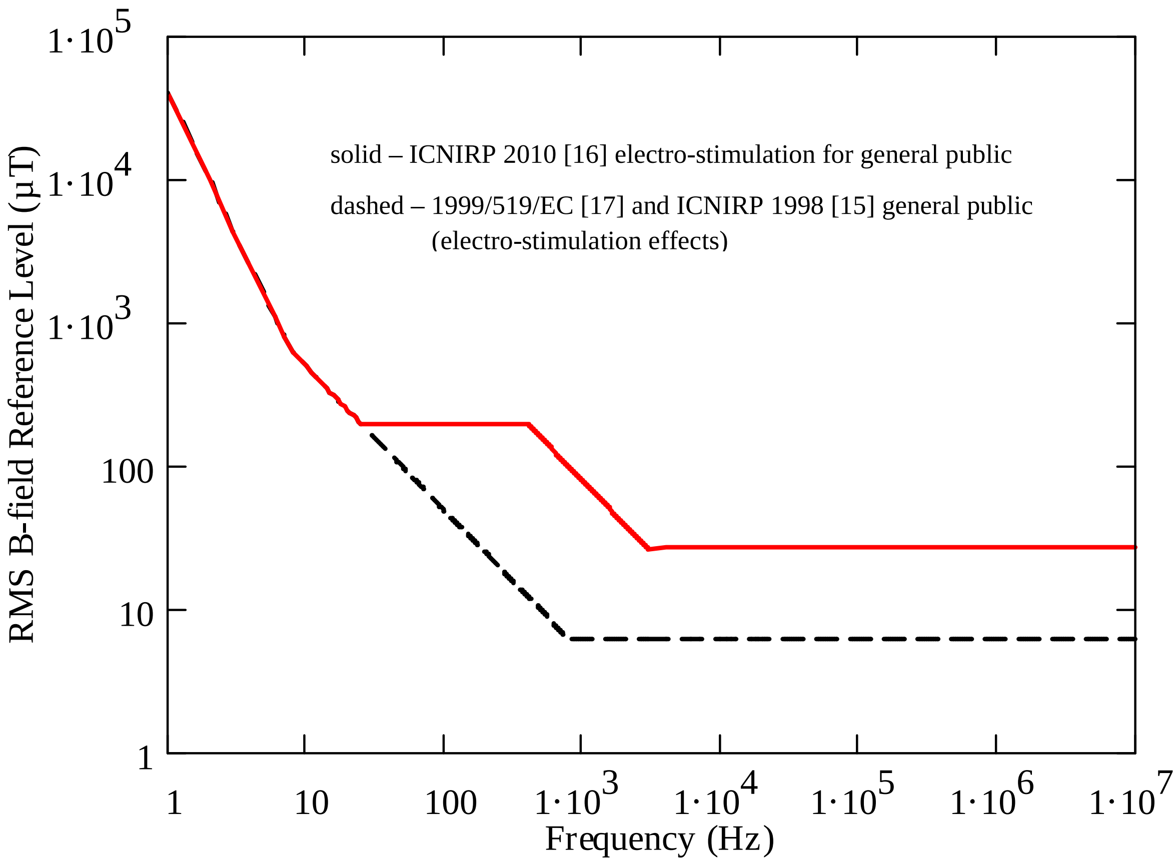

Fig. 2.1: Reference levels for RMS magnetic flux density to protect the general public against electro-stimulation effects due to broadband field exposures (1 Hz to 10 MHz)

2.1.1.2 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 ([16], [48]). In this "weighted-peak" approach 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 [16] and [48] 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:

$$ME(t_i,\mathbf{r}_j)=\sqrt{\sum_{k=1}^{3}\left[me_k(t_i,\mathbf{r}_j)\right]^2}\le 1 \quad (3.5)$$

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:

$$me_k(t_i,\mathbf{r}_j)=\left|\sum_{n=N}^{M/2}\frac{\left|B_{jkn}\right|}{\sqrt{2}B_{RL}(n\Delta)}\cos\left\{2\pi n\Delta t_i+\arg(B_{jkn})+\phi(n\Delta)\right\}\right| \quad (3.6)$$

In equation (3.6) 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 [16]) 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 [15]–[17], is multiplied by √2 in equation (3.6) 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 [49] 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 [16].

The summations for multiple frequency exposure relating to electro-stimulation start at 1 Hz in [15]–[17] and [48]. However, there are reference levels and basic restrictions defined for magnetic 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.

2.1.2 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 at least provide a conservative estimate for the exposure risk.

However, it is noted in [15] 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 [17], although neither [15] nor [17] 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 [16] 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 [16] 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.

