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IMPACT OF ENVIRONMENTAL CONDITIONS ON STRAY CURRENT IN URBAN TRACK SYSTEMS

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Abstract

In most DC-electrified urban rail systems, the running rails act as the return path for train current. If the rails are not properly insulated, voltage can cause stray currents to flow through unintended paths, such as nearby metallic pipelines, instead of returning directly to the electrical substation. Maintaining high rail-to-ground resistance is therefore essential to minimize stray currents, which can be achieved through rail insulation. However, complete insulation is often impractical in tram systems, such as those in Zagreb, where rails are fastened to the ground at discrete intervals of one meter. As a result, the rail-to-ground resistance varies depending on environmental conditions. This paper analyses how different environmental conditions affect rail-to-ground resistance and stray current levels, which can cause stray current corrosion. This type of corrosion occurs at points where current leaves the rail and enters the surrounding electrolyte. As stray current corrosion is highly localized, it can cause severe damage to rails and rail fastening systems, potentially compromising traffic safety. Therefore, careful monitoring and control of stray currents in urban rail systems are crucial to prevent structural damage.

Keywords: urban track system, DC current, stray current, rail potential, rail-to-ground resistance

1 Introduction

Urban rail systems are the primary mode of transport in many cities worldwide. To remain competitive, they must meet increasingly demanding requirements for speed, frequency, and capacity, which require modern track construction that is properly and regularly maintained and monitored. Today, most urban rail systems are electrified, with vehicles operating on DC voltages, mostly in the range of 600 V to 750 V [1, 2]. Power is supplied by traction power stations (TPS) to the vehicles or trains via a catenary system, and in most cases, rails are used as the return current path. When current flows back to the TPS, the longitudinal electrical resistance of the rails causes a voltage drop, resulting in a potential difference between the rails and the ground [3, 4]. As the rails serve as current conductors, they need to be properly insulated to prevent current from leaking into the rail fastening systems, track components, and nearby metal structures, such as buried pipelines, and thus returning to the source [5]. This leakage current, known as stray current, can cause dangerous pitting corrosion at exit points (anodic areas). At the point where the current enters the metal structure or returns to the rail near the TPS, it is cathodically protected from corrosion, and this point is called the cathodic area. The stray current flow is shown schematically in figure 1.

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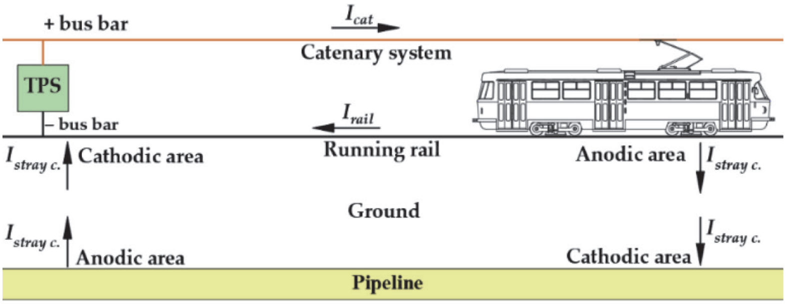

Figure 1 Stray current flow from urban tracks [6]

The value of the stray current depends on the rail potential and the resistance between the rail and earth. The rail potential is determined by the distances between power stations, the type of tram vehicles, and the number of vehicles on the track at the same time. Rail-to-ground resistance depends mainly on the type of track construction [5, 7]. According to [8], the maximum value of rail-to-ground voltage must be less than 90 V for safety reasons.

Urban tracks are typically constructed with a base of reinforced concrete (slab track), where rails are either continuously or discretely fastened. For tracks with continuously fastened rails (embedded rail), the rails are laid into grooves within the precast concrete slab, and the space between the rail and the slab is filled with elastic material so that the rails are completely insulated (figure 2a) [9]. This elastic material ensures that the rails have continuous support with specifically determined elasticity. With this type of track, stray currents are also prevented, as the elastic material has high electrical resistivity. In the case of tracks with discretely fastened rails, the rails are fastened at certain intervals using different types of fastening systems. For the tram track in Zagreb, the rails are laid every 1 m on a concrete levelling layer and fastened with a fastening system (figure 2b) [10]. The tracks can be opened and closed. In closed construction, the tracks are closed by rail top edge with reinforced concrete slabs, concrete with an asphalt layer or other material. If tracks are built as part of the road surface, they need to be closed so that road vehicles can use the track surface for driving. If the tracks are laid in a separate band they can be opened or closed, using different materials to reduce the high levels of noise and vibration generated by tram passing [9]. An example of an open and closed track is shown in figure 3.

