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Electromagnetic compatibility testing of vehicles in urban areas

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The article presents issues related to electromagnetic compatibility testing of vehicles in urban areas in relation to applicable standards and regulations. The topic of magnetic and electric field strength measurements in the range from 150 kHz to 1 GHz was discussed in detail. Vehicle measurement results were presented and discussed in relation to the required criterion. The tests were carried out in accordance with the requirements of the PN-EN 50121-3-1:2017-05 standard.

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1. Introduction

This article addresses the issue of electromagnetic interference generated by rail vehicles operating on city streets, which affects both the surrounding environment and infrastructure.

Radiated electromagnetic disturbances can impact electrical devices, ranging from minor effects such as audio interference in speakers to critical disruptions in medical implants. This underlines the necessity of meeting electromagnetic compatibility (EMC) requirements.

One contributing factor to EMC issues is insufficient contact force of pantograph slide plates, leading to weakened contact with the overhead wire. This results in contact interruptions, disturbances in the propulsion system and onboard electrical equipment, and the occurrence of highly unfavorable arcing phenomena. Such effects cause burning of both the contact wire and pantograph slide plates and, crucially, generate additional disturbances in the catenary system while significantly increasing electromagnetic field intensity around the vehicle. Accurate measurement results serve as key indicators of the pantograph's proper interaction with the catenary [1]. Years of experience in conducting such measurements confirm that this issue is among the most critical aspects when analyzing test results. However, market demands push manufacturers to develop alternatively powered vehicles, such as those utilizing onboard energy storage. While this eliminates pantograph-related issues, the complexity of alternative power supply systems introduces additional weak points. Consequently, this power supply method also requires a comprehensive EMC testing procedure.

Electromagnetic compatibility of railway vehicles has been investigated in numerous studies, particularly with regard to radiated emissions, the influence of railway infrastructure on measurement results, and disturbances generated by traction equipment and pantograph arcing. Cozza and Demoulin analysed the influence of railway infrastructure on radiated emission measurements performed according to EN 50121, demonstrating that the characteristics of the measurement site may significantly affect the obtained results [2]. Paonessa et al. investigated radiated emissions from a railway vehicle under stationary and slow-moving conditions in the frequency range from 150

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kHz to 1 GHz and compared the measured magnetic and electric field strengths with the applicable limit values [3].

Pantograph arcing is another important source of electromagnetic disturbances in electrified railway systems. Midya et al. experimentally demonstrated that pantograph arcing generates broadband conducted and radiated electromagnetic interference and analysed the influence of operating parameters on the disturbance levels [4]. Rashid and Tuli presented a broader review of electromagnetic field emissions associated with pantograph arcing and their possible influence on railway communication and signalling systems [5]. Li et al. analysed the propagation of electromagnetic disturbances generated by pantograph–catenary separation in a high-speed railway viaduct environment and showed that infrastructure conditions may affect the applicability of standard measurement distances [6].

The broader EMC challenges of modern railway systems, including interactions between traction power systems, rolling stock and signalling equipment, were discussed by Midya and Thottappillil [7]. More recent studies have also addressed electromagnetic emissions associated with the pantograph–catenary system. Yang et al. developed and experimentally verified a model of electromagnetic emissions from the traction network during the passage of an electrified train through a neutral section [8]. A review presented at CIRED 2023 summarized methods and measurements of railway radiated emissions, particularly in the frequency range from 9 kHz to 150 kHz, and emphasized the need for repeatable and reproducible EMC measurement procedures [9]. These studies indicate that reliable assessment of radiated emissions from railway vehicles requires consideration of the vehicle operating state, traction equipment, current-collection phenomena, railway infrastructure and the electromagnetic background of the measurement site.

2. Methodology of electromagnetic compatibility testing

The requirement to conduct EMC testing of trams arises from the provisions of Chapter 3, §7, section 4 of the Regulation of the Minister of Infrastructure dated March 2, 2011 (Journal of Laws 2011, No. 65, item 344) [10].

This regulation defines the technical conditions that must be met by urban rail vehicles, such as trams and trolleybuses.

The methodology for conducting EMC tests is described in the PN-EN 50121-2 standard [11], which specifies, among other things, the parameters of the recorder used for measurements, the height range relative to the rail head at which the antenna should be positioned, and the standard distance between the antenna and the track axis, which is set at 10 meters. If the tests are conducted at a site that meets all recommended criteria except for the 10-meter distance between the antenna and the track axis, the measurement results can be adjusted to be equivalent to the standard 10-meter distance using the following relation:

$$E_{10} = E_x + n \cdot 20\log_{10}\left(\frac{D}{10}\right) \quad (1)$$

where: E_{10} – value at a distance of 10 m, E_x – measured value at a distance D (in meters), n – correction factor from Table 1.

