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Application of Point-Based Characteristics of Vibration Signals in the Detection of Railway Rail Damage

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Summary
This study investigates the application of vibration signal characteristics for the detection of railway track damage. The analysis focuses on vibrations generated by the bogie system during traversal of track sections under two distinct technical conditions. A comprehensive review of rail infrastructure and maintenance methodologies is provided, emphasizing the use of advanced diagnostic tools by track maintenance organizations. The research employs a point-based analysis of dimensional and dimensionless features of vibration signals. The results confirm the effectiveness of utilizing vibration signals recorded from a moving vehicle to identify track damage that may cause decrease of vehicle's exploitation period.

Keywords: vibroacoustic, railway traction, statistical analysis, dimensionless analysis, railway damage

1. Introduction

Early detection of defects in railway infrastructure is crucial for ensuring safety and efficiency. Identifying issues in critical components such as rails, sleepers, or fastenings enables prompt remedial actions before minor defects evolve into significant problems. This approach maintains the infrastructure's high technical standard and minimizes the risk of severe failures.

Technological advancements necessitate the implementation of innovative diagnostic and maintenance methods for railway systems. Systematic and real-time data analysis allows for monitoring the wear levels of individual infrastructure elements, while precise diagnostic tools facilitate more effective maintenance management. These measures are pivotal for enhancing component reliability, extending their lifespan, and improving the overall efficiency of the system.

Rails, sleepers, and fastenings, frequently exposed to dynamic loads, are the most commonly damaged components. Issues with these elements can disrupt railway operations and affect transport organization. The growing demands of modern transportation systems, which involve designing vehicles capable of high speeds, compel infrastructure adaptation to increased loads while simultaneously reducing the wear of critical components. Consequently, monitoring the technical condition and wear levels of components has become a vital aspect of railway infrastructure management, encompassing both logistics and rolling stock production.

2. Railway infrastructure

2.1. Components of railway infrastructure

Railway infrastructure is a complex system that forms the backbone of rail transport, enabling efficient and safe movement of passengers and freight. It consists of integrated elements that collectively ensure track stability and protect against environmen-

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tal factors. Key components of the infrastructure include [5, 27, 28]:

- **Tracks**: Rails, made from durable materials such as steel, form the primary component of tracks. They are affixed to sleepers using specialized fasteners that dampen vibrations and reduce noise.
- **Sleepers**: These transfer loads from rails to the ballast, providing track stability and adequate water drainage. Modern technologies often employ concrete sleepers, which are more durable than wooden ones.
- **Ballast**: This maintains track stability, facilitates alignment, and ensures effective drainage of rainwater.
- **Traffic control systems**: Devices such as signals and switches support the safe organization of railway traffic.
- **Engineering structures**: Bridges, tunnels, and viaducts enable the crossing of terrain obstacles, maintaining route continuity.

Modern railway systems increasingly employ eco-friendly solutions, such as traction networks that support transport electrification and reduce harmful emissions [29].

Railway infrastructure is a complex system that forms the backbone of rail transport, enabling efficient and safe movement of passengers and freight. It consists of integrated elements that collectively ensure track stability and protect against environmental factors [4, 23]. Key components of the infrastructure are presented on Fig. 1.

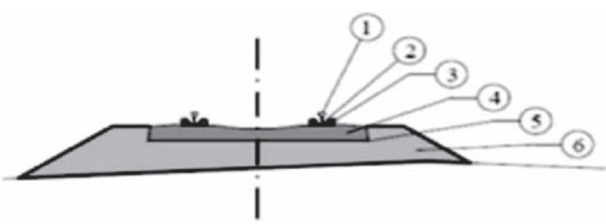

Fig 1. The structure of the railway track surface comprises: 1) rail, 2) rail fastening baseplate, 3) rail fastening connectors, 4) sleeper, 5) under-sleeper pad, 6) ballast [20]

2.2. Railway infrastructure damage

Railway infrastructure operation results in the natural wear of its elements. Regular inspections are conducted as part of maintenance to prevent major issues [12]. The most common damages include [1]:

- **Rail head cracks** (head checks): Microcracks caused by dynamic loads and material fatigue (Fig. 2). They occur primarily in areas of intense wheel-rail contact [10].
- **Surface rail deformations** (squats): Uneven load distribution leads to bulges on the rail surface, which, if not detected early, can cause significant failures (Fig. 3) [19].