2.2 Vehicle Magnetic Field Exposure

Limits on field levels recommended by ICNIRP ([15]–[16]) and the EU [17] at the frequencies of interest are set to avoid electro-stimulation. This is particularly important for the driver so it is recommended that the measurements are made at specific positions, not averaged over the volume of the body. For instance it will be necessary to carry out field measurements at the position of the control pedals (particularly if the cable connecting the controller to the motor is run close to this position) to ensure that unintended movement of the feet does not occur whilst the vehicle is in motion. This is particularly important as the magnetic fields measured for a representative drive train were found to be highest at high speed [1], when any unintended control input could have the most serious effect. It is also recommended that the measurements should not concentrate just on an adult of average height, but should also consider the threat to children and infants whose spinal cord and brain may be located closer to the source of the fields (i.e. traction current paths that could pass underneath the car body or behind the rear seats).

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 (IEC 62764-1, [67]) is under development and is expected to be published in March 2016. This scope of this document includes conventional internal combustion engine (ICE) vehicles, as well as those equipped with electrical powertrains. Although the proposed text is not available for general distribution, MIRA has seen and commented on the draft via the UK committee representative. The current version proposes a large number of test positions (up to 40 points inside the car), as well as measurements in both static and dynamic operating modes. The measurement points are not only within the passenger compartment (at points approximating the ankles, knees, seat, chest and head for adults in all occupant positions), but also in the engine bay and rear luggage space, as well as around the periphery of the vehicle (the latter at 0.2 m from the surface and 0.8 m above ground). Measurements at points near to the vehicle floor are at a height of 10 cm.

These requirements could lead to significant test durations. Using modelling of the magnetic fields within a vehicle it may be possible to recommend a reduced number of positions for these measurements to be made in a specific vehicle, but it is unlikely to be reduced to a single point due to the variation in positioning of the power cables and motors. The dynamic testing (over a range of speeds at 10 km/hr intervals up to the maximum speed, as well as under acceleration and deceleration conditions) is intended to ensure that maximum field levels can be observed. However, this requirement will make it difficult to measure the fields in the driver's position unless the vehicle can be run without a driver (but only with the vehicle on a dynamometer or with driven wheels off the floor). Note that the test scenario with the driven wheels off the floor is unlikely to provide the load conditions that are required to measure the highest fields.

The proposed frequency range of the magnetic field measurements is 1 Hz to 400 kHz. The suggested test environment should be at least 50 m from all external variable magnetic field sources (such as high-voltage transformers, power lines, electrical machines etc.) with ambient levels of no more than 5% of the selected field reference levels. During these measurements the seat and steering wheel adjustments are to be set at the mid-point of their travel except for the seat back inclination (where available), which should be set to the manufacturer's recommendation (typically 14°). For the measurements under dynamic conditions it is suggested that a dedicated test route should be defined.

A significant concern with the current IEC 62764-1 proposal is that transients with durations of less than 10 s are excluded from consideration, even though the use of a time-varying exposure measure that takes account of the relative phase of the spectral components is specified, as described in ICNIRP 2010 [16] for non-sinusoidal exposures. As the electro-stimulation phenomenon that these requirements are intended to protect against is an instantaneous effect, there is no scientific justification to modify the basic restrictions for exposures of short duration [17]. Even the railway standard EN50500 only permits transients of less than 1 s duration to be disregarded. However, the generic standard [69] has no such exclusions, and in fact recommends the use of an instrument with a peak-hold function specifically so that the risks from transients of less than 1 s duration can be evaluated.

The current draft of IEC 62764-1 also includes consideration of possible magnetic field exposure during charging, but only for wired traction battery charging systems. Measurements are indicated for the vicinity of the power inlet on the vehicle and along the cable. At present these are not fully detailed in terms of how to arrange the charging cable and exactly where to measure the magnetic field. Use of the charging cable arrangements described in UNECE Regulation 10 [6] for EMC testing of rechargeable energy storage systems (RESS) would allow the EMF measurements to be integrated more efficiently with the vehicle EMC tests. The transverse distance from the cable and power inlet could be 20 cm, as for the measurements around the car that are proposed in IEC 62764-1. Measurements at the same height as the cable will probably give the highest field levels, allowing the worst-case to be identified from scanning along the length of the cable, but for the vehicle power inlet the situation is less clear and a vertical scan may be required.