Table 1. Correction factor values n

Frequency range [MHz]	n
from 0.15 to 0.4	1.8
from 0.4 to 1.6	1.65
from 1.6 to 110	1.2
from 110 to 1000	1.0

The measured quantities are the magnetic field strength H and the electric field strength E. The following components are measured:

– the horizontal component of the magnetic field strength H, perpendicular to the track
– the horizontal and vertical components of the electric field strength E.

The measured quantities are expressed in the following units:

– dBμA/m for the magnetic field strength
– dBμV/m for the electric field strength.

For measurements conducted during motion, the recorder should use a peak detector (PK), whereas for stationary measurements, a quasi-peak detector (QPK) should be applied.

The accuracy of the measuring devices should not exceed 4 dB in accordance with the PN-EN IEC 55016-1-1 standard [12].

The antenna setup is presented in Fig. 1–3.

The frequency range of the measurements covers 150 kHz to 30 MHz for the magnetic component and 30 MHz to 1 GHz for the electric component.

The requirements that the tested vehicle must meet are specified in the PN-EN 50121-3-1:2017-05 standard [13], which distinguishes between limits for urban rail vehicles such as trams and trolleybuses (as shown in Fig. 4) and those for other railway vehicles.

Due to the stringent requirements for vehicles operating on city streets, designing equipment and installations that comply with the aforementioned standard [13] poses a significant challenge for tram and trolleybus manufacturers.

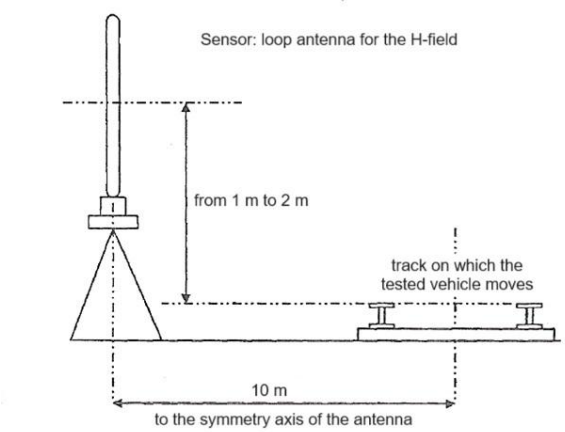


Fig. 1. Configuration of the active loop (frame) antenna

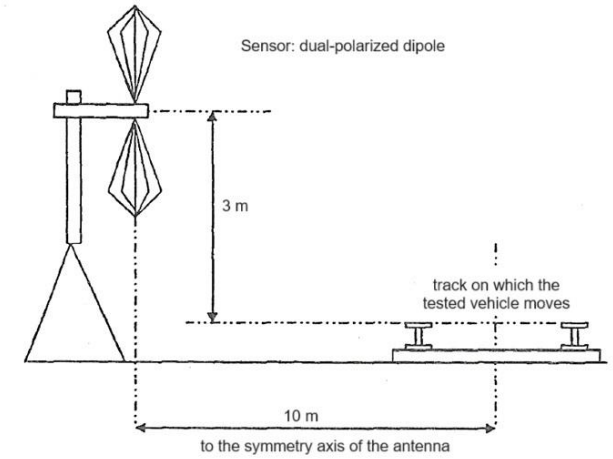


Fig. 2. Configuration of the log-periodic antenna (vertical polarization)

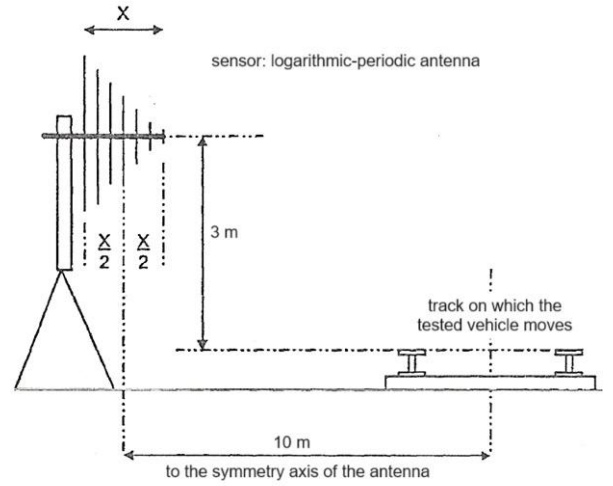


Fig. 3. Configuration of the biconical dipole (vertical polarization)

