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Convenient Procedure for Measuring the Electrical Resistance of Fastening Systems in Urban Railway Tracks

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Abstract: Electrical resistance is among the characteristics that fastening systems must meet to ensure the proper functioning of signaling systems in railway infrastructure. The EN 13146-5:2012 standard specifies a laboratory testing method for determining the electrical resistance under wet conditions between running rails provided by a fastening system on steel or concrete sleepers. In urban railway tracks, the electrical resistance of fastening systems affects the stray current; however, there is no standardized electrical resistance measuring method. There is also no definition for the minimum value that the electrical resistance of fastening systems must satisfy to prevent stray currents. For this reason, this paper analysis the possibility of using the standard EN 13146-5:2012 for the measurement and analysis of the electrical resistance of fastening systems in urban railway tracks. In this study, the electrical resistance of different fastening systems used in urban railway tracks was measured. Based on the tests results, the modifications needed in the EN 13146-5 standard for it to be suitable for urban railway tracks were identified. The proposed modifications include the use of a DC current source. The test should be performed on a rail sample fastened to the concrete base, and the current circuit should be closed by the reference electrode installed in the base. Spraying water from nozzles is not applicable for this measurement. The test should be performed under dry conditions and at different water levels (water on the top of the concrete base and on the top of the levelling layer). Different water levels were used to simulate the most common conditions in urban railway tracks built as part of the road surface, where the track-drying process is very slow. The test should not be performed when the rails are immersed in water, because the current flows directly from the rail into the water in such case, and the fastening system has no influence on the measured electrical resistance value. In addition to describing the proposed changes, the calculation of the minimum electrical resistance value that fastening systems in urban railway tracks must satisfy is also presented.

Keywords: urban railway track; rail-fastening system; electrical resistance; rail-to-earth resistance; stray current

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1. Introduction

Tram and light rail systems form the backbone of modern urban transport networks in many European cities. Currently, rail vehicles in urban areas use direct current (DC) for propulsion, where the overhead line is used as a conductor from the power source (electrical substation) to the vehicles [1–3]. Vehicles use a mounted pantograph to transmit electric current to the engine inside the train [4]. In most cases, the running rails serve as a return conductor from the vehicle to the electrical substation [1–3].

Because rail-to-earth resistance cannot be made infinite and rail resistance is nonzero, part of the returning current leaks from the rail and becomes stray current [2,5]. The stray current enters a nearby metal object and flows through that object back to the source. The current path can be very long and not harmful; however, at the point where the current leaves the metal and enters the electrolyte, an anodic reaction occurs, causing severe damage [6,7]. By examining the rail potential, anodic and cathodic zones on the rails and nearby metal objects can be identified. The anodic reaction leads to material loss and local degradation, while in the cathodic zone, the current enters back to the metal and the structure is catholically protected [7–9]. At the points where current flows from the soil into the rail, a negative rail potential is created, causing a cathodic zone on the rail and an anodic zone on the nearby metal object. A positive rail potential indicates the simultaneous occurrence of an anodic zone on the rail and a cathodic zone on metal structures [10].

According to [11], stray current causes corrosion on the rail and fastening system, leading to sharp angles on the rails, stress concentrations, and possibly to rail failure. However, despite the harmful influence of stray currents on rails, current research is mainly focused on stray current corrosion on metal objects in the vicinity, i.e., buried metal pipelines and steel in reinforced concrete or tunnels [8,9,12,13] or stray current modeling on urban railway tracks [14,15].

Because dynamic stray currents are the result of urban railway track systems, they must be reduced at the source to prevent their harmful consequences. This can be achieved by decreasing the longitudinal resistance of the rail and increasing the rail-to-earth electrical resistance, which can be achieved by insulating the rail and rail-fastening systems [16]. Currently, different types of field measurements are used to determine the rail-to-earth resistance and stray current. Some of these are described in the EN 50122-2:2011 standard [17] and in [18,19]. Despite these field measurements, it is very difficult to determine the real stray current values because they are dynamic, change with time, and many parameters affect them (vehicle type and driving style, number of vehicles, and soil resistivity) [20,21]. Therefore, to determine the real stray current value, long-term measurements should be carried out or continuous stray current monitoring should be applied.

In [22] and [23], the rail-to-earth resistance was defined for different types of urban railway tracks. However, they both defined different resistance values for the same track type. If rails are not completely insulated, when rail-to-earth resistance field measurements are taken, the results are highly dependent on soil resistance, which in turn depends on location, moisture, and soil type. If a high fastening system electrical resistance is ensured, soil resistance will not affect the stray currents. This is also confirmed in [24] where it is shown that the resistance of the material on which the rail is laid has no influence on the stray current density until the resistivity of the rail coating drops below 100 kΩm. Therefore, it is necessary to define the fastening system electrical resistance value used in urban railway tracks.

In urban railway tracks, the type of fastening system is chosen based on the deflection and vibration attenuation properties of the track [25,26]. In tracks with discretely fastened rails, if adequate drainage is provided and no water remains in the track, the fastening points are only discharge points for the currents; therefore, the fastening systems must be insulated to prevent stray currents. Because the fastening system has a great influence on the rail-to-earth resistance and stray currents, it is also necessary to determine the electrical resistance value that the fastening system must meet. However, in the European Union, the electrical resistance value is specified, and the measurement is standardized only for the fastening systems used in conventional railway infrastructure, where a high resistance, especially in wet conditions, is required to ensure the functioning of the signaling devices [27]. This measurement is described in the EN 13146-5:2012 standard [28] as a part of the fastening system validation.

The study presented herein is based on a previous paper presented at the 7th International Conference on Rail and Road Infrastructure CETRA 2022 [29], which describes laboratory measurements for electrical resistance according to the EN 13146-5:2012 standard. The measurements were performed on the W14 fastening system on the concrete sleeper, which are also described in this paper (see Section 3). This study examines the possibility of applying the laboratory test described in the EN 13146-5:2012 standard to measure the electrical resistance of fastening systems used in urban railway tracks and evaluate the influence of the fastening system resistance on the stray current.

The aim of this study is to describe the necessary modifications to the standard procedure according to EN 131416-5 for it to be suitable for fastening system electrical resistance measurement in urban railway tracks. The minimum electrical resistance values that must be met to prevent stray currents and an electrical resistance calculation equation are also proposed.

