Normative Framework for the Assessment of the Radiated Electromagnetic Emissions from Traction Power Supply and Rolling Stock

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Abstract—Radiated electromagnetic emissions from modern electric transportation systems are subject to requirements for their assessment aiming at a general compatibility with radio services. Standards known, recalled and enforced at contractual level narrow to CENELEC EN 50121 (equivalent to IEC 62236) and UMTA 85 and successive integrations. This work synthesizes similarities and differences for the methods and the required system operation, highlighting the areas where improvements are possible and opportune. Correct interpretation of narrowband and broadband phenomena, assignment of sweep time, statistical post processing and evaluation of site/setup uncertainty and repeatability are examples of considered issues that deserve more attention by the railway standardization bodies.

Keywords—Electromagnetic compatibility, Electromagnetic radiation, Electromagnetic transients, Measurement standards, Rail transportation, Repeatability, Reproducibility, Uncertainty.

I. INTRODUCTION

We may say that the main reference for the measurement of radiated electromagnetic emissions in the scope of electric transportation systems is the set of CENELEC standards, identified as EN 50121, equivalent to the IEC 62236 ones. Such standards cover both immunity and emissions, but the focus is on the latter, for which two standards are considered, the EN 50121-2 [1][2] and 50121-3-1 [3][4], applicable to emissions from the traction power supply system (line and substation) and to the rolling stock, respectively. The EN 50121 standards were delivered by the CENELEC more than 20 years ago (1996) to address several EMC problems of railway applications:

- electromagnetic emissions of the “whole system” and rolling stock alone to the outside world, thus covering disturbance to radio and TV services that occurred in the newly built systems of the ‘80s, such as high speed lines and tram lines with modern vehicles amid cities;

- similarly, equipment and components onboard and for signaling and telecom needed ad hoc test levels to cope with the severity of the electromagnetic environment (close to sources with intense emissions, first of all static converters) and the functional safety requirements.

As for today EN 50121 standards have undergone four revisions and that of 2017 (almost identical to the 2015 one) is the fifth edition. The second point (immunity testing) has been addressed and improved at each edition following updates of basic standards and the general progress in the identification and characterization of the relevant electromagnetic phenomena inside IEC and CENELEC. Conversely, electromagnetic emissions from the line and rolling stock discussed in the first point have not seen a similar progress regarding limits, definition of operating and measurement conditions, uncertainty requirements.

The second major reference is constituted by the Urban Mass Transport Association (UMTA) test procedures [5][6], backed up then by the technical specifications of the various contracts of local administrations [7][8] for the supply of rolling stock. Technically speaking, this set of specifications finds its ground in Holmstrom’s work and in the US military standards, namely the MIL-STD-461, now at rev. G [9].

With the increased number of electric transportation system projects (ranging from tramlines and LRTs, to metros, commuter and high-speed railways) serving densely populated city centers, and the widespread use of power conversion technology onboard and at substations, and the growth of radio services with manifold variants in terms of operating bands, protocols and levels of quality of service, the assessment of electromagnetic emissions needs procedures and guidelines that are comprehensive, complete and well grounded on technical rationales, harmonized with the knowledge base of standards and scientific literature. Low frequency magnetic emissions should be also considered, as discussed in sec. II.

The main issues are: i) due distinction of narrowband and broadband phenomena, ii) recognition of line resonances, iii) correct and aware management of transients, iv) (lack of) synchronization of vehicle acceleration and raking and frequency sweeps, and v) metrological characterization in terms of repeatability, reproducibility, uncertainty.

II. TEST AND MEASUREMENT SCENARIO

Electromagnetic emissions in the scope of standards EN 50121-2 [1][2] (emissions from traction power supply system) and EN 50121-3-1 [3][4] (emissions from rolling stock) were primarily put in relationship with the intermittent emissions of the electric arc at the pantograph, and in general power conversion, both at substations and on-board rolling stock. The attention is being focused on high frequency emissions in line with the other CENELEC and IEC standards for EMC of products, such as EN 55011 and EN 55022 (and recently EN 55032), considering phenomena in the MHz and GHz range.
The US administration released the UMTA standards in 1987 [5][6] with initial prescriptions for a 140 kHz – 400 MHz frequency range, with suggested expanded scope to cover between 13 kHz and 30 MHz with H-field limits and to extend the 400 MHz to 1 GHz. It is worth underlining that the UMTA 85-11 itself never gave indication of limits.