During stationary testing, all onboard receivers are activated, including the heating or air conditioning system, passenger information system, interior and exterior lighting, monitoring system, and other components. The vehicle is positioned relative to the measurement antenna so that the antenna is located directly opposite the source expected to generate the highest level of electromagnetic disturbance emissions. Typically, this source is an inverter box or a static converter, which is most commonly mounted on the vehicle roof but may also be located on the underframe or behind the driver's cabin. If no specific source of electromagnetic fields is identified, measurements are performed along the vehicle's centerline.

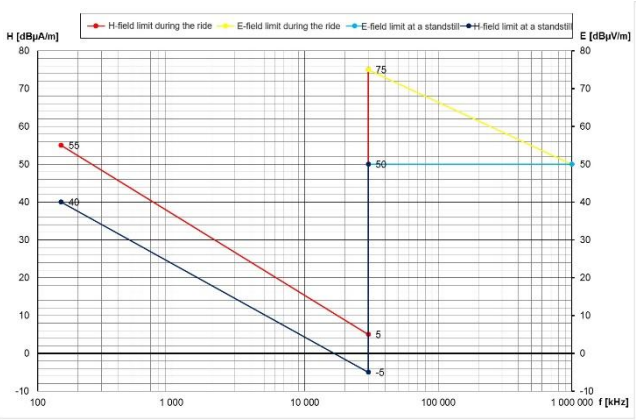


Fig. 4. Permissible radiated disturbance levels for urban vehicles

In practice, it is not possible to conduct tests covering all functions and operating states of the tested vehicle. Therefore, measurements are performed for typical operating modes that are expected to generate the highest levels of radiated electromagnetic disturbances.

From the perspective of the standard [11], the measurement location should meet the requirements of a so-called "free space" while taking into account the specific urban tram infrastructure. However, objects such as trees, walls, bridges, tunnels, or other vehicles should be avoided within a 10-meter radius. Considering the supporting structures of the overhead contact system, the measurement location should be positioned precisely between the supporting poles.

It is recommended that no other vehicles within a 2 km radius be powered from the same section during the measurement. For this reason, tram tests are typically conducted at night, when most cities with tram networks do not have passenger traffic.

Since the measurement location for vehicles operating on city streets is urban infrastructure, it is crucial to carefully select a site that provides the most "free space" possible. Typically, this is a terminal tram loop or a tram stop located away from urban architecture.

Unfortunately, urban areas are significant sources of electromagnetic interference across the entire measurement frequency range. Therefore, standard [13] requires background noise measurements to be performed both before and after the main test. Con-

ducting background measurements twice is crucial for result analysis, as background noise often fluctuates during testing, potentially leading to inaccurate interpretations. Additionally, in some frequency bands, the background noise itself may exceed the permissible limits. In such cases, standard [13] recommends that if the measured background electromagnetic field level, reduced by 6 dB, still exceeds the permissible value, measurements in those frequency bands should be disregarded. However, these excluded frequency bands must be documented in the test report.

Measurements conducted during motion should be performed at a vehicle speed that allows for electrodynamic braking. However, if no additional circuits or devices are activated during electrodynamic braking, tests related to braking are not required.

The speed range for measurements of urban vehicles is (20 ±5) km/h. Upon reaching this speed near the measurement antennas, approximately 1/3 of the maximum tractive force should be applied.

The vehicle does not always generate the maximum electromagnetic field level exactly when passing the measurement antennas; this peak may occur significantly before or after the antennas. Therefore, the measurement should be started in advance to ensure accurate data capture.

The weather conditions required during testing are:

- temperature of at least 5°C
- wind speed not exceeding 10 m/s
- dry weather is recommended (with no more than 0.1 mm of rainfall in the past 24 hours)
- humidity levels low enough to prevent condensation on the wires.

Since the organization of tests is planned well in advance, weather conditions do not always meet the above requirements. In such cases, the current weather conditions must be recorded in the test report.

Weather conditions have a significant impact on measurement results. This is confirmed by the fact that interference levels increase by approximately 20 dB when measured during rain. Additionally, icing of the catenary causes sparking, leading to a rise in emission levels. Meanwhile, strong winds affect the mechanics and tension of the catenary, influencing the contact between the pantograph's sliding strip and the contact wire.