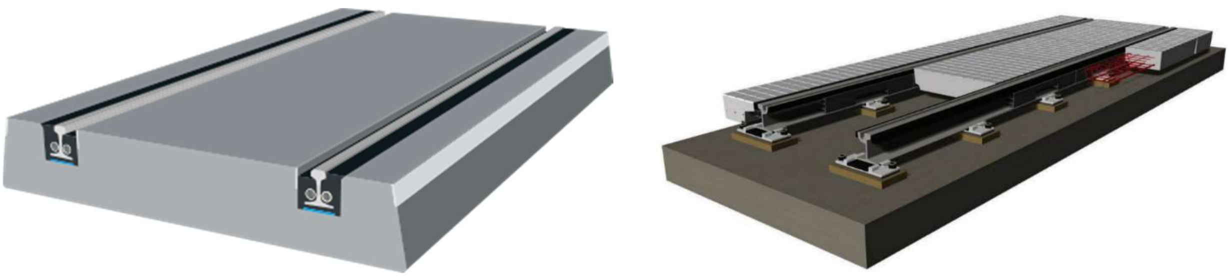
2. Types of Urban Railway Tracks

Track structures intended for tramway traffic often differ significantly from standard ballasted tracks, including the use of grooved rails, continuous reinforced concrete slabs as a base, embedding the track in the road surface, and continuously supported tracks. Track structures can be distinguished by their location (embedded in lanes shared with road vehicles or in separate bands) and according to the fastening system. Different track types have different rail-to-earth resistance values, which means that the track type affects the stray current value. Therefore, it is necessary to distinguish track types in urban areas and to define the most critical one, where the stray current is the highest. In most cases, those are tracks embedded in lanes shared with road vehicles, in which rails are fastened discretely, such as in the tram track infrastructure in Zagreb, Croatia, where the stray current problem is highly recognized.

2.1. Track Types According to the Fasting System

Based on the type of fastening system, urban railway tracks can be divided into two groups:

(i) Tracks with continuously fastened rails (Figure 1a);
(ii) Tracks with discretely fastened rails (Figure 1b).

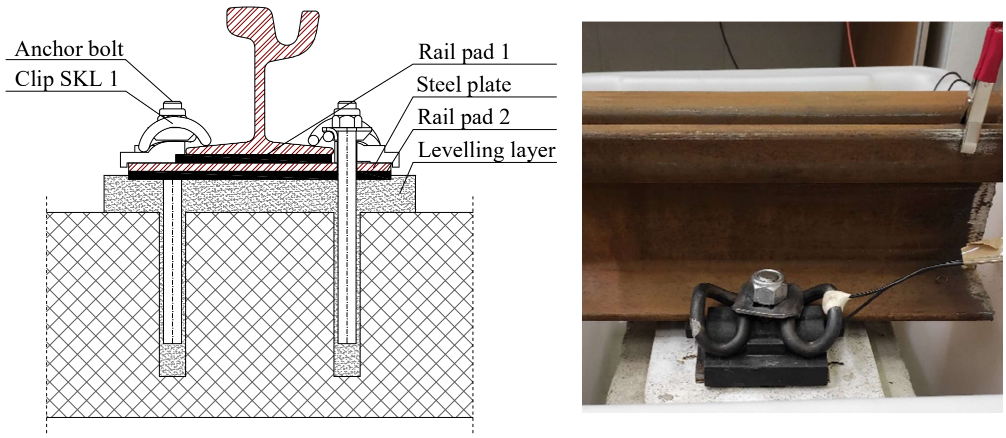


(**a**) (**b**)

Figure 1. Tracks with (**a**) continuously fastened rails (embedded rail) and (**b**) with discretely fastened rails.

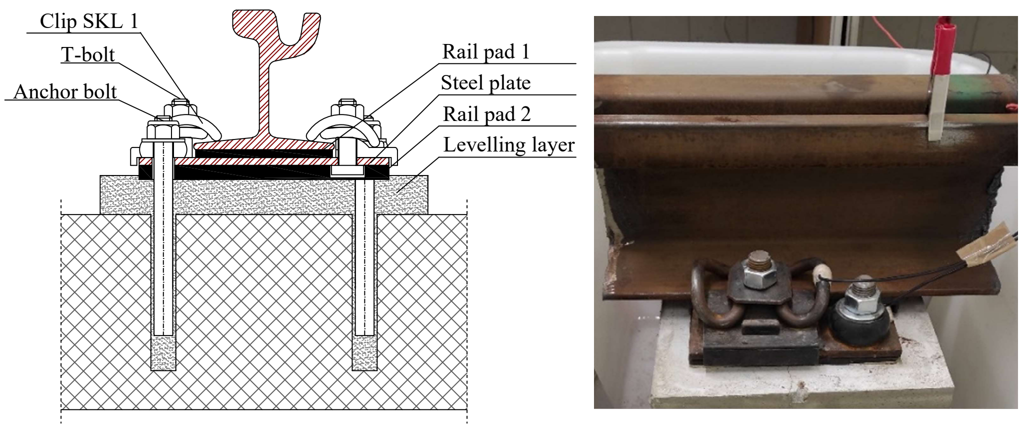
In tracks with continuously fastened rails (embedded rails), the rails are laid in the grooves of the precast concrete slab, and the free space between the rail and slab is filled with an elastic material so that the rails are fully insulated and stray current is prevented [30,31]. This elastic material ensures that the rails have continuous support throughout, with a specifically determined elasticity in accordance with the specified conditions. The empty tubes used here primarily serve to reduce the use of elastic material, and they can also be used to enclose cables for signals and other functions [32]. In embedded rail systems, rails are fully insulated using an elastic material with a defined high electrical resistance value; therefore, stray currents are prevented.

The tram track infrastructure in Zagreb is an example of a track with discretely fastened rails. In this track, the rails are laid on levelling layers every 1 meter, with the levelling layers built on a reinforcement slab. On each levelling layer, the rails are fastened to the concrete base with direct or indirect fastening systems [33]. In a direct fastening system, the rail is laid on an elastic pad and a steel plate. The steel plate is installed in the levelling layer, and the rail is fastened to the steel plate using fastening clips and anchor bolts. The anchor bolts provide anchorage for the entire fastening system in the concrete. The direct fastening system characteristics for the tram infrastructure in Zagreb are shown in Figure 2. In an indirect fastening system, the rails are laid on an elastomer pad and a steel plate. The rails are fastened to the steel plate with fastening clips and T-bolts, while the anchor bolts are dislocated and serve only to anchor the steel plate to the concrete base [33,34]. An example of an indirect fastening system is shown in Figure 3. In these type of tracks, the rail-to-earth resistance depends on the type of fastening system, the electrical resistance of the concrete slab, and the electrical resistance of the soil. Because each fastening point in this type of track represents a discharge point for the current [35], its electrical resistance must have a certain characteristic to prevent the current from flowing from the rail to the concrete slab.



(**a**) (**b**)

Figure 2. (**a**) Cross section of a direct fastening system. (**b**) Real-scale sample of the direct fastening system used in the tram track infrastructure in Zagreb, Croatia.