The UMTA standards were never updated since 1987 (a draft around 2000 was not applied), but extension of the frequency range down to 10 kHz and above up to 6 and 7.5 GHz has been considered and incorporated into contractual documents of local administrations [7][8]. It is observed that limits are all given in terms of electric field and the specified antenna below 30 MHz is indeed a rod antenna, although in the suggestion for expanded measurements in 1987 H-field measurements were considered. For the modern high-speed railway projects technical specifications point directly to the EN 50121 standards. Similarly, recognizing the peculiarity of the railway system, the measurement of emissions for the EN 50121 standards [1][3] covered the low frequency interval between 9 kHz and 30 MHz with a magnetic field measurement using a loop antenna on one axis (the horizontal axis, orthogonal to the line). The last two revisions of 2015 and 2017 [2][4] have the 9-150 kHz frequency interval removed.

It is known that emissions may radiate directly from the sources or indirectly coupled onto the catenary (or third rail), that radiates them quite efficiently as a long wire antenna. The EN 50121 recognizes this fact by the selected orientation of the loop antenna and stating that emissions at the measurement position may precede the train passage, propagating along the line. However, the 2007 version [1], sec. 5.1.6, said that the “majority of the emission is produced by the sliding contact if the train is moving”, that is not completely true if auxiliary converters onboard are also considered. However, it is recognized a significant impact on telecommunication bands by the electric arc for current collection [10][11], around which many of the preliminary study of the EN 50121 was focused.

A railway system is also a source first of all of magnetic field, related to the distribution and use of traction current through the catenary (or third rail). These emissions propagate at very long distance from the line and may be relevant for interference to scientific and medical equipment, such as geomagnetic, ultrasound and magnetic resonance systems. This was pictured in the paper [12] on the San Francisco Bay Area Rapid Transit (BART) system and the very low frequency magnetic field fluctuations visible at almost 80 km of distance with the geomagnetic equipment at the University of Berkeley. In general magnetic emissions encompass supply harmonics [13], especially for dc transit systems. It is believed that they have become more and more important, considering the increase of both installed power and traction current intensity, and of medical and scientific equipment sensitivity [14][15].

Measurement distances were evidently selected by the standards to cope with the large size of the source of emissions:

- the EN 50121-2 and -3-1 prescribe 10 m with the possibility of correcting the values for different distances with a table of coefficient values quantifying the expected path loss for different frequencies;
- the UMTA set two distances which two different limit curves belong to: 50 feet (15.2 m) and 100 feet (30.5 m).

For the instrumentation and the main measurement settings there is substantial agreement between the various standards, although some differences are substantial:

- antennas are well-known rod, loop, biconical and log-periodic antennas, with variants (horn antenna) and combinations (bi-log antenna); these antennas are well documented in the literature and CISPR standards;
- antenna orientation (or polarization): the EN 50121 requires both polarizations (vertical and horizontal) for the E-field, whereas the loop is standing vertical, with its plane parallel to the line; UMTA standard originally asked for vertical polarization up to 30 MHz, both polarizations for 30-200 MHz, and only horizontal polarization for 200-400 MHz, justifying it with the polarization of AM and FM radio signals;
- the detector is in general the Peak detector, no averaging or video filter allowed; the EN 50121-3-1, however, for stationary tests requires a Quasi-Peak detector, that, although in line with CISPR [16], does not allow a direct comparison with the results for dynamic tests;
- Resolution Bandwidth (RBW) values are taken from the CISPR 16 for the EN 50121, whereas the UMTA rely on the MIL-STD-461: they are 200 Hz (for the 9-150 kHz interval [1][3], optionally incremented to 1 kHz for a sweep speed exigency), 9 kHz and 120 kHz for the EN 50121, 10 and 100 kHz for the UMTA [5].

Both EN 50121 and UMTA agree on vehicle operation during tests to cover acceleration, coasting and braking conditions, although the EN 50121 is much more detailed on this, specifying speed and effort to apply for acceleration and braking. It is agreed that acceleration and braking shall be applied when passing in front of the antenna, but would be better saying “the measurement area in front of the antenna”, as in sec. III.A. The UMTA standard, however, does not consider measurements of emissions from the traction line as a whole.

The limits of US specs and EN 50121 are shown in Fig. 1, with EN 50121 values expressed in $\text{dB} \mu \text{V/m/MHz}$, E-field equivalent and 100 ft measurement distance.

