



THE EFFECT OF RAIL GRINDING AND RAIL CORRUGATION ON TRAMWAY TRACK NOISE AND VIBRATION LEVELS

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Abstract

Rail corrugation is one of the common types of rail running surface irregularity that significantly affects noise and vibration levels in railway and tramway systems. In urban environments, where tram tracks are often located close to residential areas, increased noise levels represent an important environmental concern. Rail grinding is widely used as a maintenance measure for removing rail surface irregularities, with its common use on corrugated rails, thus improving the acoustic performance of rail infrastructure. This paper investigates the relationship between rail corrugation and noise and vibration generated by tram traffic through on-site measurements conducted on the Zagreb tramway network. The results have shown that significant rail corrugation was present on the analyzed track section prior to grinding, particularly in the wavelength range of 30–100 mm. After the grinding operation, the amplitudes of rail surface irregularities were considerably reduced and most of the measured data was reduced within acceptable limits defined by the relevant standards. Additionally, a noticeable reduction in pass-by noise levels and vehicle vibration levels after grinding was observed, with the average equivalent sound pressure level during the passage of representative tram vehicles decreased from 4 to 6 dB. Frequency-domain analysis indicated that rail corrugation primarily influenced noise levels in the frequency range between 100 Hz and 315 Hz. The results confirmed a strong relationship between rail surface condition with noise and vibration generated by tram traffic, demonstrating that rail grinding can be an effective maintenance measure for reducing rail corrugation and thus consequentially improving acoustic conditions in urban tramway systems.

Keywords: rail corrugation, rail grinding, tramway noise and vibration, in-situ measurements, track maintenance

1 Introduction

Urban tram systems are an important part of public transport in many cities. Because tram tracks often run close to residential areas, noise from tram traffic can have a noticeable impact on the surrounding environment. High noise levels may affect the quality of life of residents and therefore represent an important issue in the operation and maintenance of tram infrastructure [1]. One of the common causes of increased noise in rail systems is rail corrugation. Rail corrugation is a periodic irregularity that develops on the running surface of the rail during track operation. These surface waves are created due to the dynamic interaction between the wheel and the rail. When a tram passes over such irregularities, additional vibrations are generated, which can lead to increased noise emission. Corrugation leads to increased dynamic forces, accelerated wear of track components and higher noise and vibration levels [2].

Corrugation can occur in different wavelength ranges and is commonly classified as short-pitch and long-pitch corrugation. Short-pitch corrugation generally occurs in the wavelength range between approximately 30 mm and 100 mm, while long-pitch corrugation typically occurs in the range of 100 mm to 300 mm. Shorter wavelengths generally excite higher-frequency vibrations, which fall within the frequency range most perceptible to the human ear. Because of this, short-pitch corrugation is often associated with the so-called “roaring rail” noise phenomenon [3]. The formation of corrugation is particularly common in tram systems, because trams often operate in curves with small radii and are subject to frequent acceleration and braking. Prof. Grassie identified several possible formation mechanisms including pinned–pinned rail resonance, P2 resonance of the vehicle–track system and friction-related wear processes in the wheel–rail contact zone [3]. In tramway systems, corrugation often develops in curves with relatively small radii where increased tangential forces and wheel–rail slip occur [4]. When a tram vehicle passes over corrugated rails, the periodic irregularities excite vibrations in the wheel–rail system. These vibrations propagate through the rail and track structure and are emitted as airborne noise [5]. The frequency range of the generated noise depends primarily on the wavelength of the corrugation and the speed of the vehicle [2, 5].

Considering the direct relationship between rail surface condition and noise emission, maintenance measures aimed at improving rail surface quality play a key role in reducing environmental noise in rail transport systems. There are various measures to mitigate the formation and rail corrugation development with acoustic rail grinding being identified as most effective [6]. It is widely used as a maintenance measure to remove irregularities from the rail surface. During grinding, a thin layer of material is removed from the rail head in order to restore a smooth running surface. This process reduces dynamic forces between the wheel and the rail and can also reduce noise and vibration levels [7]. Even relatively small amplitudes of corrugation may lead to noticeable increases in sound pressure levels, particularly in urban environments where tram tracks are located close to residential areas [1]. The aim of this paper was to investigate the relationship between rail corrugation with noise and vibration generated by tram traffic. Field measurements were conducted on the tram network of the City of Zagreb with rail running surface unevenness, pass-by noise and vehicle vibration levels measured before and after rail grinding to evaluate the influence of grinding on the condition of the rail surface and the resulting noise and vibration levels.