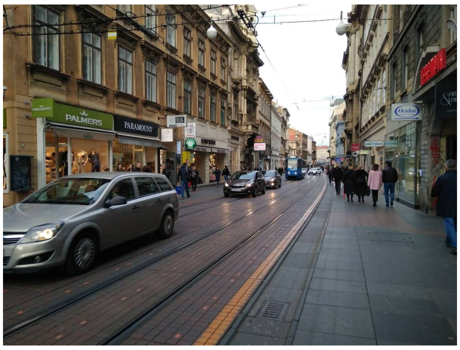


(**a**) (**b**)

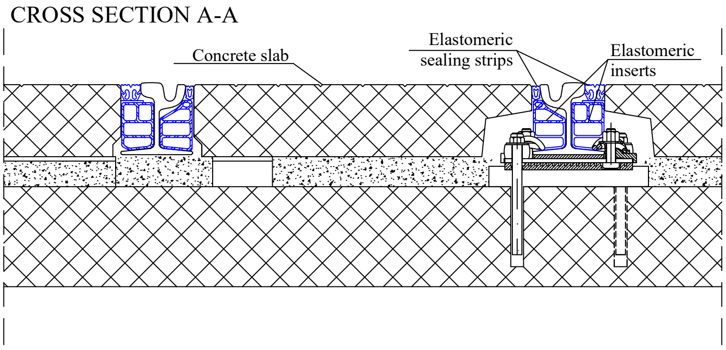
Figure 3. (**a**) Cross section of an indirect fastening system. (**b**) Real-scale sample of the indirect fastening system used in the tram track infrastructure in Zagreb, Croatia.

2.2. Track Types According to Their Position with Respect to Road Traffic

Tracks can be embedded in lanes shared with road vehicles or built in separate rail corridors. When they are embedded in a car lane, they must be paved so that road vehicles can use the track surface for driving (Figure 4). With this track type, it is very difficult to provide proper water drainage, and the drying process takes a very long time; accordingly, the water remains in the tracks for most of the year [34]. If the fastening systems are not properly insulated, the rail-to-earth resistance depends on the resistivity of the concrete and can vary greatly during the year because the electrical resistance of concrete depends on many parameters, as described in [36] and [37]. When the rails are in direct contact with water, the current flows directly from the rail into the water, resulting in a very low rail-to-earth resistance.



(a)



(b)

Figure 4. (**a**) Paved tram track structure in Zagreb, Croatia, built as part of the road surface cross section, as shown in (**b**).

3. Electrical Resistance Measurement of Fastening Systems and Sleepers According to the EN 13146-5-2012 Standard

The EN 13146-5:2012 standard [28] describes the electrical resistance measurement of fastening systems on concrete or steel sleepers. Different fastening systems have different electrical resistance values. According to [38,39], the electrical resistance of the Nabla fastening system on a concrete sleeper is greater than 15 kΩ, and that of the W14 fastening system on a concrete sleeper is greater than 5 kΩ.

Furthermore, according to the EN 13146-5-2012 standard [28], the electrical resistance measurement must be performed under cover and protected from rain and draughts in a room with an air temperature ranging from 15 to 30 °C. Because the sleeper must be sprayed with water during the test, four nozzles should be placed above the sleeper. Each nozzle should spray 7 ± 1 L of water in one minute. Before the measurement, the electrical conductivity of water must be determined according to the EN 27888 standard. The electrical conductivity of water should be measured at a reference water temperature of 25 ± 0.1 °C. If the conductivity measurement is not possible at the reference temperature, the temperature correction factor defined in the EN 27888 standard can be used; however, according to [40], a conductivity measurement made with the sample at the reference temperature is always more accurate than a temperature-compensated measurement. Temperature is important because the conductivity of water increases with temperature and can affect the electrical resistance of the fastening system [41]. Electrical resistance measurement according to the standard is also described in [27], including the testing methodology, necessary equipment, and the dependence of electrical resistance on variables such as water conductivity, temperature, and relative humidity.

The laboratory measurement according to [28] of the fastening system electrical resistance on a concrete sleeper B70 2.6 W-60 [29] is further described as an example of standardized measurement. Type 60 E1 rails, with a length of 50 cm, were used in the test. The rails were placed on an elastic pad and fastened to the sleeper using a W14 fastening system. To perform the test, the sleeper was placed on two electrically insulating blocks to prevent current leakage from the sleeper. An AC power supply of 30 ± 3 V RMS and 50 ± 15 Hz was used for measurement. The voltage during the test was 31 V, and the current depended on the electrical resistance of the sleeper and fastening system. Voltage and current were measured using a multimeter with continuous logging of parameters on a personal computer. Prior to testing, the electrical resistance of the multimeter and current conductors used to connect the current source to the tested sample was measured. The multimeter was connected to a 10-kΩ resistor, and the current and voltage were measured. The measured electrical resistance was 10,00044 kΩ.

The prepared samples and test equipment used for the measurement are shown in Figure 5.

(a) (b)

Figure 5. (**a**) Sample for the electrical resistance testing. (**b**) Equipment used for the measurement.

One rail was connected to the positive pole of the current source, and the circuit was closed by connecting the second rail to the negative pole. The current entering the rail connected to the positive pole flows through the fastening system and sleeper to the other rail and returns to the current source (Figure 6).

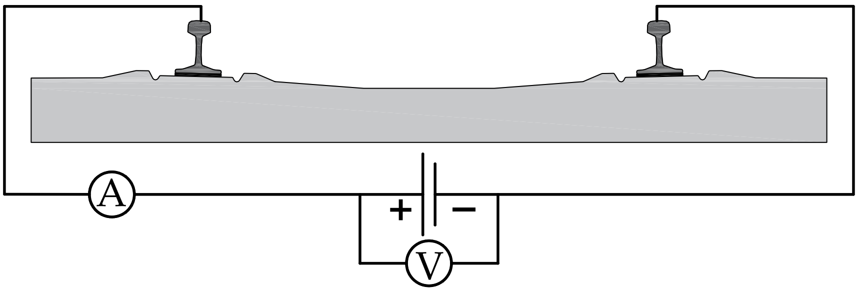


Figure 6. Current circuit for detecting the electrical resistance of the fastening system.

After the current was switched on, the spraying of water from the nozzles started and lasted for 2 min, as required by the standard. The measurement starts before the nozzles start spraying the water to determine the electrical resistance under dry conditions and must continue for at least 10 min after the water spraying has stopped. This measurement was repeated for two other similar test samples. If this is not possible, the same sample can be used for all three measurements. In this case, the next measurement can be performed after 120 h, which is the time required for the sample to become surface-dry. The measurement was performed three times with the same sample. During the drying period, the equipment remained connected to the rails, and only the current source was switched off.

Prior to the measurement, the electrical conductivity of the water was measured according to the EN 27888:2008 standard [42] using an adequate conductometer (Figure 7). Because the water temperature was 15.8 °C, the temperature of the water sample taken for the electrical conductivity measurement was increased to 25 °C. The measured electrical conductivity was 775 µS/cm. The water conductivity was too high; therefore, deionized water was added, and the conductivity measurement was repeated until the water conductivity was in the range of 50 ± 5 mS/m, as recommended in [28]. The measured water conductivity before the test was 492 µS/cm (49.2 mS/m).