![Fig. 1. Comparison of limits as E-field per MHz (far field calculation from H-field by applying +51.5 dB; linear with respect to RBW) at distance of 100 ft: EN 50121-3-1 dynamic Peak limits for railways (black), metros (blue), trams (violet); New York R211 limits (red); Los Angeles HR4000 limits (brown).](image-url)
III. OPERATING CONDITIONS AND MEASUREMENT PROCEDURES

The focus now is moved on elements such as line traffic, operating conditions and measurement methods and how they should be considered.

A. Vehicle as moving source

The vehicle is not a steady source, nor a point source, as long as the wavelength and the measuring distance are both comparable with its dimensions [20], even considering only emissions originating from pantograph and vehicle body, neglecting catenary contribution. While the vehicle is passing in front of the antenna, significant variations of the measured intensity may be observed.

Frequency sweeps are triggered with the rolling stock passage through the measurement area. For line emissions measurements are extended also to vehicle positions relatively far from the antenna. Dynamic conditions are also different and speed is generally faster: braking is required, but acceleration is not mentioned, focusing on nearly commercial speed cruising.

While the vehicle is moving, its distance from the measuring antenna changes: when the vehicle approaches the antenna, the distance reduces to the minimum distance $r^\ast$, that is the prescribed antenna-track distance; change of distance causes a slow amplitude modulation of the measured components. Assuming far-field conditions, the electric field intensity $E [\text{V/m}]$ is inversely proportional to distance $r [\text{m}]$; with an acceptable reduction of 1 or 3 dB, the corresponding distance may be easily determined:

$$E(r) = \frac{E_0}{r}, \quad E^\ast = E(r^\ast) \quad \delta E = \frac{E^\ast - E(r)}{E^\ast} = 1 - \frac{r^\ast}{r} \quad (1)$$

The -1 and -3 dB correspond to distance increase of 12 and 41%, corresponding to angles of 30° and 45°, defining the measurement area shown in Fig. 2. The intercepts define track points P1, P2 and Q1, Q2 that delimit the measurement area for train passage: the sweep is started when the vehicle passes past point “1” and the sweeping parameters adjusted so that the sweep has finished approximately when the vehicle leaves the measuring area after point “2”. The sweep over the frequency axis is combined with the time evolution of emissions as the vehicle changes its position and its distance from the measuring antenna. Since for the measurement of emissions the vehicle is either accelerating or braking in the area in front of the antenna, then its operating conditions are changing rapidly.

![Fig. 2. Scheme of the measurement area with vehicle passage points.](image)

Acknowledging a moving source, measurements are all taken with the Peak detector, by either sweep mode (advisable) or by just selecting a set of frequencies successively scanned by the Spectrum Analyzer (SA) or EMI Receiver to speed up the measurement. Alternative methods in time domain have been proposed, consisting of baseband sampling and data acquisition (e.g. a high performance oscilloscope) or using a Real Time Spectrum Analyzer (that samples on a conveniently large bandwidth after demodulation down to the IF frequency).

B. Environmental conditions

Low humidity and absence of condensation are required, possibly explained with the increase of the apparent soil conductivity and field propagation especially at high frequency: not only field attenuation is slightly larger, but also distribution between horizontally and vertically polarized components may change. It is however believed that there is no appreciable influence up to about 30 MHz. If, conversely, humidity on the catenary or third rail may alter the current collection and arcing dynamics, this was never considered in the literature to author’s knowledge. Ice and snow are of course a completely different problem and have a dramatic impact on emissions.

C. Traffic conditions, line loading and train composition

Traffic and line conditions shall be annotated, but “physically-remote but electrically-near” trains or vehicles of 2006 version are now, in 2015, considered an insignificant factor (sec. 5.4.3). However, there is still the recommendation in sec. 5.1.2 to measure emissions “for a sufficient duration before and after the vehicle passage”, since “the noise may not attain its maximum value as the traction vehicle passes the measuring point, but may occur when the vehicle is a long distance away.” Experience says that vehicle emissions are recognizable up to 1 km of distance, that roughly corresponds to the definition of physically-remote, but electrically-near train. Whether this change is in conjunction with the removal of the limit over the frequency interval A for very low frequency emissions below 150 kHz is not clear, although sec. A.9.3 hints in this sense.

Similarly, the required substation loading and number of trains on the line is a pre-condition that was removed in 2015: this means that tests as per EN 50121-2 are meaningful now with one train or vehicle only (and not a fully loaded line), and the substation load may be around 10-15% (by knowledge of typical sizing of the power supply and the level of exploitation under peak hour). But the EN 50121-2, sec. 5.1.3, still reads “A feature of railway substations is that the load can change widely in short times. Since emission can be related to load, the actual loading of the substation shall be noted during emission tests.”, that means nothing, besides raising a general concern about loose test conditions and unknown limit adjustment with respect to load.