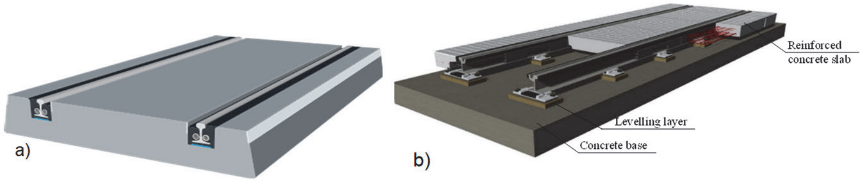

Figure 2 3D model of track: a) with continuously fastened rails, b) with discretely fastened rails

Figure 3 Track with discretely fastened rails: a) opened and located in separate band, b) closed and built as part of the road surface

For tracks with discretely fastened rails, rail-to-ground resistance varies over the year due to insufficient rail insulation and depends on the environmental conditions. This value depends on the resistance of the concrete slab of the track and the resistance of the soil. According to [11], wet concrete behaves like a semiconductor with a resistivity in the order of 10^5 Ωmm, while oven-dried concrete behaves like an insulator with resistivity in the order of 10^{12} Ωmm. The influence of different values of soil resistivity on the value of leakage current is studied in [12], where it is shown that as the electrical resistivity of the soil decreases, the value of stray current increases. Soil resistivity is determined by the content of its electrolyte, which consists of moisture content, minerals, temperature and dissolved salt [13].

2 Influence of environmental conditions on rail-to-ground resistance and stray current in urban tracks

The maximum allowed rail-to-ground electrical conductivity and time averaged rail potential shift ΔU_{RE} that needs to be met so that stray current does not pose a danger to the track construction are defined in standard EN 50122-2:2022 [14] and are as follows:

- $G_{RE} \leq 0.5$ S/km per track and $\Delta U_{RE} \leq +5$ V for open track construction
- $G_{RE} \leq 2.5$ S/km per track and $\Delta U_{RE} \leq +1$ V for closed track construction.

However, it is difficult to measure these parameters in practice. Since the ambient conditions influence the rail-to-ground conductance for track with discretely fastened rails, the measurement must be carried out over a longer period to obtain a real picture of stray current value. Stray current monitoring systems have been developed for this purpose, but only a few operators have installed such a system in their infrastructure.

2.1 Environmental conditions in closed tracks and their influence on track component

An analysis of drainage systems in railway tracks is presented in [15], which highlights the negative consequences of water retention in the track structure, as it leads to corrosion of rails and fastening systems. The corrosion rate and the magnitude of stray currents depend on external weather conditions. During the summer months, when there is no precipitation, the track remains dry, which reduces the corrosion rate. As a result, the rail-to-ground resistance increases, leading to lower stray current values. Conversely, during periods of precipitation, water seeps into the track structure and often accumulates within it. This increases the corrosiveness of the environment, as track elements come into direct contact with the electrolyte and all conditions necessary for corrosion processes are fulfilled. In addition, the rail-to-ground resistance is reduced. The condition of the track during most of the year is shown in figure 4. This track condition was observed during track reconstruction, after the concrete slabs used for track closure had been removed.

Figure 4 Condition in closed track structure during the most period in a year

The corrosion rate of the track embedded in the road infrastructure and the reduction of the rail-to-ground resistance are also favored by the presence of de-icing salts, which are used to treat road surfaces when the road surface is wet, the air temperature is below 0 °C, just before the onset of snow, when “freezing rain” is expected and when the grip of the road surface is reduced. Sodium and calcium chloride without sand or fine gravel are used as de-icing salts [16, 17]. These salts dissolve in water and seep into the track, where they remain and further promote corrosion reactions. According to [18], the loss of material at the rail foot caused by aggressive corrosion processes leads to a reduction in the rail cross-section and the formation of sharp edges. This can have a negative effect on the transmission of forces and loads and possibly lead to rail foot fractures or the development of permanent plastic deformations. In addition, the loss of material at the rail foot weakens the fastening force and increases the risk of track widening in small radius curves. Research [9, 19-21] has shown that the most severe degradation due to corrosion and stray currents in highly aggressive environments occurs not only at the rail foot (lateral and bottom sides), but also at the components of the fastening system. Examples of corroded rails and clip, a component of the fastening system, are shown in figure 5.