3. Result analysis

A common practice of laboratories conducting tests, in accordance with client expectations, is not only to provide measurement results but also to determine whether they comply or do not comply with the requirements. To achieve this, it is necessary to determine measurement uncertainty, as explicitly required by PN-EN ISO/IEC 17025:2018-02 [14].

For a full understanding of the measurement result, it is essential to mention the decision-making principle and compliance assessment. The most commonly used decision-making method in measurement technology is the simple acceptance rule, based on ILAC-G8: 09/2019 [15]. This principle is graphically illustrated in Fig. 5.

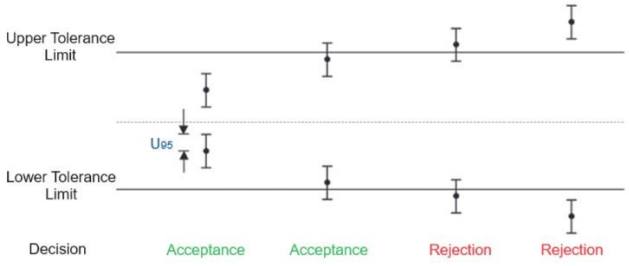


Fig. 5. Simple acceptance rule [16]

The procedure is as follows: if the measurement result is below the limit or within the specified tolerance range, the laboratory can confirm its compliance. However, if the measurement result exceeds the limit or falls outside the specified tolerance range, it is considered non-compliant.

In this case, the risk of false acceptance can be up to 50% for results close to the tolerance limit.

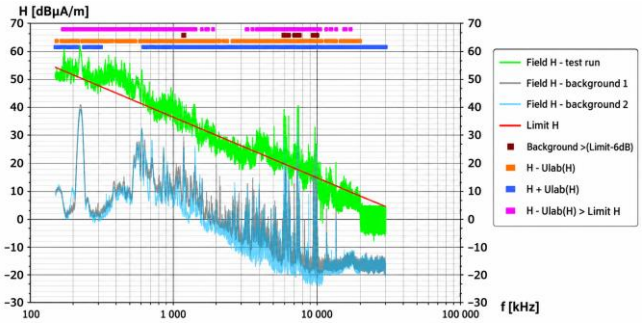


Fig. 6. Illustrates the results of one of the tests, showing exceedances of the applicable limit for the magnetic field component in several frequency bands

In Figure 6, the red line indicates the applicable limit. Blue rectangles represent values for which, considering measurement uncertainty, conditional compliance is assumed (with up to 50% risk). Orange rectangles indicate values deemed conditionally non-compliant (with up to 50% risk). Purple rectangles highlight measurements that exceed the permissible value even after accounting for uncertainty. Thus, rejection of compliance applies to orange and purple values. Brown rectangles signal frequency bands where the background noise level exceeds the limit

reduced by 6 dB, meaning these bands are excluded from evaluation.

Figure 6 illustrates the results of one of the tests, showing significant exceedances of permissible values for the magnetic component. A noticeable increase is observed over a wide frequency range, from 150 kHz to just under 50 MHz.

To achieve a more precise analysis of the source of exceedances, it is useful to compare the results of the test run with measurements taken while stationary. This allows for determining which disturbances are related to the vehicle's dynamics and drive system operation and which are continuously emitted by onboard equipment. Figure 7 shows the magnetic component disturbances measured in a stationary set-up.

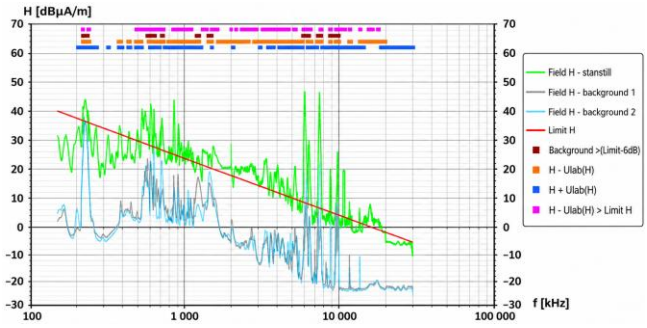


Fig. 7. Summary of radiated H-field disturbances recorded during stationary tests

At first glance, a common band of exceedances is visible for frequencies between 500 kHz and just under 50 MHz. Thus, in the initial frequency phase, we can observe the influence of the controlled drive. The localization of the problem poses significant challenges for manufacturers, especially given the wide range of potential sources. Possible causes of excessive magnetic field emissions include improper or insufficient grounding of individual parts or components, improper cable routing, and the use of unshielded cables in main power circuits.. Another factor contributing to increased magnetic field emissions is improper cable routing or the use of unshielded cables in main power circuits.