Figure 7. Measuring the electrical conductivity of water using the SI Analytics Lab 945 conductometer.

The electrical resistance from all three measurement cycles was plotted as a function of time, as shown in Figure 8. The electrical resistance of the sample in the dry state is high, but since the measurements were performed on the same sample, the resistance in the dry state decreases with each cycle, since the sample is only surface dry after the drying period. After the nozzles start spraying water, the electrical resistance decreases drastically. The minimum value of resistance in cycle 1 is 5.81 kΩ, in cycle 2 the minimum value is 5.69 kΩ and in cycle 3 it is 5.32 kΩ. The spraying with water lasted 120 s, and after the end of the spraying, the electrical resistance starts to increase when the sample starts to dry.

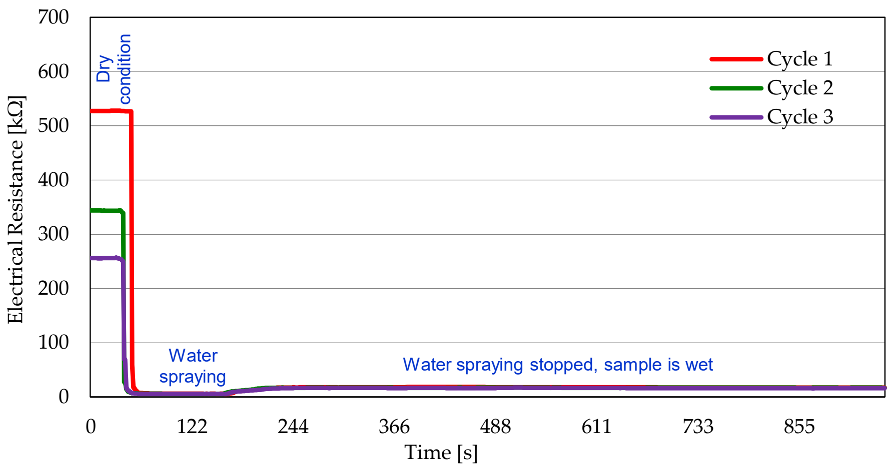


Figure 8. Electrical resistance of the W14 fastening system as a function of time for all three measured cycles.

The minimum electrical resistance of the fastening system and sleeper was calculated as the arithmetic mean of the minimum values from all three measured cycles.

4. Proposed Modification to the EN 13146-5-2012 Standard for the Electrical Resistance Measurement of Fastening Systems in Urban Railways Tracks

Because different types of track structures can be found on tramway tracks, where rails are usually not laid on the sleepers and vehicles use DC current for driving, the electrical resistance measurement method defined in the EN 13146-5:2012 standard cannot be applied without modifications. In this section, the proposed test setup for a convenient electrical resistance measurement for slab and embedded tracks usually found on tramway tracks is described.

4.1. Sample Preparation

Laboratory tests should be performed on a real-scale sample with the rail fastened to the concrete base using all components of the fastening system. A single fastening point is sufficient for testing; however, a reference electrode must be installed in the concrete base during construction. This reference electrode is used to close the current circuit. For our purpose and to analyze the electrical resistance of fastening systems in urban railway tracks, laboratory measurements were performed on the fastening systems used in tracks with discretely fastened rails that are characteristic of the tram infrastructure in Zagreb and on an embedded rail sample. The sample preparation procedure corresponded to the in situ track construction procedure. First, a concrete block was prepared for each sample. Two steel ribs were placed in each block, representing the reference electrode. The levelling layers for discretely fastened rail samples were made in situ using the top-down method, primarily adjusting the rail direction and height and then pouring the levelling blocks. When preparing the samples, the steel base plates were raised approximately 5 cm above the concrete block, which corresponds to the height of the levelling blocks on the tracks (Figure 9a), and levelling blocks were poured using micro-synthetic concrete. Finally, the 50-cm-long rail samples were placed on steel plates and fastened to the base. For the continuously embedded rail sample, the rail was placed in the groove of the concrete base and isolated with an elastomeric material (Figure 9b). All samples were placed in plastic tubes.

(**a**)

(**b**)

Figure 9. Sample preparation for the laboratory measurement: (**a**) discretely fastened rail and (**b**) embedded rail.

4.2. Testing Methodology

4.2.1. Current Circuit

Because the urban railway tracks are operated with DC current, the electrical resistance measurement should be performed using the DC current from the laboratory rectifier. In this test, as the current leaks from the rail through the fastening system into the concrete base, the rail should be connected to the positive pole of the current source, and the circuit needs to be closed with the reference electrode installed in the concrete base (Figure 10). It is recommended to perform the test using the current voltage expected in the rails at the tracks. According to [43] a high rail voltage can be dangerous for people near the tracks, so the maximum rail-to-earth voltage must be 90 V, which is also the maximum voltage that should be used in the laboratory test. During the test, the current and voltage were measured continuously with a multimeter. Prior to the measurement, the electrical resistance of the test instrument should be verified.

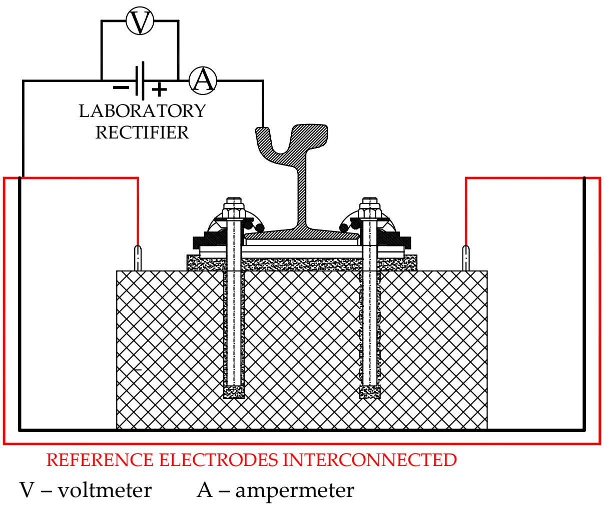


Figure 10. Current circuit during the test.

Before starting the laboratory test, it is important to check whether there is a good connection between the rail and conductors. If this is the case, the resistance between them must be below 0.1 Ω. In this test, the measured resistance was 0.01 Ω.