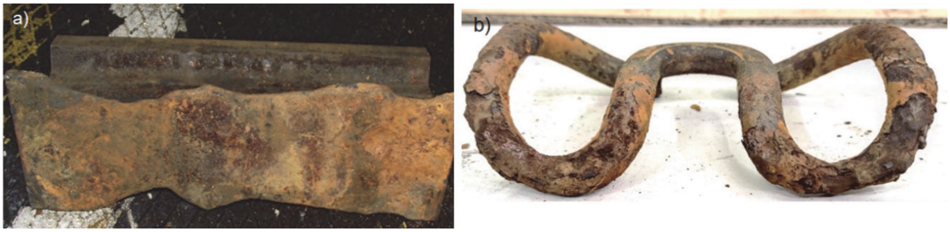

Figure 5 Sample of corroded rail and clip taken from urban track infrastructures

Unfortunately, despite the detrimental effects and loss of material that corrosion causes in track construction, this is still something that operators do not consider important, so many guidelines do not include instructions on insulating the rail and preventing corrosion and stray current.

2.2 Laboratory simulations

In [9], laboratory simulations were carried out to investigate the effects of different environmental conditions on rail-to-ground resistance. The measurements were carried out for embedded tracks and for tracks with discretely fastened rails, using the fastening system characteristics for tram infrastructure in the city of Zagreb (so called PPE fastening system). In the case of embedded track, the 50 cm long rail is inserted into the groove in the reinforced concrete base and fastened with elastomeric material (figure 6a). In the PPE fastening system, the rail is placed on the elastic pad and the steel plate. Rail is fastened to the levelling layer and the concrete base with clips and anchor bolts (figure 6b). The tests were carried out under different conditions:

- when the samples were dry
- water level by upper edge of concrete base
- water level by upper edge of levelling layer (applicable only for PPE fastening system)
- water level by rail foot (applicable only for PPE fastening system)
- water level by the middle of rail height (applicable only for PPE fastening system).

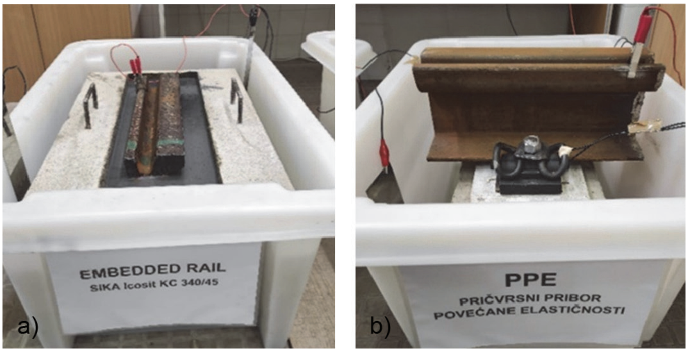

Figure 6 Testing samples, a) embedded track, b) PPE fastening system

Laboratory samples were threatened with the 26 V DC of the laboratory power supply. The rail was connected to the positive busbar of the power supply and the steel bar embedded in the concrete base was connected to the negative busbar. The circuit is shown schematically in figure 7.

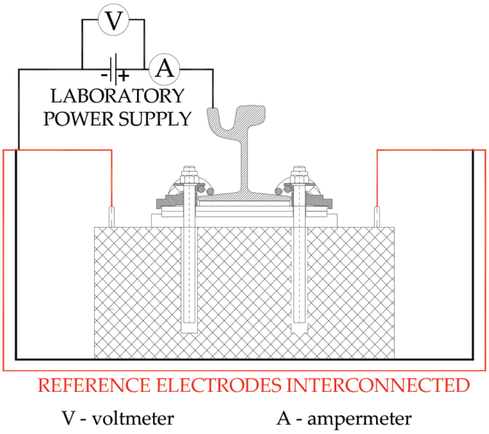

Figure 7 Schematic view of the current circuit

The current flowed from the rail via the fastening systems and the concrete base back to the source. The electrical current and voltage were measured and the electrical resistance calculated. The electrical resistance of the embedded rail differed when the sample was dry and when the concrete base was immersed in water, but the values were still very high, so stray current is prevented in both cases. The difference between the values is the result of the different electrical resistance of the concrete. When dry, the concrete has high electrical resistivity, but with increasing moisture, the concrete becomes a semiconductor.