2.3 Wireless Inductive Charging Magnetic Field Exposure

Although wireless inductive charging may be used with inactive stationary vehicles, as with wired charging schemes, freedom from a wired connection also makes dynamic charging schemes possible. In some scenarios electric vehicles that are routinely stationary at specific locations, such as buses and taxis, could take advantage of regular periods of waiting time to recharge their batteries using primary coils embedded in the road at bus stops and taxi ranks. In South Korea, however, a scheme is already in operation in which buses recharge while driving by using primary coils that are stretched out into rails embedded in the road along significant portions of their route [54]. Thus, the driver and other occupants could be inside a vehicle during wireless charging of the traction batteries. Furthermore, there may be people in close proximity to such vehicles during the charging process, perhaps waiting to board a bus or taxi, or just passing by. Moreover, it is not unusual for sleeping children (for instance) to be left in a car for some time at the end of a journey, so this should be taken into account. For wireless inductive charging systems, therefore, methods for assessing electromagnetic field exposure will be required for both vehicle occupants and bystanders.

The scope of IEC 62764-1 specifically excludes magnetic field exposure threats from wireless inductive charging of traction batteries, but an IEC standard specifically for wireless inductive charging systems is also currently under development (IEC 61980-1 Ed. 1.0, [74]) with a forecast publication date of December 2014. The contents of the current draft of this document are not known to any of the HEMIS consortium members, but an earlier draft [53] did include a requirement for magnetic fields at frequencies from 25 kHz to 30 MHz to comply with the ICNIRP guidelines in the passenger compartment, as well as in the region beyond the vehicle footprint, although no standards for this were referenced. Consequently, it is expected that the new draft of IEC 61980 will also include consideration of these issues.

The standard EN 62369 [68] 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 [69]. The measurement and calculation methods described in EN 62369 are referenced by EN 50364 [70], which is listed as a harmonised standard for the Directives 1999/5/EC [10] and 2006/95/EC [12]. 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. Nonetheless, the field distributions from such devices are expected to be relatively uniform in the vicinity of the head and torso of exposed individuals. 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.

The restriction of measurements to the head and torso in EN 62369 probably reflects the fact that the basic restrictions of the ICNIRP 1998 guidelines [15] were focussed on the central nervous system (head and spinal column). However, as the more recent ICNIRP 2010 guidelines [16] also include basic restrictions for the peripheral nervous system, there is a case for extending the scope of the field exposure evaluation to encompass the limbs as well. Furthermore, children may also be exposed to magnetic fields from wireless inductive charging systems, and as they are not of adult height and could also be seated in a push-chair that places their head and torso even closer to ground level they could experience higher levels of exposure than adults on account of their closer proximity to the power transmission region between the primary coil mounted in the surface of the road and the secondary coil mounted on the underside of the vehicle. Consequently, it is recommended that the measured region should be extended to include regions below the torso of a standing 1.75 m adult, perhaps to within 10 cm of ground level. A 10 cm offset from the floor should allow sufficient space for field transducers to be positioned for the measurements. In addition, it is recommended that the maximum field value, rather than a spatial average, should be used to characterize the exposure due to the potentially close proximity of the source. Thus, a grid of measurement points, as outlined in EN 62369 for assessing average body exposure, is probably less appropriate for this application and could perhaps be better replaced with measurements at points that are representative of the expected closest approach to the source.

The magnetic field measurements will need to take into account that:

- the vehicle may not be positioned perfectly over the induction loop of the energy source and may be at different heights (depending on the type of vehicle), so there may be varying leakage of energy;
- the vehicle occupants will generally be seated, although in busses standing passengers may also be permitted in some areas.

Thus, the measurements should allow for possible misalignment tolerances and take account of the likely pose and position of the exposed individuals.

The Society of Automotive Engineers (SAE) have adopted a nominal operating frequency of 85 kHz for wireless inductive charging [75]. Consequently, the fundamental frequency should be assessed against the field reference levels for electro-stimulation. It should be noted, however, that any harmonics will exceed 100 kHz and will therefore need to be assessed against the field reference levels for both electro-stimulation and tissue heating (which are slightly different). As the charging source is sinusoidal the simple summations of in-phase frequency components described in [15]–[17] could be used to evaluate the additive effects of multiple frequency exposure. However, under dynamic charging conditions the exposure evaluation would also need to take account of the additive effects of the contributions from exposure to the lower frequency powertrain magnetic fields.

2.3.1 Within the vehicle

In a passenger car there are only a few seats so it is practicable to assess the exposure for each occupant location. For a bus, however, it would be impracticable to assess all occupant locations so it is proposed that a more restricted sample should be defined. It is recommended that the driver's seat should always be investigated, since the driver must maintain control while driving the vehicle. In a bus the passenger seat that is closest to the secondary coil, where the exposure to stray magnetic fields from the coils is likely to be highest, should also be investigated. Other areas that may need to be considered are those passenger locations that are in closest proximity to electrical energy storage devices (e.g. batteries, super-capacitors) and cables carrying traction currents.