The current circuit in Figure 10 can be shown as resistors connected in series (Figure 11), where the electrical resistance of the fastening point R_{FP} depends on the resistance of the rail R_{RAIL}, fastening system R_{FS}, and concrete R_{CON} and can be calculated using 1.

$$R_{FP} = R_{RAIL} + R_{FS} + R_{CON} \quad (1)$$

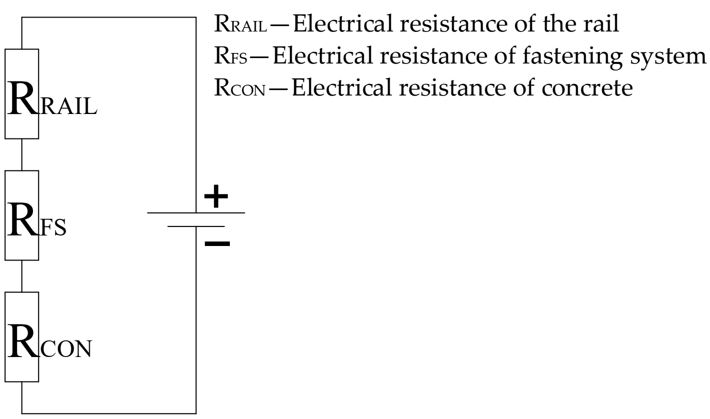


Figure 11. Current circuit during the laboratory test as resistors connected in series.

The electrical resistance of the rail is almost zero and can be neglected; therefore, the final resistance value at the fastening point depends on the resistance of the fastening system and concrete.

The electrical resistance of the fastening system depends primarily on the resistivity of the elastomeric components. If the fastening system is not sufficiently insulated, the electrical resistance of the concrete has a significant effect on the measured resistance. If, by contrast, a high electrical resistance of the fastening system is ensured, the concrete resistance does not have a significant influence on the measured resistance.

To verify that the anchor bolts are adequately insulated from the steel plate in indirect fastening systems, the voltage in the anchor bolts can be measured. If they are sufficiently insulated, the voltage in the bolts should approach zero. The electrical resistance can also be measured when the circuit is closed by connecting the negative pole to the anchor bolt. In this case, the dominant resistance in this circuit is the resistance of the elastomer elements.

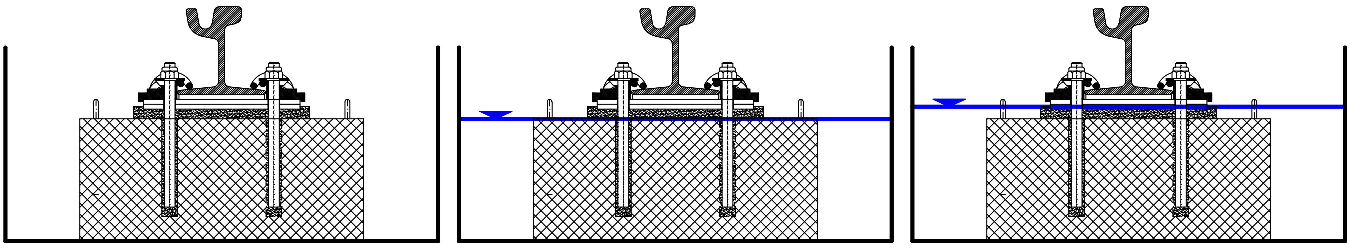
Owing to the described challenges regarding drainage in tracks embedded in road surfaces, the test should be performed under dry conditions and at various water levels relative to the top surface of the concrete slab, as described next.

4.2.2. Testing under Different Conditions

The standard describes the electrical resistance measurement for classic railway tracks, where the rails are laid on sleepers and embedded in a ballast. In this case, the drainage capability is substantial, and in the case of precipitation, the water flows to the lower part of the structure without building up in the track at the fastening system level. Therefore, the test was performed by spraying water using the nozzles, simulating heavy rain conditions.

In the case of tracks paved on a car-running surface, the drying process is very slow; therefore, the concrete base and levelling layers are wet most of the year, which leads to their low electrical resistance. Accordingly, to analyze the resistance of fastening systems, various conditions should be simulated in laboratory tests. The measurement must be performed in the following cases:

(i) Case I: dry condition (Figure 12a);
(ii) Case II: when the water is on top of the concrete base (Figure 12b);
(iii) Case III: when the water is on top of the levelling layer (Figure 12c).



(**a**) (**b**) (**c**)

Figure 12. Conditions for the fastening system resistance measurement: (**a**) Case I: dry condition; (**b**) Case II: when the water is on top of the concrete base; and (**c**) Case III: when the water is on top of the levelling layer.

The test does not need to be carried out in a submerged state (when the rail is in contact with water) because when the water builds up and does not drain from the tracks, the rails are in direct contact with the water and the current flows directly from the rail to the water, so the type of fastening system used does not affect the electrical resistance [32].

During the test, the current circuit must be turned on continuously, and the electrical resistance measurement should be performed continuously for one hour in each case in Figure 12. After finishing the measurement in Case I, water should be poured over the top of the concrete base, and the next measurement should be conducted after 72 h because, according to [44], the concrete should be immersed in water for 72 h to reach a water saturation of more than 95%. For Case III, the water level should be increased to the top of the levelling layer, and the measurement can start after 72 h. By pouring water into the test samples, the electrical resistance is reduced if the fastening systems are not appropriately insulated, as stated in [24]. Prior to the measurement, the electrical conductivity of the water should be measured. This measurement is described in the EN 27888 standard and should be 50 ± 5 mS/m. The samples before starting the measurement are shown in Figure 13.

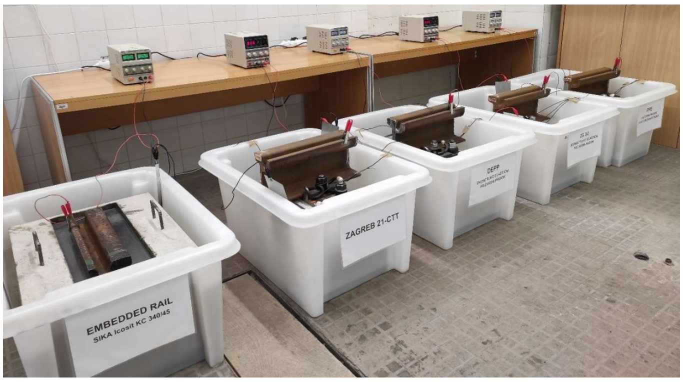


Figure 13. Samples before starting the experiment and electrical resistance measurement.

4.3. Calculating the Electrical Resistance of Fastening Systems

For each case in Figure 12, the average electrical resistance value must be calculated. Because the drying process of urban railway tracks built as part of the road surface is very slow, the electrical resistance reference value should be the value corresponding to the most unfavorable conditions, that is, when the water level reaches the top of the levelling layer. If the fastening systems are adequately insulated, the electrical resistance is not reduced by the wet concrete base and levelling layer. The measured electrical resistance for the five fastening systems in Figure 13 are shown in Figure 14. It can be observed that the different water levels in the specimens do not affect the electrical resistance when the electrical resistance of the fastening system is high (indirect fastening system II and continuously fastened rail).