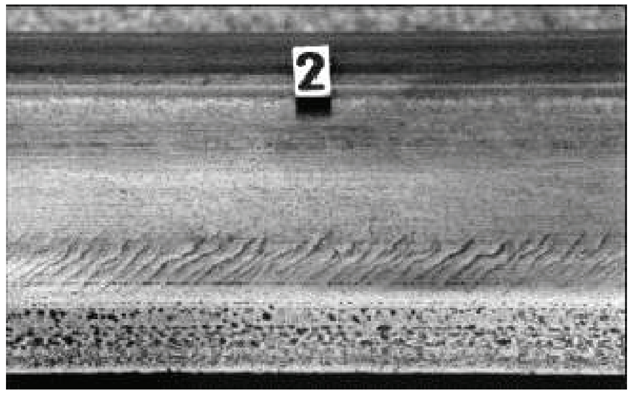

Fig. 2. Example of a “head checks” defect [15]

Fig. 3. Example of a “squat” defect [16]

If not identified and addressed, such defects can result in track failures and potential collisions. Damage to rail fastenings destabilizes tracks, posing safety risks. Concrete sleepers are prone to cracks, fractures, and surface spalling, while wooden sleepers can suffer from moisture and temperature-related degradation, including fungal growth, compromising track stability and necessitating replacement during inspections [7, 13, 30].

2.3. Vibrations generated at the wheel-rail interface

Vibrations arising from wheel-rail interaction provide critical insights into the technical condition of tracks. Their analysis allows assessment of the overall state of the railway infrastructure and identification of potential defects. Key vibration indicators include amplitude, frequency, harmonic content, and impulse characteristics (Fig. 4).

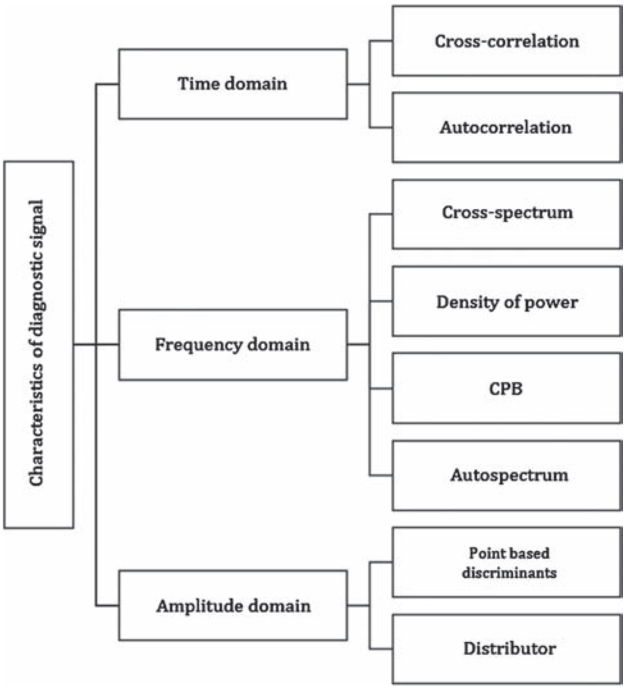

Fig. 4. Selected parameters of vibration diagnostics signals [own elaboration]

Piezoelectric sensors detect these vibrations by converting mechanical motion into electrical signals. Real-time data processing enables continuous monitoring, allowing for early identification of track segments requiring maintenance before severe damage occurs.

Track vibrations reflect changes in their technical state, such as excessive wear, cracks, or deformations. Comparative analysis of these signals against reference values highlights deviations indicating potential defects. Advanced measurement tools facilitate both the prevention of major failures and the optimization of maintenance activities [18, 22].

3. Railway infrastructure diagnostics

3.1. Inspection using a measurement trolley

Measurement trolleys are vital for monitoring railway infrastructure. Equipped with advanced technologies like laser measurement systems and data acquisition tools, these vehicles enable precise inspection of track geometry, rail profiles, and sleeper conditions.

Diagnostic vehicles, compliant with European Train Control System (ETCS) Level 2 standards, ensure compatibility with European railway management systems. For instance, the PKP PLK diagnostic locomotive (Fig. 5) with diesel propulsion can reach speeds of up to 120 km/h, allowing rapid inspection of extensive track segments with minimal disruption to train schedules.

Measurement trolleys also monitor traction networks, diagnosing the condition of critical elements like wires, supports, and power supplies. Centralized monitoring systems receive real-time measurement data, enabling prompt decisions regarding necessary repairs or maintenance [8, 24].

Fig. 5. Railway measurement trolley [3]

3.2. Inspections and technical assessments of infrastructure

Regular inspections are essential for maintaining railway infrastructure functionality and safety. All system components, including rails, sleepers, fastenings, engineering structures, signaling systems, bridges, and tunnels, undergo evaluation by trained personnel using advanced measurement technologies.

Inspections focus on track conditions, as rail damage can lead to significant failures. Evaluations include rail geometry, sleeper wear and stability, and fastening functionality. Signal systems are also routinely checked to detect and address issues before they disrupt transport operations.

Inspections are conducted in accordance with national and international standards. In Poland, PKP PLK regulations define inspection frequency and testing requirements for different track segments. Special attention is given to high-wear areas, such as tracks with tighter curves, which may require more frequent inspections and detailed analyses [11, 21].