The height of the torso grid for the seated positions would be defined by the seat surface, and its vertical axis aligned with the centre of the seat. For standing passenger locations, if any, it is suggested that measurements should be made at heights of 10 cm, 50 cm, 90 cm, 130 cm and 170 cm, thus allowing for small children who would experience higher levels of exposure than adults on account of their closer proximity to the magnetic field source. In this case the measurement locations should be chosen to reflect the standing passenger position that is closest to the secondary coil. For seated positions it is suggested that the measurement points should represent the ankles, knees, seat, chest and head for adults (as in the draft of IEC 62764-1).

2.3.2 Outside the vehicle

Since the magnetic field is expected to decay rapidly with distance it is probably sufficient to monitor positions that are representative of closest approach for bystanders. Bystanders may be exposed to fields generated by the inductive module during both static and dynamic charging. For systems with rail-like primary coils (providing charging while moving) there may even be the possibility that a child in a push-chair could be placed directly over energised rails while crossing the road behind a passing vehicle. Thus, it is also necessary to define measurement positions that reflect these exposure scenarios.

Two possible vehicle configurations could be that the secondary coil is located close to one corner of the vehicle, or on the axis of the vehicle but close to one end of the vehicle. In the latter case, it is proposed that measurements are made on the three sides of the vehicle that are closest to the secondary coil. For the former case, however, measurements could perhaps be limited to only the two sides that are adjacent to the corner that is closest to the secondary coil. A third possibility is that the coil is centrally located, in which case it is proposed that measurements should be carried out aligned with the midpoints on all four sides of the vehicle. For systems that are used in a dynamic mode with the vehicle in motion it is also recommended that the region behind the vehicle should also be investigated, even if the secondary coil is located closer to the front of the vehicle. For larger vehicles such as buses it may also be advisable to investigate the external magnetic field levels in the vicinity of electrical energy storage devices (e.g. batteries, super-capacitors) and cables carrying traction currents.

It is proposed that the external measurements should be made at heights of 10 cm, 50 cm, 90 cm, 130 cm and 170 cm, and that the separation between the measurement points and the vehicle boundary should be 20 cm (as for the measurements around the vehicle that are proposed in IEC 62764-1). The measurements on each side should be carried out aligned with the centre of the source, and also at other locations displaced to either side of the source centre for more extended sources (in order to give coverage of the source width). For a charging coil, for example, perhaps 15 measurement points could be used over a vertical plane on each side to be tested.

3. Whole Vehicle EMC

3.1 Emissions Measurement

Current vehicle-level radiated emissions test requirements [5]-[6] 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 [20], 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 [5]–[6], 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 [21]–[23]. Although this is also an issue for conventional vehicles, the potential for multi-motor architectures, range extenders including ICEs with no coupling to the mechanical transmission, 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 [8], which is referenced by the Automotive EMC Directive [5]. 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 [24], 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 [6]. Neither the Automotive EMC Directive nor UNECE Regulation 10 references the most recent edition of CISPR 12 [25]; 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 [27], 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 [26] 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 [28] mirrors CISPR 12, it is CISPR 12 that UNECE Regulation 10 refers to.

Amendments to UNECE Regulation 10 adopted in 2012 [6] also describe new radiated emissions test requirements relating to on-board conductively-coupled rechargeable electrical energy storage systems (RESS), which are outlined in section 5.1 of D5.1. Wireless inductive charging of vehicle traction batteries, which is currently of growing interest, is discussed later.

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 fully electric vehicles (FEVs [29]) also includes electric vehicles with range extenders, it is 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 necessarily be 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 inverter, if the inverter is located adjacent to the traction battery;
- on both sides of the vehicle, in line with the ICE, for vehicles equipped with this type of range extender.

Adopting this approach could therefore increase the number of points at which off-board emissions are measured, depending on the specific architecture of the electrical powertrain under test.

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 [30], could perhaps help to limit the potential for longer test time associated with these additional antenna positions. At the time of writing, however, there is no information on the IEC web pages regarding progress or a forecast publication date for the 7th Edition of CISPR 12.

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 [30] 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 [30] 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 [30] 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 and could also be speed dependent. In the standards that deal with EMC in the railway environment (the EN 50121-X series) a solution to this is partly achieved during the whole train emissions test (part 3-2 [76]) 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 [32] 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 [33] 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 [32] was carried out may make time constraints less of an issue.

In [32] 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 [33] 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 [33]. 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 [5] –[6].

If spark ignition is not present (i.e. vehicles that do not employ an ICE) then the quasi-peak detector is not required. The test requirements and limits could be adjusted to use peak and/or average detectors.