2 Measurement campaign

Direct (longitudinal rail profile – unevenness of the rail running surface) and indirect measurements (wayside pass-by noise and vehicle-based vibrations measurements) were conducted before and after rail grinding on a selected track section located near John F. Kennedy Square. Rail corrugation was measured using the RM 1200 D device, while noise measurements were carried out using a Brüel & Kjær 2270 sound level analyzer and vehicle vibration measurement with data acquisition system acquiring bogie frame acceleration data. The evaluation of directly measured rail surface irregularities was performed according to the HRN EN 13231-2 standard [8], which defines procedures for measuring the longitudinal rail profile and assessing rail surface quality after rail reprofiling operations along with HRN EN 15610 [9] standard used for evaluation of acoustic rail roughness. The standard HRN EN ISO 3095 [10] was used to analyze the noise generated by tramway vehicle during pass-by. It defines the measurement conditions and microphone positioning in order to ensure repeatability and comparability of results.

2.1 Test location

All of the on-site measurements were conducted the selected test section situated near John F. Kennedy Square, where rail corrugation had previously been visually observed on the running surface of the rails. The tram track at this section passes through a densely populated urban area with a high concentration of residential buildings, educational institutions, and student dormitories (figure 1); as a result, noise and vibration from tram traffic represent a significant environmental concern. These factors were taken into consideration when choosing this location. The measurements were performed in a horizontal curve with a radius of approximately 340 m, while neighbouring curves have radii of 285 m and 760 m.

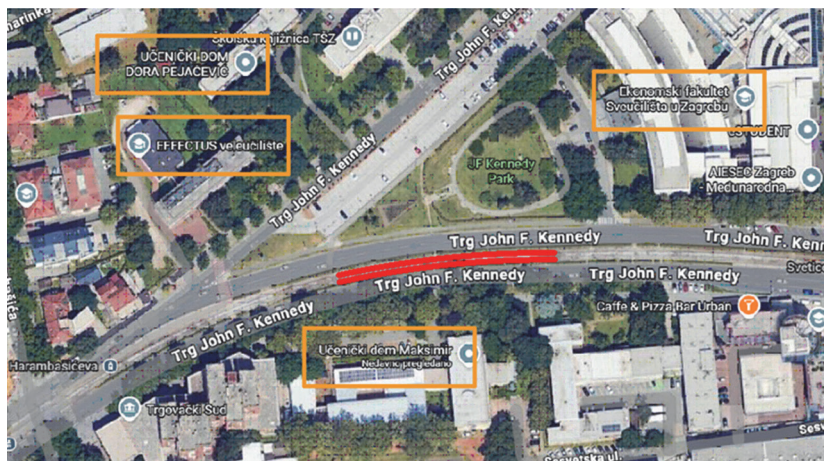


Figure 1 Location of the corrugated test track section and grinded section with nearby buildings

Curved track sections are known to be more susceptible to the development of rail corrugation due to increased tangential forces and wheel–rail slip. The last reconstruction of the test tram track section was performed in 2010, meaning that the rails had been in service for more than a decade prior to the conducted measurements. The test section is part of the Zagreb tram network used by several tram lines, including lines 1, 9 and 17, representing a very high density of the tramway traffic and consequently high traffic load. The track superstructure at the investigated location is a ballastless tram track with DEPP fastening system, which is commonly used on the Zagreb tramway network (figure 2).

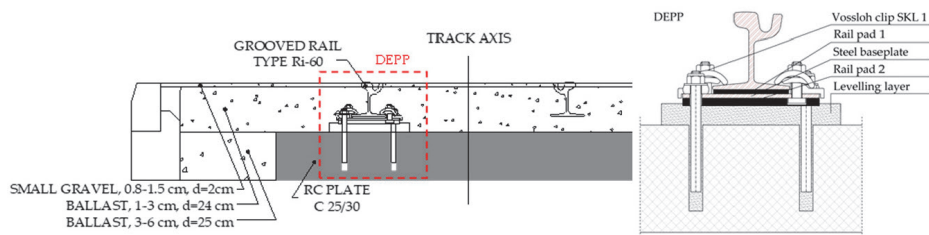


Figure 2 Cross section of the track superstructure with the detail of DEPP fastening system [2]

2.2 Measurement of rail corrugation

Rail corrugation was measured using the RM 1200 D device, which is designed for precise measurement of the longitudinal rail profile and rail surface irregularities. The RM 1200 D system measures the longitudinal rail profile over a measuring base length of 1.2 m. The device records surface irregularities at intervals of 2 mm with a measurement resolution of 0.01 mm, allowing for detailed analysis of the rail running surface. Measurements were performed both before and after rail grinding in order to evaluate the effectiveness of grinding in reducing rail corrugation.