For the train it is recognized that coupled vehicles may cause higher emissions (sec. A.10), but no decision is taken nor indication is given regarding the minimum test conditions.

These three points result in some confusion on whether the so-obtained measurement results are really representative of the system emissions in real conditions, and if the limits are suitably specified, now that from the 2006 to the 2015 version the overall loading has reduced by about a factor of 3 or more.
D. Rolling stock modes, driving style and synchronization

Tests in general reproduce the conditions of acceleration, cruising and braking. The EN 50121-3-1 requires acceleration and braking at 1/3 of the maximum intensity when passing in the measurement area. If the vehicle is capable of electric braking, tests in EN 50121-2 are required at “a brake power of at least 80% of the rated maximum brake power.” This condition may again be difficult to fulfill if the trains are not loaded and ballasted to ensure adhesion and stability; moreover, if the train is too light, intense braking decelerates too fast and the stopping distance is very short, in less time than that of a complete scan, with the train remaining significantly inside the measurement area. UMTA and US specs do not require any particular traction or braking effort, or cruise speed.

When measuring vehicle emissions with EN 50121-3-1, the synchronization between the frequency sweep and the vehicle passage affects the location of spectrum peaks captured by the sweep; the impulsive energy content of the broadband transient is distributed evenly over a large frequency interval and is captured with similar intensity for different frequency values; the appearance of higher spectrum components will depend on the sweep frequency when the transient has occurred. The result after a sweep will be the impression of a line resonance or a specific vehicle emission; only by carefully shifting the synchronization of the sweep and train passage with multiple test runs, it will be possible to check if a frequency shift of such peaks occurs. Conversely, traction line emissions with EN 50121-2 are not so closely related to rolling stock passage, since recordings are performed in more variable operating conditions and positions with respect to the measurement area.

The driving style has in any case a significant impact on the shape of the recorded emissions: the consideration on the use of max hold approach or statistical methods is again valid and advisable, provided that the sweep time is fast to have several sweeps for one train passage. To this aim the used of modern RF equipment operating in time domain is advisable.

Similarly, clarifying and agreeing the driving style and how acceleration and braking is applied is beneficial for repeatability.

E. Stationary conditions and background noise

Stationary conditions are useful to discriminate between the various sources of emissions, but are not strictly required for testing by all standards. They are usually put in relation to rolling stock tests (among others required by the EN 50121-3-1 using a QP detector), but should be equally applicable to the measurement of line emissions.

Background noise measurements are needed to identify external sources (EN 50121-2, sec. 5.1.12), but no criteria were given in the 2006 version to determine suitable margins with respect to limits, set to 6 dB in the 2015 version (frequencies with background noise intensity above the 6 dB threshold will be excluded from the successive evaluation). This 6 dB margin should be evaluated against measurement uncertainty, indicated in the EN 50121-2 (2006) as ±4 dB for instrumentation, recognizing also a repeatability in the order of 10 dB. It is clear that a 6 dB margin specification against an expected variability of 10 dB, without requiring repeated measurements and statistical assessment of the real data dispersion (see sec. IV.C), is a bit groundless.

Being the distribution and correlation of noise sources quite diversified, it is difficult to suggest a method (detector, time duration, post processing) that is effective and does not cause excessive exclusions for all sources.

It is apparent that for a meaningful comparison between background noise, stationary emissions and dynamic emissions the same measurement method should be used: the Peak detector is advisable, as proposed by UMTA [5][6] and MIL-STD-461 [9]. The difficulty is confirmed by sec. A.2 of EN 50121-2 (2015): “It appears difficult to establish an exact link between the values obtained with the peak and quasi-peak methods.”

F. Line resonances

Propagation of emissions along the traction line and radiation of conducted emissions is variable and depend on line resonances, where line impedance undergoes significant variations. This is particularly evident in the frequency interval one or few hundreds kHz, but the removal of interval A (9-150 kHz) from normative requirements impedes further analyzing. Two phenomena may be connected to line resonances: at low frequency attenuation is particularly low, so that emissions can be noticed when the train is still far from the measurement location (about hundreds m up to one km); field intensity at line resonance may be highly variable depending on antenna height and orientation, especially for third rail systems. In any case the identification of traction line resonances is due to fulfill the requirement appearing in sec. 5.1.9 and B.10 of EN 50121-2 (2006) (corresponding to sec. 5.1.2 and A.8 of the 2015 version) and sec. 6.3.1 in the EN 50121-3-1 (2006 and 2015).