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. [32]). The American Society of Automotive Engineers (SAE) have published a Recommended Practice J551-5 (updated in 2012 [34]), 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 [36]. 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.

At the time of writing there is also work in progress to develop a new IEC standard for vehicle level emissions measurements below 30 MHz (IEC 62862, "Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurements of radiated field below 30 MHz"). . The forecast publication date for this is currently indicated as March 2016 [77], and the scope is likely to be similar to SAE J551-5.

SAE J551-5:2012

For radiated emissions, SAE J551-5 [34] 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 [5]:

(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 [5]–[6], and is expected to meet the functional failure criteria defined for the various immunity related functions. A minimum set of criteria are specified in [5]–[6], 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.

4. Component Level

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 [35]. However, there is currently a 3rd Edition [36], and a 4th Edition is currently under development [37], although the forecast publication date has passed and no further information is available at the time of writing. The 3rd Edition introduced the following significant changes with respect to the earlier edition [37]:

- 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 have been proposed for the 4th Edition include the following [30]:

- 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 [30] 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 adaptations 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 limits for electrical/electronic subassemblies (ESAs) 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 emission of the equipment under test (EUT). 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 [13]), the HV network is isolated from the vehicle chassis, and the power cables are often shielded. Investigation of these issues [38] suggests that a new HV AN design is required for reliable conducted emissions testing on electric powertrain components. A set of AN for HV applications that claim compliance with the requirements of the (as yet unpublished) 4th Edition of CISPR 25 are already being marketed [78].

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 (unlike at the EMF frequencies) maximum load may not necessarily generate the highest emissions. This is because at these frequencies the rate of change of voltage and current are the generating mechanism and there may be less switching within the inverter at high loads.

It is noted in [39] 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. It is recommended that the cable configuration in component level emissions tests should be arranged to reflect the intended vehicle installation as closely as is practicable.

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 [40], 11452-3 [41], 11452-4 [42] or 11452-5 [43], 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 in 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, where horizontal polarisation is also required.

ISO standard 7637-2 [44] 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. 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 networks, whereas traction power networks for vehicles with electrical powertrains may operate at much higher voltages.

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 all 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 [40] and BCI [42], 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 [45], 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 [46].

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 always attempt to simulate the actual installation in the vehicle, in which case the equipment should be grounded if that is intended to be the case in the vehicle. This also raises questions as to body ground definition in a vehicle with a composite bodyshell. It is recommended that the grounding arrangements in component level tests should be as representative as is practicable of the grounding conditions that will be implemented in the intended vehicle installation.

5. Traction Battery Charging Systems

Charging of automotive traction batteries from an external electrical power supply may be achieved by either wired or wireless power transfer methods. The latter is currently the subject of much interest, for various reasons. As wireless power transfer avoids the need to connect a cable between the vehicle and the external power supply it is more convenient for the user and avoids potential vandalism threats at public charging stations. Furthermore, the absence of a cable also allows dynamic charging schemes, rather than just static approaches, to be considered.

The on-board elements of such charging systems are considered (see Low Voltage Directive Working Party statement [14]) to be within the vehicle type approval framework [1], and therefore subject to automotive EMC requirements. Although the amendments to UNECE Regulation No. 10 adopted in 2012 [6] include requirements relating to the EMC performance of in-vehicle charging equipment for RESS and their associated coupling systems, these requirements only relate to wired charging systems. However, work on requirements for wireless charging systems is being carried out by the IEC [55]–[56] and SAE [57].

5.1 Wired battery charging

The tests specified in UNECE Regulation 10 involve application of IEC 61000-3-2 [51] and IEC 61000-3-12 [52], 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 [79] 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.
- Radio frequency 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 [30] 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 [80] in the frequency range 150 kHz to 30 MHz;
- radiated emission to be added in CISPR 12.

It is also recommended that off-board radiated emissions measurements at frequencies below 30 MHz, based on SAE J5515 [34] requirements, should also be carried out.

5.2 Wireless battery charging

The standard IEC 61980 was originally intended to address wired battery charging systems. However, increasing interest in wireless charging of electric vehicles (e.g. [54]) appears to have caused a change of direction for IEC 61980, as the proposed titles for the various parts are now as follows:

- IEC 61980-1: “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 [55]).
- IEC 61980-3: “Electric vehicle wireless power transfer (WPT) systems – Specific requirements for the magnetic field power transfer systems” (potential new work item [56]).

The SAE have also established a taskforce on wireless charging and vehicle positioning (SAE J2954 [57]). 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 publicly available.