Figure 3 Measurement setup for rail roughness and pass-by noise measurements

At the investigated location a total length of 12 m of track was measured (10 measuring intervals – MP (figure 3) and the measured data was analyzed using signal processing and filtering procedures that classify rail irregularities into wavelength ranges defined by the HRN EN 13231-2 standard [8] and HRN EN 15610 standard (third-octave frequency bands) [9].

2.3 Pass-by noise measurements

Noise measurements were performed using a Brüel & Kjær 2270 sound level analyzer. The measurement methodology was based on the principles defined in the HRN EN ISO 3095 standard [10], which specifies measurement conditions for noise generated by railway vehicles during pass-by events. According to the standard, the measuring microphone is typically positioned at a distance of 7.5 m from the track axis and 1.2 m above the rail head according to the HRN ISO 3095 standard [10]. However, due to spatial constraints at the investigated location, the sound level analyzer was positioned at a distance of 2.0 m from the track axis, while maintaining the height of 1.2 m above the rail head (figure 3). The recorded sound signals were later processed using the Evaluator Type 7820-7821 software.

2.4 Vehicle vibration measurements

The Končar TMK 2200 low-floor tramway vehicle's on-board monitoring equipment was used to acquire the vibrations dataset. The three units that together make up the acquisition system are the GNSS unit, which is mounted on the roof of the tramway vehicle for positioning and communication, the power unit, which is located inside the vehicle behind the information display with a battery pack and communication cables, and the acquisition unit, which has accelerometers mounted on the bogie frame on both sides of the vehicle. The research in [2] used the same acquisition system on the instrumented in-service train, and this is described in more details in the cited work.

2.5 Rail grinding

Rail grinding was performed as a corrective maintenance measure in order to remove rail corrugation and restore the smooth running surface of the rail head. The grinding operation was carried out using a self-propelled rail grinding machine equipped with grinding stones designed to remove a thin layer of material from the rail surface. The grinding process removes surface irregularities and restores the correct rail profile, thereby reducing the dynamic interaction forces between the wheel and rail. Following the grinding operation, the same measurement procedures for rail corrugation and noise were repeated in order to evaluate the effectiveness of the grinding process.

3 Results analysis

The effectiveness of rail grinding has been evaluated using both direct measurements (rail roughness and corrugation in accordance with HRN EN 13231-3 [8] and HRN EN 15610 [9]) and indirect measurements (vehicle-based vibrations and wayside measured pass-by noise).

3.1 Influence of rail grinding on rail corrugation – HRN EN 13231-3 [8] and HRN EN 15610 standard [9]

To analyze rail corrugation according to the HRN EN 13231-3 standard [8], longitudinal rail profile values were compared to the defined limits, both before and after grinding. Direct measurements ($n = 10$) of the longitudinal rail profile before grinding showed pronounced short-pitch corrugation, most significantly in the 10 to 30 mm and 30 to 100 mm wavelength ranges. Several averaged values for a 12.0 m measurement section exceeded the 5% limit set by the standard by a high margin ($> 60\%$) for 30 to 100 mm wavelength range, and $> 45\%$ for 100-300 mm range. Table 1 shows that grinding considerably improved the rail running surface condition by reducing corrugation and non-compliant measurement values.

Table 1 Average amplitude exceedances [%] of rail corrugation according to the HRN EN 13231-3 standard [8] defined limits for 10-30 mm; 30-100 mm; 100-300 mm; 300-1000 wavelength ranges before and after the grinding

Before grinding (BG)/ After grinding (AG)	Left/Right rail	10-30 [mm]	30-100 [mm]	100-300 [mm]	300-1000 [mm]
BG	LR	4.9%	73.9%	47.3%	0%
	RR	10.2%	63.7%	47.3%	0%
AG	LR	0%	1.7%	4.1%	0%
	RR	0%	0.2%	0.9%	0%

It should be noted that the grinding process was performed more intensively on the right rail than on the left rail. Consequently, the remaining irregularities on the left rail may be partly attributed to the lower grinding intensity. With a more intensive grinding process, it is likely that the corrugation values on the left rail would also be reduced to fully acceptable levels. Graphical representations of the longitudinal rail profile according to the HRN EN 15610 [9] (figure 4) show that the grinding process successfully removed the periodic surface irregularities associated with corrugation. The results confirm that rail grinding effectively restored a smoother running surface of the rail head.