The first paragraph of sec. 5.1.9 of EN 50121-2 states “if line resonance exists, this should be noted in the test report”. It is however extremely difficult to recognize a resonance and distinguish it from a peak of emissions, such as the switching frequency of some on-board converter: usually resonances have a lower factor of merit and most of all they move with train position, so that beginning the scan at different train positions may result in a peak shift.

As shown in Fig. 3, variability of the measured magnetic field as a function of distance clearly indicates the need of verifying the uniformity of the field distribution [17].

![Fig. 3. H field intensity at three distances d=4 m (solid black), 6 m (dotted black), 10 m (dashed black); height above ground h = 0.25 m.](image-url)
IV. INSTRUMENTS SETTINGS AND SPECTRAL CHARACTERIZATION

In this section the current required settings and related assumptions for the instrumentation are considered with respect to the impact on uncertainty, accuracy, and in particular verification of compliance to limits [18]-[21].

A. Limits and broadband/narrowband assumption

Limits, as anticipated, are expressed in dBμV/m for EN 50121 and dBμV/m/MHz for US specifications.

A signal may be classified as narrowband or broadband: it is “dependent on the signal's occupied frequency spectrum relative to the bandwidth (resolution bandwidth) of the measuring instrument” [22]. Then, to understand the effect of the resolution bandwidth, we shall further divide broadband signals into impulsive and random: the former are coherent signals with component amplitude that add in phase, so that a measuring bandwidth increase of 10 times results in a 20 dB increase of measured amplitude; random signals (e.g. white noise) are incoherent and additive in terms of power. This justifies expressing the measured values per MHz (frequency band normalization): a broadband impulsive signal assumption. However, for impulsive broadband signals the normalization should be done using the correct parameter, that is the “impulse bandwidth” B and not RBW: the latter corresponds to either a -3 or -6 dB IF filter bandwidth, and the former depending on the type of IF filter is in the range 1.2-2.0 times the RBW [23].

It shall also be underlined that repetitive impulsive signals (as caused by commutation transients and electric arc) will give different amplitude readings depending on the used RBW, compared to their Pulse Repetition Frequency (PRF), simply because larger RBWs will capture more and more spectrum lines resulting in an increased amplitude reading. Modern converters have switching frequencies of some or several kHz, across the mostly used RBW value, maximizing the sensitivity of results to this phenomenon.

So, the results may be quite different depending on the type of signal (transient, sinusoidal tone, modulated or not) and its repetition rate, and do not support a unique conversion factor between narrowband and broadband measurements. For this reason the MIL-STD-461 asked until its Rev. C for separate narrowband and broadband measurements, using different limits (the latter specified as dBμV/m/MHz).

B. Sweep time and resolution bandwidth

The first requisite stems from the known problem of the moving source: the sweep time must be fast enough to assume that the variation of train operating conditions and position are under control, and the distance from antenna is within the tolerance discussed in sec. III.A. Additionally, the sweep time shall suitably capture transient emissions, allowing plotting the spectrum of impulsive emissions by max hold mode and persistence [22][23]. Conversely, a minimum bound for the sweep time is represented by the selected RBW (and the transient response of the IF filter of the Spectrum Analyzer) and the number of points making a trace: the dwell time is the time spent for each point to quantify IF filter output; multiplied by the number of points in the trace Ns gives the total sweep time (with some approximation, so excluding other delays and operations performed by the SA) [24].

Required sweep time values for the three standard EN 50121-2, EN 50121-3-1 and MIL STD 461 are all different, although the dynamic measurements are all taken in Peak mode and at least for the first two the sources of emissions are the same, already discussed in sections I and II. Sweep time values are compared in Table I.

| Frequency Interval | Specification of each standard |
|--------------------|-------------------------------|
|                    | EN 50121-2 (Table 2)         | EN 50121-3-1 (Table B.1) | MIL STD 461G (Table II) |
| 0.15-30 MHz        | 300 ms / 60 kmph             | 37 ms / MHz              | 1.5 s / MHz             |
|                   | 60 ms / 300 kmph (overall freq. interval) | 0.2 ms / MHz | 0.15 s / MHz |
| 30-1000 MHz        |                               |                           |                          |