The registered waveforms of the same object after modifications are shown in Fig. 8 and Fig. 9. Improvements included correcting grounding cable connections and using cables with a larger cross-section. Additionally, the static converter was reprogrammed.

Very often, considering the complex structure of the vehicle, the causes of exceedances turn out to be quite trivial. In the case presented below in Fig. 10 and Fig. 11, time-consuming tests with sequentially switched-off onboard devices proved that the source of the problem was a faulty power supply of the front LED information display.

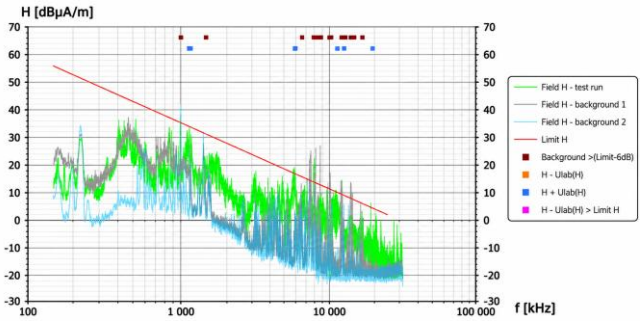


Fig. 8. Comparison of radiated magnetic field H disturbances recorded during motion – after modifications

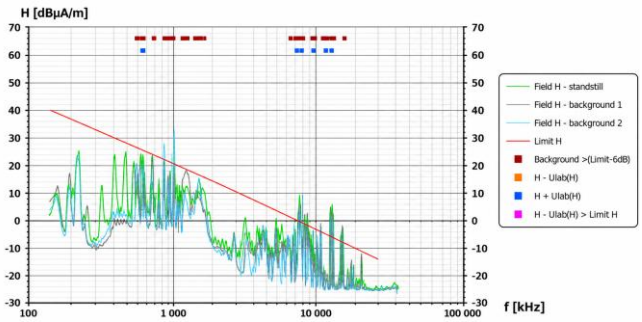


Fig. 9. Comparison of radiated magnetic field H disturbances recorded at standstill – after modifications

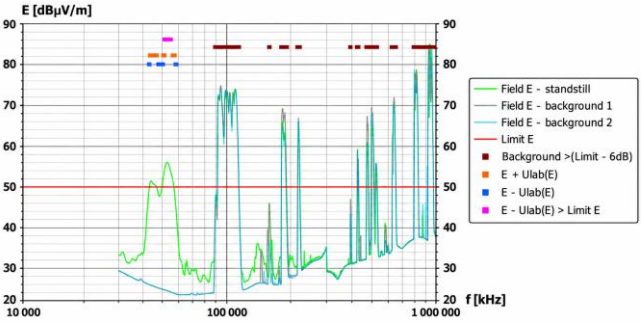


Fig. 10. Comparison of radiated electric field E disturbances recorded at standstill, horizontal antenna polarization – LED display turned on

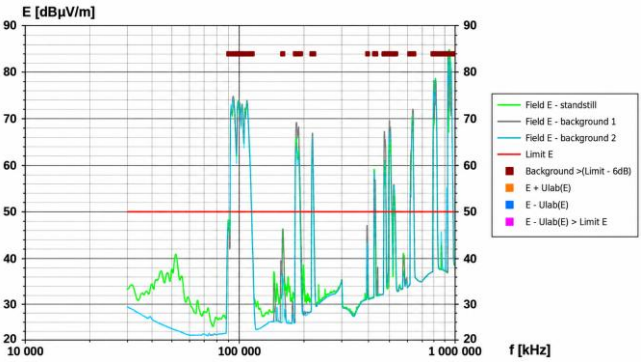


Fig. 11. Comparison of radiated electric field E disturbances recorded at standstill, horizontal antenna polarization – LED display turned off

Increasingly, urban infrastructure conditions or the pursuit of meeting environmental requirements lead to the introduction of city vehicles powered by alternative means, such as both the catenary system and energy storage units. When vehicles are powered in this way, it is necessary to perform compatibility tests separately for each power source. The results obtained in this manner are presented in Fig. 12 and Fig. 13. With a properly adjusted collector for a vehicle powered by the catenary system, the interference levels recorded during tests of a vehicle powered by a battery system are often higher.