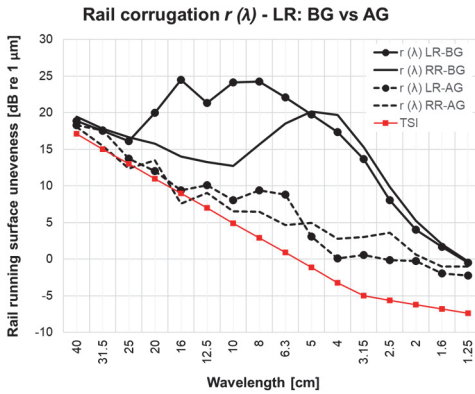


Figure 4 Rail corrugation on left and right rail before and after the grinding according to the HRN EN 15610 standard [g] in the wavelength domain

3.2 Influence of rail grinding on rail corrugation – pass-by noise

Pass-by noise and vehicle vibration measurements were carried out before and after rail grinding to determine the influence of rail surface condition on noise and vibration generated by tram traffic. The influence of rail corrugation on noise generation was clearly reflected in the noise measurements conducted during the field investigation. Before rail grinding, the equivalent noise level recorded during the passage of representative tram vehicles averaged 83.5 dB. After the grinding operation, the average equivalent noise level decreased to 78.4 dB (table 2). When analyzing individual tram passages with comparable vehicle speeds, the observed reduction in noise levels ranged between 4 dB and 6 dB. A reduction of approximately 6 dB corresponds to a sound pressure level that is approximately two times lower, which represents a significant improvement from the perspective of human sound perception.

Table 2 Equivalent pass-by noise levels for passages of Končar TMK 2200 low-floor tramway vehicle, before and after the grinding with operating speed for each passage

Before grinding (BG)/After grinding (AG)	Tramway passage nr.	Operating speed [km/h]	Pass-by noise levels [dB]
BG	1	30.5	80.2
	2	39.7	83.6
	3	46.7	86.6
	Average	38.9	83.5
AG	4	31.7	77.5
	5	34.5	77.9
	6	39.7	78.6
	Average	35.3	78.4

3.3 Influence of rail grinding on rail corrugation – vehicle vibrations

Further insight into the relationship between rail corrugation, pass-by noise and vehicle vibration generation can be obtained from the frequency-domain analysis of the measured data.

The analysis shown that when the tram vehicle travels at 40 km/h (figure 5b), the dominant rail corrugation wavelength of about 4 to 5 cm on the right rail before grinding (RR-BG; figure 4) generated vibrations in the frequency range of 200 to 315 Hz. The same comparison is shown for the left rail (LR-BG; figure 4), where the dominating wavelength prior to grinding is 16 cm, corresponding 63 Hz for the same operating speed (figure 5a).

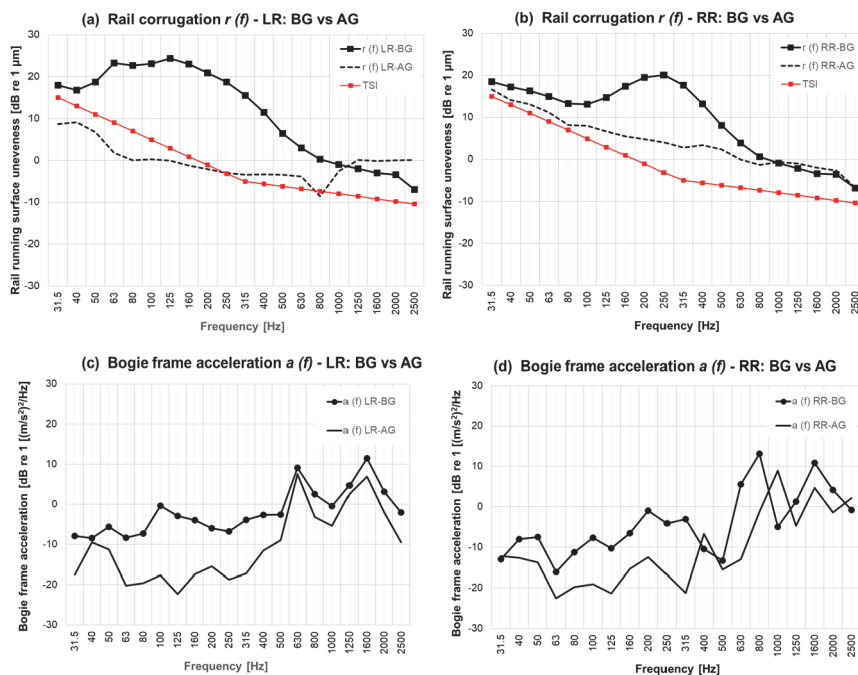


Figure 5 Rail corrugation (a, b) and bogie frame acceleration levels (c, d) before and after the grinding presented in the third-octave frequency bands