It is observed that CENELEC 50121 standards require a much faster sweep than MIL STD 461; from a general viewpoint for high vehicle speeds the already conservative sweep time values of EN 50121-3-1 should be reduced, increasing correspondingly the number of sub-intervals to comply with the 60 to 300 ms requirement that is applicable as sweep time value to the entire swept frequency interval. The EN 50121-2 does not make any attempt to clarify settings and assumptions, in that at sec. A.3 reads “Fields are measured (...) with peak detection within a short time window, 50 ms being recommended, at the selected frequency”; that is a cause of misunderstanding, indicating a 50 ms dwell time per frequency point, rather than a sweep time as in Table I, that is much faster. So, this 50 ms value is different, not to say in contrast, with the required sweep time of EN 50121-2 itself at Table 2. With similar RBW values, the MIL STD 461G requirement sweep times are in general quite slower by a factor of 10 to 50. The use of FFT methods is thus advisable [25] to push to faster sweep times with the possibility of multiple sweeps during train passage and the use of max hold or statistical values.

C. Uncertainty, repeatability and statistical significance

The EN 50121 standard set forth ambiguously the topic of reproducibility and uncertainty, in that low reproducibility is invoked for the removal of the 9-150 kHz interval for tests (remaining as informative) and uncertainty is limited to the instrumental one hastily referring to CISPR standards [16].

The definitions of reproducibility and uncertainty may be set as follows:

- reproducibility is the closeness of the agreement between the results of measurements of the same measurand carried out with same methodology described in a scientific reference;
- uncertainty is a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand [17]; in the presence of a systematic error, uncertainty is properly evaluated after correction is applied, although the correction itself brings in a term of uncertainty due to the incomplete knowledge of the value of the correction to apply.

It is evident that uncertainty encompasses various and different terms that have influence on the measurement error, and that may be led back to the used instrumentation, to the...
measurement setup and instrumentation settings, to the operating conditions and in general bias points of the system, and in general to the assumptions related to the measurement model and the effect of the environment. The system under test is complex and measurement procedures quite articulated and not exempt from flaws and ambiguous points, as we have reviewed so far. Evaluation of uncertainty should be attacked thus from two standpoints, stigmatized by Type A and Type B methods of evaluation, that can be synthesized in the statistical analysis of a series of observation and other methods of evaluation, namely most often the declared instrument uncertainty with assumptions of the distribution of errors and combination of setup non-ideality.

The Type A approach, corresponds to the evaluation of repeatability, that is the closeness of the agreement between the results of successive measurements of the same measurand carried out under the same measurement conditions. Provided that the sample size is significant and that a preliminary screening is carried out to remove aberrations and outliers, sample standard deviation and higher order statistic moments give an accurate estimate of repeatability and uncertainty.

It is recalled that the EN 50121-2 (2006) specified an accuracy limit of ±4 dB for instrumentation, indicating a recognized repeatability in the order of 10 dB. Now, the 2015 version speaks of uncertainty and makes reference to CISPR 16-1-1 (instrumentation) and 16-1-4 (antennas and site uncertainty), underlining that “due to the measurement method, the normalized site attenuation may not be considered in the measurement uncertainty.” As a matter of fact any reference to repeatability and data dispersion (extremely important to cover non-ideality and conditions not under operator’s control in terms of Type A uncertainty) is lost.

Reproducibility instead is determined by clarity and completeness of procedures for repeatability by different operators and transfer of methods to different, but similar, systems. It is not clear how low reproducibility could be invoked as ground for justifying the removal of the 9-150 kHz from the specification of limits of the 2015 versions of the EN 50121-2 and -3-1, where the largest emissions are expected.

V. CONCLUSIONS

The standards have been considered for the measurement of EMC with the outside world of electric transportation systems and rolling stock in terms of radiated emissions. Several aspects have been discussed for the CENELEC EN 50121-2 and -3-1 standards and the UMTA specifications together with the MIL STD 461G. The main aspects, influencing the measurement results and their uncertainty, are instrumentation settings, rolling stock operating conditions, line electromagnetic behavior, the measurement distance and time duration of frequency sweeps, and in general how transients and phenomena with complex time evolution should be evaluated.

The problem is complex and necessitates requirements and guidelines for uncertainty and statistical assessment of measured data, rather than the progressive reduction and smearing of requisites observed in the CENELEC EN 50121. It is believed that a thorough discussion and integration of requirements from similar disciplines can support sound and comprehensive measurement techniques, suitable for the assessment of EMC of future generation vehicles.

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