In the absence of any specific standards, or prior knowledge of proposed requirements for emerging standards, suggestions are made below for EMC testing of the three main elements of a wireless battery charging system. These are the off-board power supply, the on-board control and charging equipment, and a communications link to initiate the charging process and optimise vehicle positioning relative to the primary coil.

5.2.1 Off-board power supply

The roadside and in-road elements of the inductive charging system fall within the scope of the general EMC Directive 2004/108/EC [50], as there is no relevant specific directive, and are considered as fixed installations in this context. Nonetheless, it would not be possible to test such a system without a vehicle being charged, so the vehicle under charge also becomes part of the fixed installation.

Suggested immunity tests are listed in Table 5.1, based on the measurement methods described in the EN 61000-4 series. Appropriate limits for the immunity tests are taken from EN 61000-6-2 [64] (generic immunity standard for industrial environments), in order to allow for use in a wide range of operating environments.

Port	Description	Standard/Test specification	Limits/Comments
Enclosure (off-board equipment)	Electrostatic discharge	EN 61000-4-2 [82]	EN 61000-6-2 [64], Table 1
	Radiated EM field	EN 61000-4-3 [63]	EN 61000-6-2, Table 1 (In suitable absorber-lined shielded room)
	50/60 Hz magnetic field	EN 61000-4-8	
AC power	Electrical fast transient/burst	EN 61000-4-4 [65]	EN 61000-6-2, Table 4
	Surge	EN 61000-4-5 [66]	
	Conducted disturbance induced by RF fields	EN 61000-4-6 [83]	
	Voltage dips/interruptions	EN 61000-4-11 [84]	EN 61000-6-2, Table 4 (If input current is ≤16 A per phase)
	Voltage dips/interruptions	EN 61000-4-34 [85]	EN 61000-6-2, Table 4 (If input current is >16 A per phase)
Signal data	Electrical fast transient/burst	EN 61000-4-4	EN 61000-6-2, Table 2
	Surge	EN 61000-4-5	
	Conducted disturbance induced by RF fields	EN 61000-4-6	
Earth	Electrical fast transient/burst	EN 61000-4-4	EN 61000-6-2, Table 4
	Surge	EN 61000-4-5	
	Conducted disturbance induced by RF fields	EN 61000-4-6	

Table 5.1: Immunity test requirements for off-board power supply

Suggested emissions tests are listed in Table 5.2, based on the EN 61000-3 series and EN 55011 [58], which is applicable to "industrial scientific and medical 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". In Table 5.2 it is assumed that the radiated emissions can be measured using qualified test sites, but EN 55011 does not specify radiated emissions limits below 30 MHz in this case. Thus, a low frequency radiated magnetic field test based on EN 50121-2 [59], which gives limits for in situ measurement of emissions from trams and rail/tram sub-stations, is also recommended. However, in situ measurements may be unavoidable for some systems. Although EN 55011 specifies limits down to 150 kHz for in situ measurements, the Class C limits of EN 50121-2 are acceptable for urban trams.

Port	Description	Standard/Test specification	Limits/Comments
Enclosure (including vehicle)	Radiated EM field (30–1000 MHz)	EN 55011 [58]	EN 55011 Group 1 - limits appropriate to class (A or B)(Highest values at 10 m on test site)
	Radiated magnetic field (9 kHz to 30 MHz)	EN 50121-2 [59]	EN 50121-2 Class C vehicle limits (Highest values at 10 m)
AC power	Harmonic currents in low-voltage power supply systems for equipment with rated current ≤16 A	EN 61000-3-2 [51]	EN 61000-3-2 (If input current is ≤16 A per phase)
	Harmonic currents in low-voltage power supply systems for equipment with rated current >16 A and ≤75 A	EN 61000-3-12 [52]	EN 61000-3-12 (If input current is >16 A and ≤75 A per phase)
	Voltage fluctuations and flicker in low-voltage power supply systems for equipment with rated current ≤16 A	EN 61000-3-3 [60]	EN 61000-3-3 (If input current is ≤16 A per phase)
	Voltage fluctuations and flicker in low-voltage power supply systems for equipment with rated current ≤75 A	EN 61000-3-11 [61]	EN 61000-3-11 (If input current is >16 A and ≤75 A per phase)
	Conducted RF (0.15-30 MHz)	EN 55011	EN 55011 Group 1 - limits appropriate to class (A or B)

Table 5.2: Emissions test requirements for off-board power supply

In EN 55011, equipment in Groups 1 and 2 (which is based on application) 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.