The research revealed that the reduction in rail corrugation amplitudes was most noticeable at frequencies between 31.5 and 1000 Hz at both rails, with the highest reduction of values occurring at 125 Hz on the left rail and up to 15 dB at 250 Hz on the right rail. With respect to the rail corrugation amplitudes in figure 5a, b, the vehicle vibration data (bogie frame acceleration) showed the largest reduction of 18 dB at the left rail (125 Hz) and 15 dB at the right rail (315 Hz) in the 31.5 to 500 Hz frequency range (figure 5c, d).

The presented comparison was additionally validated by the spectrum analysis of noise signals and vehicle vibration in figure 6. The analysis revealed that the rail grinding contribution to noise and vibration levels was most substantial in the 100 to 500 Hz range, with values reducing from 5 to 15 dB. After the rail grinding, pass-by noise levels decreased significantly, up to 15 dB at 250 Hz. This showed good agreement with the averaged vehicle vibration levels, as shown in figure 6. The left and right sides were averaged to provide a single value that took into account the contributions of both rails; and the most significant reduction of vibration levels was up to 15.5 dB also at 250 Hz.

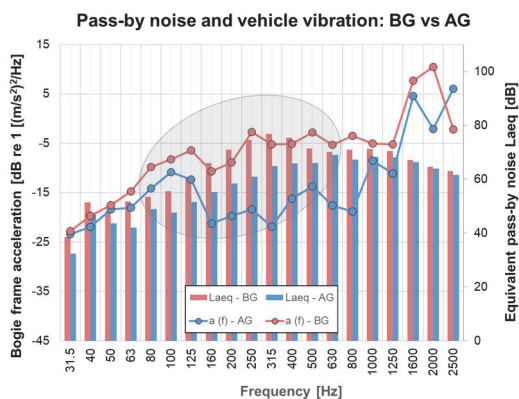


Figure 6 Pass-by noise levels and vehicle vibration for a passage of tramway vehicle Končar TMK 2200 with $v = 40$ km/h, before and after the grinding

The comparison of both direct and indirect measurements that were carried out before and after rail grinding showed a significant reduction in rail corrugation amplitudes and a corresponding reduction in noise and vibration levels confirming the close relationship between rail corrugation and noise and vibration generated by tram traffic.

4 Conclusion

In this research, on-site measurements were conducted on a section of the Zagreb tramway network in order to analyse the influence of rail corrugation and rail grinding on noise and vibration levels generated by tram traffic. Measurements of the longitudinal rail profile, pass-by noise and vehicle vibration were performed before and after rail grinding. The results of the measurements showed the presence of corrugation on the investigated track section prior to grinding with highest amplitudes in 30 – 100 mm and 100 – 300 mm wavelength ranges. After the rail grinding, the amplitudes of rail surface irregularities were significantly reduced (up to 15 dB), indicating an improvement in the condition of the rail running surface. Pass-by noise and vehicle vibration measurements conducted after grinding correspondingly showed lower noise levels during tram passage with up to 20 dB reduction at some frequency bands for a 40 km/h tramway passages. The results therefore confirmed the relationship between rail surface condition with noise and vibration generation in tramway systems. The study showed that pass-by noise and vehicle vibration measurements can be a helpful tool for assessing how rail grinding improves the state of the rail running surface, resulting in lower levels of pass-by and vehicle vibration. Accordingly, frequent grinding program implementation can support both the long-term longevity of tramway infrastructure and better acoustic circumstances in urban settings. Future studies should, however, also look into how rail grinding affects the resulting rail hardness profile, especially since certain grinding machinery could increase the rail temperature up to 800 °C. Additionally, the advantages of grinding in lowering noise and vibration levels should be weighed against its possible negative effect on the rail life cycle, which could result in additional costs for the operator as well as risks to the comfort and safety of tramway traffic.

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