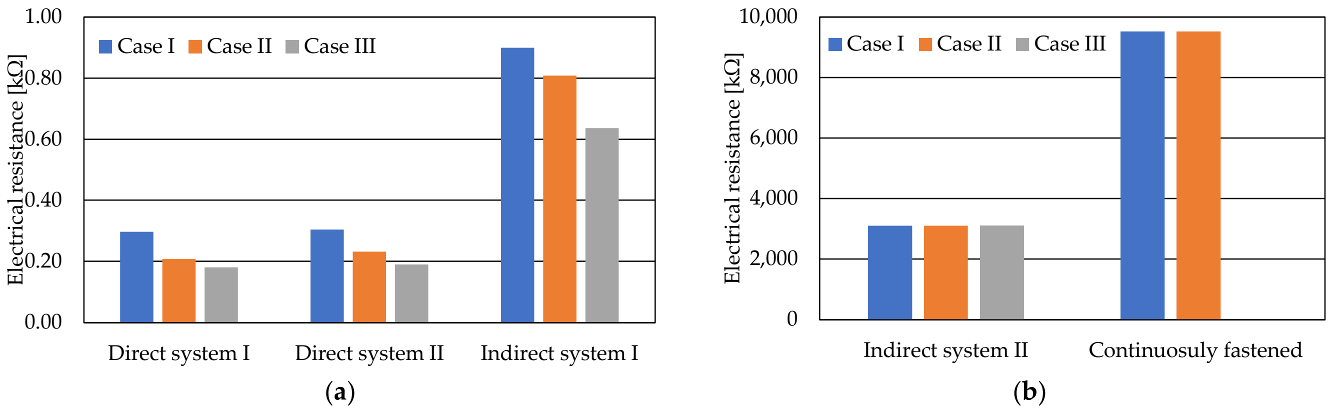


Figure 14. Measured electrical resistance values in different cases for: (**a**) two different direct fastening systems and an indirect fastening system where anchor bolts are not insulated, (**b**) an indirect fastening system with insulated anchor bolts and a continuously fastened rail sample.

A high electrical resistance is achieved in Indirect system II owing to the good insulation of the steel plate from the levelling layer and anchor bolts. As the electrical resistance of elastomeric materials can vary greatly depending on the fillers added to the rubber during manufacture [45], the electrical resistivity of elastomeric components of fastening systems must be among the defined properties in indirect fastening systems, and the electrical resistivity measurement of elastomeric elements should also be standardized. In this study, the electrical resistance was measured on an elastic rail pad, and the electrical resistivity was calculated. If all elastomer components of the fastening systems are made of the same material, the electrical resistivity for all elements can be calculated by measuring the resistance of only one element, e.g., the rail pad.

To measure the resistance of the rail pad, the pad should be placed on the steel plate with the rail placed on the pad. The rail should be connected to the positive pole of the current source and the steel plate to the negative pole (Figure 15). In this type of circuit, the dominant resistance is the that of the elastic pad.

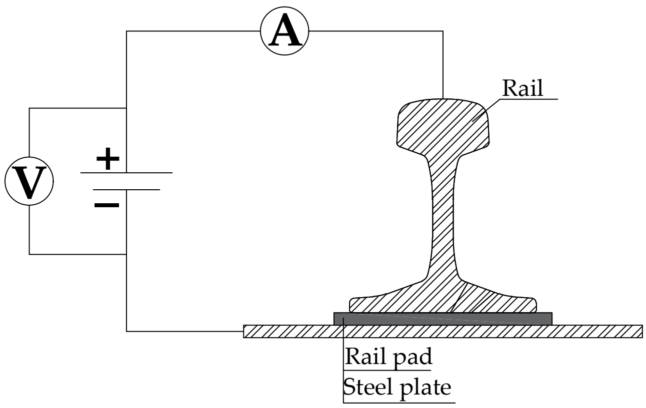


Figure 15. Measuring the electrical resistance of the elastic pad.

By measuring the current and voltage, the electrical resistance can be obtained, and the electrical resistivity of the material can be calculated as follows:

$$\rho = R \cdot \frac{S}{l} \tag{2}$$

where R is the calculated resistance based on the measured current and voltage, S is the surface of the contact between the elastic pad and rail or elastic pad and steel plate, and L is the elastic pad height.

5. Minimum Allowed Fastening System Electrical Resistance in Urban Railways Tracks

The stray current value depends on the rail current, voltage, longitudinal rail resistance, and rail-to-earth resistance. Current flows through the rail, but each point of the fastening system represents the discharge point for the current, and the stray current value depends on the electrical resistance of the fastening system.

According to the EN 50122-2:2011 standard [17], damage to individual tracks does not occur over a 25-year period if the average stray current per length of a single track line does not exceed I = 2.5 mA/m. Based on the maximum allowed stray current and the maximum voltage in the rail, the minimum rail-to-earth resistance value can be calculated as follows:

$$R_{RE,\ \min} = \frac{U_{RE}}{I/2} \tag{3}$$

where $R_{RE,\min}$ [Ωkm] is the minimum allowed rail-to-earth resistance value, U_{RE} [Ω] is the rail potential, and $I/2$ is the maximum allowed stray current per rail, as defined in the standard.

According to [35], each fastening point represents the discharge point for the current, and the rail-to-earth resistance depends on the number of fastening points per unit length and their electrical resistance. In this case, the minimum resistance at the fastening point $R_{FP,calc}$ can be calculated as follows:

$$\begin{gathered} R_{RE,\ \min} = \frac{R_{FP,calc}}{n} \\ R_{FP,\ calc} = R_{RE,\min} \cdot n \end{gathered} \tag{4}$$

where $R_{RE,\min}$ [Ωkm] is the calculated minimum rail-to-earth resistance value, $R_{FP,calc}$ [Ω] is the calculated minimum electrical resistance at the fastening point, and n is the number of fastening points on 1 km, per rail.

To prevent stray current in the urban railway track, the measured R_{FP} value determined by the laboratory test must be equal to or greater than $R_{FP,calc}$ (as in Equation (5)).

$$R_{FP} \geq R_{FP,calc} \quad (5)$$

All components of the direct fastening systems used in this laboratory test are in direct contact, so the final electrical resistance value for these types of fastening systems is close to zero, and the resistance at these fastening points depends only on the resistance of the concrete.

The final electrical resistance in indirect fastening systems depends on the resistivity of the elastomer used to insulate the anchor bolts and the resistance of the concrete. If we neglect the electrical resistance of the concrete, which can vary greatly depending on many parameters, 2, 3, and 4 can be used to determine the minimum electrical resistance that the elastomeric material must meet to prevent stray currents.