5.2.1.1 On-board control and charging system

For original equipment, supplied with the vehicle, the on-board control and charging system would be subject to UNECE Regulation 10 requirements. Aftermarket equipment that is mechanically fastened to the vehicle, cannot be removed without tools, and is not restricted by technical means to use on an immobilised vehicle should be tested to EN 50498 [62], which details the appropriate sub-set of 2004/104/EC [5] test requirements (the same as UNECE Regulation 10 [6]). The relevant immunity requirements are detailed in Table 5.3, while Table 5.4 lists the emissions requirements.

Port	Description	Standard/Test specification	Limits/Comments
Supply lines and other connections	Immunity to conducted transient test pulses 1, 2a, 2b, 3a, 3b and 4 of ISO 7637-2	ISO 7637-2 [44]	ISO 7637-2 (Immunity test level III)

Table 5.3: Immunity test requirements for on-board control and charging system

Port	Description	Standard/Test specification	Limits/Comments
Sub-system enclosure	Broadband radiated field (30-1000 MHz)	UNECE Regulation 10 [6]	UNECE Regulation 10
	Narrowband radiated field (30-1000 MHz)		
Supply lines	Conducted transient disturbances (maximum pulse amplitude)	UNECE Regulation 10	UNECE Regulation 10 (Only specified for 12V and 24 V systems)

Table 5.4: Emissions test requirements for on-board control and charging system

For vehicles fitted with tyres, the vehicle body/chassis can be considered to be an electrically isolated structure. Significant electrostatic forces in relation to the vehicle's external environment only occur at the moment of occupant entry into or exit from the vehicle. As the vehicle is stationary at these moments, no type-approval test for electrostatic discharge is deemed necessary. Vehicle installations or ESAs that do not include an electronic oscillator with an operating frequency greater than 9 kHz are deemed to comply with the requirements on narrowband emissions.

It is assumed that emissions from the on-board equipment during charging, for either static or dynamic schemes, would be covered by Table 5.2. Methods for measuring emissions from moving vehicles during dynamic charging could be based on the method described for moving trains and similar vehicles (i.e. trams and trolleybuses) in EN 50121-2 [59] and EN50121-3-1 [31]. The latter specifies measurements for both stationary and slow moving vehicles. In particular, speeds of 20±5 km/hr are specified for urban vehicles. A quasi-peak detector is used for the static emissions measurements, but this would be too slow (of the order of 1 s per frequency) for measurements on a moving vehicle. Consequently, a different approach is described in [31] and [59], using receiving equipment that is operated in a swept frequency measurement mode using a peak detector with a “max-hold” function implemented. This may require the band of interest to be split into a number of sub-bands for separate evaluation. The peak limits for these dynamic measurements are set 10 dB higher than the quasi-peak limits for the static measurements. The railway standards also provide limits for the frequency band 9 kHz to 30 MHz, which is not addressed in [5]–[6].

5.2.1.2 Communications link

For the communications element of the system, suitable standards for use in demonstrating compliance with Directive 1999/5/EC [10] should be selected from the list in [11], depending on the particular technology that is used.

6. Automotive EMC Conclusions

The current situation regarding automotive EMC standards is a lack of 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 Table 1, which is repeated from deliverable 5.1 with additional comments.

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 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; some possibilities are suggested in section 3.1.2.2.

Component level EMC is also currently aimed at internal combustion engines, with UNECE Regulation 10 referencing the 2nd Edition (2002 plus 2004 corrigendum [35]) 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 body shell (although this is not FEV specific).

Amendments to UNECE Regulation 10 adopted in 2012 [6] include EMC requirements for RESS when using a wired charging system; these additions are not present in the Automotive EMC Directive 7, but this will be replaced by UNECE Regulation 10 from 1st November 2014 for EC whole-vehicle type approval [7]. 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. IEC and EN) are lacking in information, test methodology and emission limits. Some of these are expected to be addressed by newly emerging standards and future revisions of existing standards. In the meantime, however, alternative test procedures that may be suitable to address some of the current limitations have been suggested.

ISO 11452-8:2007 [86] specifies methods of testing and suggested levels for immunity to magnetic fields at frequencies from 15 Hz to 150 kHz. It should be noted that the ICNIRP 2010 [16] limits for magnetic fields to which the public should be subjected to are higher than the level 1 and 2 immunity limits specified in this standard up to approximately 700 Hz and are higher than the level 4 immunity levels specified above approximately 7 kHz. The highest magnetic fields will exist at the drive frequency of the motor and are likely to be at frequencies less than 100 Hz, although may be higher depending on the motor type being used. It is therefore possible that the magnetic fields within the vehicle, close to the power cables and motor, will be higher than those levels currently specified for immunity testing even when the magnetic fields are low enough to comply with the ICNIRP 2010 EMF limits. It should be considered whether the immunity test limits need to be increased in this frequency range as the fields could exist over a considerable period of time, not allowing potential problems to clear themselves.