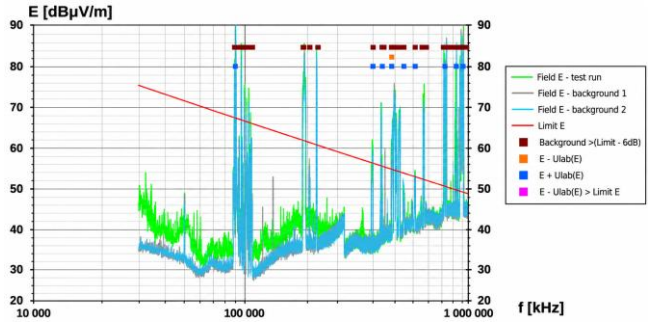


Fig. 12. Comparison of radiated electric field E disturbances powered from the catenary, recorded during the ride, vertical antenna polarization

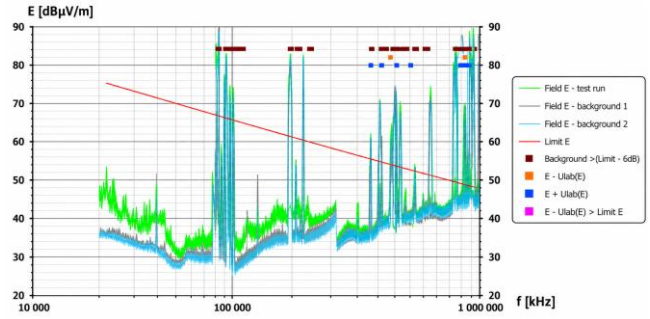


Fig. 13. Comparison of radiated electric field disturbances powered from the traction battery, recorded during the ride, vertical antenna polarization

It is worth noting that during electric field measurements, the impact of background radiated interference is the dominant factor. It is extremely difficult to find an urban area that does not generate interference in its surroundings. By nature, the expansion of public transportation occurs in highly urbanized areas. The amount of interference in such environments necessitates, according to the standard, the exclusion of these frequency bands from the assessment. So far, there are no definitive, confirmed results indicating whether additional disturbances originating from the tested object are introduced in these frequency bands. One method to minimize the influence of external sources on interference measurements is to conduct them at night, as shown in Fig. 14.



Fig. 14. EMC testing in urban conditions during nighttime hours

4. Summary

The conducted tests confirmed that radiated electromagnetic disturbances generated by urban rail vehicles may vary significantly depending on the vehicle operating condition, the active onboard equipment and the power supply mode. In the investigated case, the most significant exceedances were observed for the magnetic field component. During the test run, increased disturbance levels were recorded over a wide frequency range, from approximately 150 kHz to below 50 MHz. Comparison with the stationary measurement showed a common band of increased disturbances from approximately 500 kHz to below 50 MHz, which made it possible to distinguish disturbances associated with the traction drive operation from those continuously generated by onboard equipment.

The diagnostic measurements also demonstrated that the sources of excessive emissions may be related to relatively simple installation issues. In the investigated vehicle, corrective actions included modification of grounding connections, the use of grounding cables with a larger cross-section and reprogramming of the static converter. The measurements performed after these modifications showed a reduction in the recorded disturbance levels.

A separate series of stationary measurements showed that the source of increased electric field disturbances could also be an individual onboard device. Sequential switching-off of onboard equipment made it possible to identify the faulty power supply of the front LED information display as the source of the observed disturbances.

The tests performed for different vehicle power supply modes also showed that the emission level depends on the operating configuration. In the presented case, disturbance levels recorded during battery operation were in some frequency ranges higher than

those measured when the vehicle was supplied from the overhead contact line.

The measurements further confirmed the significant influence of the electromagnetic background on the assessment of radiated electric field disturbances in urban areas. For this reason, background measurements performed before and after the main test, together with the exclusion of frequency bands in which the background level is too high, are essential for a reliable assessment of vehicle compliance. Conducting measurements during nighttime hours may additionally reduce the influence of external electromagnetic sources.

The obtained results confirm that reliable EMC assessment of urban rail vehicles requires not only comparison with the applicable limits, but also measurements under different operating conditions and systematic identification of the sources of disturbances. The presented test procedure proved useful both for conformity assessment and for locating the causes of excessive electromagnetic emissions and verifying the effectiveness of corrective actions.

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