6. Accuracy and Repeatability of the Proposed Measurement

To confirm the accuracy of the measurements, the measurements were performed in three cycles, as specified in the standard. If the measurements are performed on the same sample, a drying period of 120 h is specified between each measurement. After the drying period, the sample is only surface dry, so the measured value under dry conditions in the next cycle will differ greatly from the previous cycle, as can be seen in Figure 8. As described in [27] the relative humidity of the sleeper increases with the number of measurement cycles. It should be noted that the drying process of urban railway tracks embedded in lanes shared with road vehicles is very slow and their concrete slab and levelling layer are usually only surface dry; therefore, the mean measured resistance in all three measurement cycles can be considered as a representative value for the dry condition. Because the measured electrical resistance depends strongly on the electrical resistance of the water, which in turn depends on its temperature, the water resistance must be measured before each cycle.

Considering the wide range of environmental conditions in conventional railway infrastructure, the effects of different conditions are minimized in the measurement defined in the standard, where the measured electrical resistance value represents the resistance between the sleeper and fastening system. In addition, in urban railway tracks, many parameters that are not simulated in laboratory measurements have an influence on rail-to-earth resistance, such as the electrical resistance of the soil and the electrical resistance of the water that remains in the pores of the concrete slabs [36,46]. However, if the measured electrical resistance of the fastening system is high, other parameters do not affect the electrical resistance, as shown in Figure 14.

7. Conclusions

Because of the significant corrosion damage that stray currents cause in urban areas, it is necessary to prevent it at the source. In urban railway tracks, stray currents can be determined by measuring the rail-to-earth resistance, but the stray current value depends on many parameters; therefore, it is difficult to determine the actual values via a single field measurement. The rail-to-earth resistance depends on the type of track, type of fastening system, track drainage characteristics, and soil moisture.

Stray currents can be prevented by insulating the fastening systems in the tracks using discretely fastened rails. However, the electrical resistance of the fastening system is not among the characteristics that the fastening systems must satisfy; it is a consequence of other characteristics. Furthermore, the electrical resistance measurement is also not standardized. In this study, the EN 13146-5 standard for the electrical resistance measurement of fastening systems used in urban railway tracks is analyzed and modifications to the standard are proposed to make it suitable for the electrical resistance measurement of fastening systems in urban railway tracks. The minimum electrical resistance values that fastening systems must satisfy to prevent stray currents are also defined.

Reducing stray currents at the source results in significantly lower maintenance costs for the track infrastructure and all nearby structures. Therefore, it is necessary to achieve high rail-to-earth resistance using fastening systems that are appropriately insulated and whose electrical properties are determined in laboratory tests.

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References

1. Zaboli, A.; Vahidi, B.; Yousefi, S.; Hosseini-Biyouki, M.M. Evaluation and Control of Stray Current in DC-Electrified Railway Systems. *IEEE Trans. Veh. Technol.* **2017**, *66*, 974–980. [CrossRef]
2. Cai, Z.; Zhang, X.; Cheng, H. Evaluation of DC-Subway stray current corrosion with integrated multi-physical modeling and electrochemical analysis. *IEEE Access.* **2019**, *7*, 168404–168411. [CrossRef]
3. Ibrahem, A.; Elrayyah, A.; Sozer, Y.; De Abreu-Garcia, J.A. DC Railway System Emulator for Stray Current and Touch Voltage Prediction. *IEEE Trans. Ind. Appl.* **2017**, *53*, 439–446. [CrossRef]
4. Song, Y.; Liu, Z.; Ronnquist, A.; Navik, P.; Liu, Z. Contact Wire Irregularity Stochastics and Effect on High-Speed Railway Pantograph-Catenary Interactions. *IEEE Trans. Instrum. Meas.* **2020**, *69*, 8196–8206. [CrossRef]
5. Chen, Z.G.; Qin, C.K.; Zhang, Y.J.; Yang, X.C. Application of a stray current monitoring system base upon virtual instrument. In Proceedings of the 2010 IEEE International Conference on Automation and Logistics, Hong Kong, China, 16–20 August 2010; pp. 341–344.
6. Vidov, V. Influence of stray current on the corrosion of structures near light rail tracks. In Proceedings of the Conference Dani prometnica, Zagreb, Croatia, 25–26 March 2013; pp. 453–513.
7. Chuchit, T.; Kulworawanichpong, T. Stray current assessment for DC transit systems based on modelling of earthing and bonding. *Electr. Eng.* **2019**, *101*, 81–90. [CrossRef]
8. Chen, Z.; Koleva, D.; Van Breugel, K. A review on stray current-induced steel corrosion in infrastructure. *Corros. Rev.* **2017**, *35*, 397–423. [CrossRef]
9. Bertolini, L.; Carsana, M.; Pedeferri, P. Corrosion behaviour of steel in concrete in the presence of stray current. *Corros. Sci.* **2007**, *49*, 1056–1068. [CrossRef]
10. Zakowski, K.; Darowicki, K. Methods of Evaluation of the Corrosion Hazard Caused by Stray Currents to Metal Structures Containing Aggressive Media. *Polish J. Environ. Stud.* **2000**, *9*, 237–241.
11. Robles Hernández, F.C.; Plascencia, G.; Koch, K. Rail base corrosion problem for North American transit systems. *Eng. Fail Anal.* **2009**, *16*, 281–294. [CrossRef]
12. Zhu, Q.; Cao, A.; Zaifend, W.; Song, J.; Shengli, C. Stray current corrosion in buried pipeline. *Anti-Corros. Methods Mater* **2011**, *58*, 234–237. [CrossRef]
13. Lucca, G. Evaluating stray current interference from DC traction lines on a pipeline network by means of a stochastic approach. *Electr. Eng.* **2021**, *103*, 417–428. [CrossRef]
14. Wang, C.; Li, W.; Wang, Y.; Xu, S.; Fan, M. Stray current distributing model in the subway system: A review and outlook. *Int. J. Electrochem. Sci.* **2018**, *13*, 1700–1727. [CrossRef] [PubMed]
15. Gu, J.; Yang, X.; Zheng, T.Q.; Shang, Z.; Zhao, Z.; Guo, W. Negative Resistance Converter Traction Power System for Reducing Rail Potential and Stray Current in the Urban Rail Transit. *IEEE Trans. Transp. Electrif.* **2020**, *7*, 225–239. [CrossRef]