The electrical resistance of the sample with PPE fastening system is much lower than that of the embedded rail, and as the water level increases, the resistance decreases. When the rail and fastening system are in direct contact with the electrolyte (water), the current flows directly from the rail and fastening system components into the water, resulting in harmful pitting corrosion. The results are shown in figure 8.

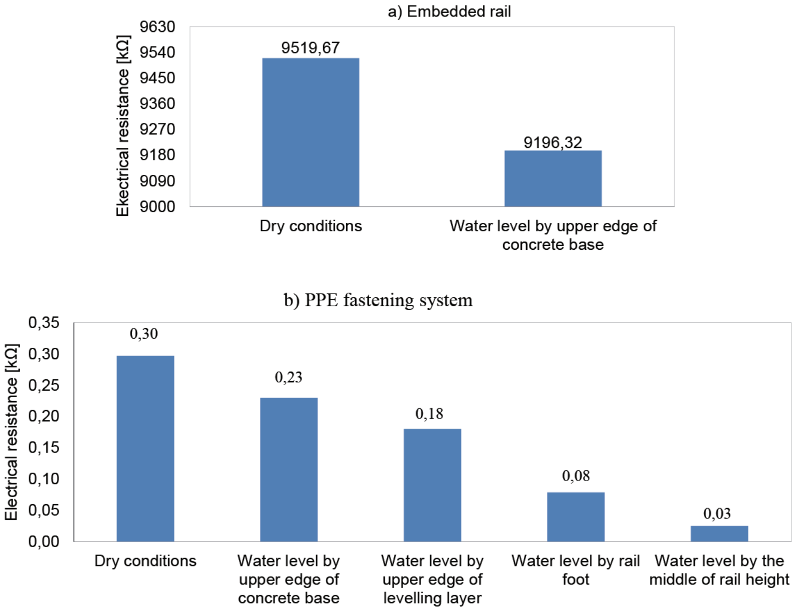

Figure 8 Measured values of electrical resistance of laboratory samples: a) embedded rail, b) track with discretely fastened rails

From this laboratory measurement it can be concluded that the electrical resistance of track in which the rails are discretely fastened is strongly dependent on the ambient conditions. A reduction in electrical resistance leads to a high stray current value. When the water level in the track rises, the rails and the components of the fastening system are also in direct contact with water, causing not only stray current corrosion but also other types of corrosion. Under real track conditions, the corrosion rate is higher and the electrical resistance lower, as chlorides and other particles remain in the track.

3 Conclusion

This paper shows the influence of environmental conditions on corrosion and rail-to-ground resistance in urban tracks causing stray currents. If rails are not adequately insulated, the rail-to-ground resistance will differ during the year. Despite harmful degradation that corrosion and stray current causes on tracks, operators still do not take enough care about this topic. In most cases rails are not appropriately insulated, electrical resistance of fastening system is not defined, and stray currents are not monitored during the lifetime of the track construction. Furthermore, in many infrastructures, corrosion can only be detected by visual inspection, which is not possible in closed track systems. Laboratory simulations confirm that increasing moisture content significantly reduces electrical resistance and increases the effects of stray current. To avoid stray current and minimize the corrosive effects of environmental conditions, urban rail operators should therefore pay more attention to effective track drainage, especially in closed track systems. Regular monitoring and maintenance should be enforced through systematic inspections of rail and rail fasteners to detect early signs of corrosion and replace severely corroded components immediately to avoid track instability and safety risks. The development of real-time monitoring systems to track environmental conditions such as moisture, temperature and chloride concentration in rail structures would provide real-time data on rail-to-ground resistance and potential stray current leakage.

Today, the effects of corrosion and stray currents are not considered in the design of urban track systems, and track maintenance is mostly reactive – damaged parts are only replaced when corrosion becomes visible. To minimize the damaging effects of corrosion and stray currents, appropriate protective measures should be taken when designing the track structure and a numerical model should be used to predict corrosion degradation and the occurrence of stray currents during the lifetime of the track structure.