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 (for component level immunity) 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 [13]). Nonetheless, the only difference introduced in UNECE Regulation 10 so far in relation to electric vehicles [6] is a requirement for an additional vehicle immunity test mode in which the on-board RESS is charged from an external electrical supply.

Table 6.1: Gaps in existing EMC Standards relating to FEV

<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>comment</th><th>Standard</th><th>Gaps</th><th>comment</th></tr>
<tr><td rowspan="4">Whole vehicle EMC testing</td><td rowspan="4">UNECE
Regulation 10
Calls CISPR 12</td><td>Height scanning

See section 3.1</td><td>To avoid measuring a minimum field caused by reflection of emissions from the ground plane, antenna height should be scanned</td><td rowspan="4">UNECE

Regulation 10

Calls ISO 11451</td><td rowspan="4">Pulse criteria for conducted disturbances Regulation 10 only relate to 12 V and 24 V vehicles

See section 5</td><td rowspan="4">Further development of UNECE Regulation 10 likely to keep pace with FEV immunity.</td></tr>
<tr><td>Receive antenna location

See section 3.1.2</td><td>Additional positions should be tested. Note that the emissions may not be symmetrical around the vehicle.</td></tr>
<tr><td>Questionable 20dB correction factor for quasi-peak measurements

See section 3.1.2.3</td><td>Without the spark ignition, the quasi-peak detector is not required, limits could be adjusted to peak and/or average only.</td></tr>
<tr><td>Vehicle operating mode

See section 3.1.1</td><td>Low frequency emissions are dependent on vehicle speed and load so a stationary or free-wheeling vehicle will not be a sufficient test.</td></tr>
</table>

Task	Emissions			Immunity		
	Standard	Gaps	comment	Standard	Gaps	comment
		Low frequency emissions (below 30MHz) See section 3.1.2.4	SAE J551-5 for 150kHz to 30MHz Future IEC 62862 for radiated emissions below 30 MHz			
Testing of ESAs/ Components	UNECE Regulation 10 Calls CISPR 25 (2002)	UNECE Regulation 10 does not call latest version See section 4.1	UNECE Regulation 10 needs updating to reflect advances in CISPR 25 – currently (2014) 4th Edition under development	UNECE Regulation 10 Calls ISO11452-X Series	Choice of test procedures can lead to manufacturers picking 'easier' tests with lower limits See section 4.2	Magnetic field levels in ISO11452-8:2007 should be examined and adjusted to suit EMF levels for human safety.
		Load influence on emission levels See section 4.1	Expected 4th Edition of CISPR 25 should be adapted		Test methods in different parts of ISO 11452 are not equivalent See section 4.2	Problem for all vehicle types
		Instrumentation tailored to combustion engines See section 4.1	Quasi-peak detector not required for electrical powertrain. Replace detector with peak or average detector and adjust limits accordingly. Quasi-peak detector still required if ICE is used as range extender.		Use of vertical polarisation only See section 4.2	Problem for all vehicle types
					Size of the Ground plane used: FEV RESS and powertrain packages potentially very large See section 4.3	Not addressed

Task	Emissions				Immunity		
	Standard	Gaps	comment		Standard	Gaps	comment
						Ground plane materials – not necessarily representative of composite bodyshell See section 4.3.2	Problem for all vehicle types
		Load simulator not defined for traction package	Motor needs loading to obtain higher levels of emissions.				
		AN definition not applicable to high voltage networks See section 4.1.1	Higher voltage AN required				
		Loading of FEV drive See section 4.1.2	Not addressed				
		No radiated emission limits below 30MHz See section 4.1.2	Not addressed, the installation of the unit in a vehicle is likely to reduce the radiated emissions.				
		Cable harness arrangement for traction package See section 4.1.2	Cables need to be laid out as they would be in the vehicle (ie with the same spacing)				

Task	Emissions			Immunity		
	Standard	Gaps	comment	Standard	Gaps	comment
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		In Annex 14 and 15 of Addendum 9 :2012 the only criterion for immunity of the vehicle to surges and transients when charging is theta vehicle does not move. There is no comment about damage to components or the unit stopping charging.
		Low frequency radiated emission limits not present below 30MHz	Future CISPR 12 7th Edition expected to extend down to 150kHz (conducted emission according to CISPR 14-1) for charging mode. SAE J551-5 for 150kHz to 30MHz Future IEC 62862 for radiated emissions below 30 MHz			
Testing of wireless charging systems	No consideration in current standards	No consideration in current standards See section 5.2	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 under development

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