16. Memon, S.A.; Fromme, P. Stray Current Corrosion Mitigation, Testing and Maintenance in DC Transit System. *Int. J. Transp. Dev. Integr.* **2017**, *1*, 205–213. [CrossRef]
17. CENELEC. EN 50122-2:2011; Railway Applications-Fixed Installations-Electrical Safety, Earthing and the Return Circuit—Part 2: Provisions against the Effects of Stray Currents Caused by d.c. *Traction Systems.* Available online: https://standards.iteh.ai/catalog/standards/clc/bbc881bc-baa8-4ecc-908e-4e01216a7c81/en-50122-2-2010 (accessed on 30 November 2022).
18. Bongiorno, J.; Mariscotti, A. Track insulation verification and measurement. *MATEC Web Conf.* **2018**, *180*, 6. [CrossRef]
19. Vranešić, K.; Lakušić, S.; Kolar, V.; Placek, J. Stray current measurement at the tramway infrastructure in Ostrava, Czech Republic. In Proceedings of the 6th International Conference on Road and Rail Infrastructure CETRA 2020*, Zagreb, Croatia, 20–21 May 2021; pp. 575–482.
20. Allahkaram, S.R.; Isakhani-Zakaria, M.; Derakhshani, M.; Samadian, M.; Sharifi-Rasaey, H.; Razmjoo, A. Investigation on corrosion rate and a novel corrosion criterion for gas pipelines affected by dynamic stray current. *J. Nat. Gas Sci. Eng.* **2015**, *26*, 453–460. [CrossRef]
21. Chen, S.L.; Hsu, S.C.; Tseng, C.T.; Yan, K.H.; Chou, H.Y.; Too, T.M. Analysis of rail potential and stray current for Taipei Metro. *IEEE Trans. Veh. Technol.* **2006**, *55*, 67–75. [CrossRef]
22. LRT Design Criteria Manual Valley Metro Light Rail Transit Projects. Available online: https://www.valleymetro.org/sites/default/files/uploads/event-resources/design_criteria_manual_january_2018.pdf (accessed on 15 December 2022).
23. Central Corridor Light Rail Project Design Criteria. Available online: https://metrocouncil.org/Transportation/Publications-And-Resources/Transit/LIGHT-RAIL/Central-Corridor-Light-Rail-Transit-Design-Criteri.aspx (accessed on 21 November 2022).
24. Charalambous, C.A. Stray Current Control and Corrosion for DC Mass Transit Systems. Doctoral Thesis, University of Manchester, Manchester, UK, 2005.
25. Zagreb Electric Tram (ZET). *Propisnik o Održavanju Pruge i Pružnih Postrojenja*; Guidelines; Zagreb Electric Tram (ZET): Zagreb, Croatia, 1982.
26. Baniček, M.; Uroš, M.; Lakušić, S. Development of a new and modification of existing elastic clips for rails fastening. *J. Croat. Assoc. Civ. Eng.* **2022**, *74*, 503–517.
27. Barroso, F.J.; Guarner, P.; López, C. Study on the electrical resistance of the sleeper-fastening elements system in railway tracks. *Mater. Constr.* **2012**, *62*, 455–460. [CrossRef]
28. CEN. EN 13146-5:2012; Railway Applications–Track-Test Methods for Fastening Systems Determination of Electrical Resistance. Available online: https://standards.iteh.ai/catalog/standards/cen/81b44d0b-ce53-47f7-a4d2-73bd9533bd0e/en-13146-5-2012 (accessed on 12 March 2022).
29. Vranešić, K.; Haladin, I.; Lakušić, S. Determination of electrical resistance of rail fastening system according to the standard EN 13146_5-2012. In Proceedings of the 7th International Conference on Road and Rail Infrastructure CETRA 2022, Pula, Croatia, 11–13 May 2022; pp. 261–267.
30. Ludvigh, E. Elastic behaviour of continuously embedded rail systems. *Period Polytech. Civ. Eng.* **2002**, *46*, 103–114.
31. Gailiene, I.; Laurinavičius, A. The need and benefit of slab track: Case of Lithuania. *J. Croat. Assoc. Civ. Eng.* **2017**, *69*, 387–396.
32. Vranešić, K. Impact of Stray Currents on Rail Fastening Components in Urban Areas. Doctoral Thesis, University of Zagreb, Faculty of Civil Engineering, Zagreb, Croatia, 2022.
33. Lakušić, S.; Haladin, I.; Ahac, M. The effect of rail fastening system modifications on tram traffic noise and vibration. *Shock Vib.* **2016**, *2016*, 4671302. [CrossRef]
34. Vranešić, K.; Lakušić, S.; Serdar, M. Corrosion and stray currents at urban track infrastructure. *J. Croat. Assoc. Civ. Eng.* **2020**, *72*, 593–606.
35. Charalambous, C.A. Comprehensive modeling to allow informed calculation of DC traction systems' stray cur-rent levels. *IEEE Trans. Veh. Technol.* **2017**, *66*, 9667–9677. [CrossRef]
36. Madhavi, T.C.; Annamalai, S. Electrical conductivity of concrete. *ARPN J. Eng. Appl. Sci.* **2016**, *11*, 5979–5982.
37. Yang, S.; Yang, X. Evaluation of stray current corrosion resistance of concrete in metro construction. *Front. Arch. Civ. Eng. China* **2008**, *2*, 246–252. [CrossRef]
38. Pandrol: Nabla Evolution Rail Fastening System. 2019. Available online: https://www.pandrol.com/product/nabla-evolution/ (accessed on 14 November 2022).
39. Israel Railways LTD: Technical Specification for Manufacture and Supply of Rail Fastening System W14 with SKL14 for Universal Prestressed Monoblock Concrete Sleepers. Available online: https://www.rail.co.il/tenders/Documents/shlomit/42012/Technical%20Specification%20for%20Rail%20Fastening%20System%20W14%20with%20SKL14%20_followed_by__Changes.pdf (accessed on 14 November 2022).
40. Barron, J.J.; Ashton, C. The Effect of Temperature on Conductivity Measurement. A Reagecon Technical Paper. Available online: https://sitefiles.camlab.co.uk/Tech_papers/TempCondMeas.pdf (accessed on 21 February 2022).
41. Smith, S.H. Temperature correction in conductivity measurements. *Limnol. Oceanogr.* **1962**, *7*, 330–334. [CrossRef]
42. CEN. EN 27888:2008; Water Quality-Determination of Electrical Conductivity (ISO 7888:1985; EN 27888:1993). Available online: https://standards.iteh.ai/catalog/standards/iso/ee68b1e3-f2e7-4f4d-8c36-f57456d28550/iso-7888-1985 (accessed on 2 February 2022).
43. Aatif, S.; Hu, H.; Rafiq, F.; He, Z. Analysis of rail potential and stray current in MVDC railway electrification system. *Railw. Eng. Sci.* **2021**, *29*, 394–407. [CrossRef]

44. Zhang, G.; Li, X.; Wei, H. Experimental study on concrete humidity under water environment. *Adv. Sci. Technol. Water Resour.* **2019**, *39*, 51–55.
45. Burcar, D. Ispitivanje Svojstava Gumenih Tvorevina. Master's Thesis, University of Zagreb, Zagreb, Croatia, 2010.
46. Zhichao, C.; Cheng, H. Evaluation of metro stray current corrosion based on finite element model. *J. Eng.* **2019**, *2019*, 2261–2265. [CrossRef]