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Rerefences

[1] Popescu, M., Bitoleanu, A.: A review of the energy efficiency improvement in DC railway systems, Energies, 12 (2019) 6, 1092, DOI: https://doi.org/10.3390/en12061092

[2] Tzeng, Y.S., Lee, C.H.: Analysis of rail potential and stray currents in a direct-current transit system, IEEE Trans Power Deliv, 25 (2010) 3, pp. 1516-25, DOI: https://doi.org/10.1109/TPWRD.2010.2040631

[3] Dolara, A., Leva, S.: Calculation of Rail Internal Impedance by Using Finite Elements Methods and Complex Magnetic Permeability, Int J Veh Technol, 2009., DOI: https://doi.org/10.1155/2009/5052

[4] Paul, D.: DC traction power system grounding, IEEE Trans Ind Appl, 38 (2002) 3, pp. 818-24, DOI: https://doi.org/10.1109/TIA.2002.1003435

[5] Du, G., Zhang, D., Li, G., Wang, C., Liu, J.: Evaluation of Rail Potential Based on Power Distribution in DC Traction Power Systems, Energies, 9 (2016) 9, 729, DOI: https://doi.org/10.3390/en9090729

[6] Vranešić, K., Bhagat, S., Mariscotti, A., Vail, R.: Measures and Prescriptions to Reduce Stray Current in the Design of New Track Corridors, Energies, 16 (2023) 17, 6252, DOI: https://doi.org/10.3390/en16176252

[7] Wu, G., Song, K.: Decreasing the Rail Potential of High-Speed Railways Using Ground Wires, Appl Sci, 13 (2023) 13, 7944, DOI: https://doi.org/10.3390/app13137944

[8] Aatif, S., Hu, H., Rafiq, F., He, Z.: Analysis of rail potential and stray current in MVDC railway electrification system, Railw Eng Sci, 29 (2021), pp. 394-407

[9] Vranešić, K.: Impact of stray currents on rail fastening components in urban areas, doctoral thesis, University of Zagreb, Faculty of Civil Engineering, 2022.

[10] Lakušić, S., Haladin, I., Ahac, M.: The effect of rail fastening system modifications on tram traffic noise and vibration, Shock Vib, 2016.

[11] Madhavi, T.C., Annamalai, S.: Electrical conductivity of concrete, ARPN J Eng Appl Sci, 11 (2016) pp. 5979–82

[12] 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, 66 (2017), pp. 974–80, DOI: https://doi.org/10.1109/TVT.2016.2555485

[13] Azhar, A.T.S., Ayuni, S.A., Ezree, A.M., Nizam, Z.M., Aziman, M., Hazreek, Z.A.M., et al.: The Use of Electrical Resistivity Method to Mapping the Migration of Heavy Metals by Electrokinetic, IOP Conf Ser Mater Sci Eng, 226 (2017), DOI: https://doi.org/10.1088/1757-899X/226/1/012062

[14] CENELEC: EN_50122-2_2022: Railway applications - Fixed installations - Electrical safety, earthing and the return circuit - Part 2: Provisions against the effects of stray currents caused by DC traction systems

[15] Sañudo, R., Miranda, M., García, C., García-Sanchez, D.: Drainage in railways, Constr Build Mater, 210 (2019), pp. 391-412, DOI: https://doi.org/10.1016/j.conbuildmat.2019.03.104

[16] Vranešić, K., Lakušić, S., Serdar, M.: Corrosion and stray currents at urban track infrastructure, Građevinar, 72 (2020) 7, pp. 593-606, DOI: https://doi.org/10.14256/JCE.2909.2020

[17] Kušter Marić, M., Mandić Ivanković, A., Vlašić, A., Bleiziffer, J., Srbić, M., Skokandić, D.: Assessment of reinforcement corrosion and concrete damage on bridges using non-destructive testing, Građevinar, 71 (2019) 10, pp. 843–62, DOI: https://doi.org/10.14256/JCE.2724.2019

[18] Guidelines for Rail Base Inspection and Rail Condemnation Limits for Corrosion-Induced Material Loss, Transit Cooperative Research Program (TCRP), Washington, D.C.: Transportation Research Board, http://www.nap.edu/catalog/21941

[19] Robles Hernández, F.C., Plascencia, G., Koch, K.: Rail base corrosion problem for North American transit systems, Eng Fail Anal, 16 (2009), pp. 281–94

[20] Vranešić, K., Lakušić, S., Serdar, M., Alar, V.: Detrimental effect of stray current on rails and fastening systems in urban railway tracks, Constr Build Mater, 400 (2023), 132645, DOI: https://doi.org/10.1016/j.conbuildmat.2023.132645

[21] Isozaki, H., Oosawa, J., Kawano, Y., Hirasawa, R., Kubota, S., Konishi, S.: Measures Against Electrolytic Rail Corrosion in Tokyo Metro Subway Tunnels, Procedia Eng, 165 (2016), pp. 583-92, DOI: https://doi.org/10.1016/10.1016/j.proeng.2016.11.754