3.3. Defectoscopic testing

Defectoscopic testing is one of the most critical methods for identifying hidden defects in railway tracks and associated components. Non-destructive techniques are employed to assess the technical condition of tracks without dismantling them. These methods allow precise identification of irregularities, such as cracks, corrosion, inclusions, or other defects that could compromise safety. The most common defectoscopic methods include:

- **Ultrasonography**: Utilizes sound waves to penetrate track material, detecting internal defects like cracks, inclusions, or voids. This technique is particularly effective for identifying microcracks that could lead to severe damage if undetected.
- **Magnetoscopy**: Employs magnetic fields to analyze rails and other metal components, effectively identifying surface defects, such as microcracks and distortions, that might be missed during visual inspections.
- **Radiography**: Uses X-ray or gamma radiation to image internal track structures. It reveals non-surface-visible defects, such as hidden cracks or material irregularities, providing a detailed assessment of structural integrity.
- **Thermography**: Monitors surface temperature variations on tracks to identify thermal anomalies caused by excessive friction or mechanical damage. This method is especially effective for diagnosing surface-level issues that could escalate into larger problems.

Defectoscopic testing (Fig. 6) is performed regularly, with the frequency determined by the track's usage and the speed of trains. High-speed tracks (above 160 km/h) are inspected four times annually, tracks with speeds between 120–160 km/h three times per year, and tracks operating below these speeds undergo inspections less frequently, with annual checks for the slowest routes [18, 31].

Fig. 6. Defectoscope for single rail inspection [17]

3.4. Challenges related to railway infrastructure diagnostics

Railway infrastructure diagnostics, particularly using vibration analysis and other advanced measurement methods, is a complex process involving numerous challenges. Real-time monitoring of technical conditions requires specialized measurement equipment and sophisticated data analysis algorithms. One of the main challenges is accurately analyzing vibration signals, which can be influenced by external factors like weather conditions. For instance, rain, snow, or high temperatures can alter vibration characteristics, requiring these variables to be accounted for during analysis.

Modern diagnostic technologies collect real-time vibration data, enabling ongoing analysis and early defect detection. However, this requires precise calibration of measurement equipment to ensure accurate results. Advanced mathematical algorithms are also necessary to filter noise and analyze signals effectively, detecting even subtle defects.

Another significant challenge lies in the material and construction diversity of railway infrastructure components. Variations in rail, sleeper, and fastening materials, as well as differences in their load-bearing capacities, influence how vibrations are generated. Analytical methods must be adapted to the specific characteristics of each track type.

Despite these challenges, diagnostic technologies such as vibration analysis remain among the most effective tools for assessing the technical condition of railway infrastructure. Regular monitoring using modern sensors and data analysis systems enables early defect detection, reducing the risk of severe failures and enhancing rail transport safety [6].

4. Methodology

4.1. Measurement Methodology and Scope of Research

The study aimed to analyze vibrations generated by trains traveling over different track sections, providing a precise assessment of the technical condition of the infrastructure. Two track segments were compared: one identified as damaged based on visual inspection and another serving as a reference point with no visible defects or deformations.

Measurements were conducted under uniform conditions to eliminate variables that could affect data quality. A diagnostic vehicle traveled at a constant speed of 10 km/h, ensuring stable data collection. Recorded signals were analyzed for parameters such as vibration amplitude, frequency, and duration, providing detailed insights into track conditions.

To ensure analysis accuracy, the data were normalized in the time domain[7], allowing comparisons

[7] The domain refers to the name of the variable for which calculations are made, e.g. averaging, calculating point measures (according to: S. Niziński, R. Michalski, R.B. Randall).

between signals from different track sections. Parameters such as signal amplitude and amplitude ratios were examined to detect differences between the reference and damaged segments.

This methodology provided a comprehensive view of track conditions, enabling early detection of defects that might otherwise lead to more severe damage if left unaddressed [2, 14, 16].

4.2. Measurement Equipment

Specialized diagnostic vehicles equipped with advanced measurement instruments were used for the study, the technical data of the vehicle is presented in the Table 1. Piezoelectric sensors, installed at two strategic locations on the vehicle (on the bogie frame and vehicle floor), were key components of the equipment.

- **Bogie frame sensors** (Table 2, Fig. 7): Recorded vibrations generated by the track, enabling the identification of microcracks and other deformations.
- **Vehicle floor sensors** (Table 3, Fig. 8): Captured vibrations affecting passenger comfort, evaluating the efficiency of vibration damping systems.

Table 1

Basic Technical Data of the Vehicle[8]

Property	Value
Gauge:	Per PN-EN 15273-2:2013+A1:2017-03, profile G2,
Axle configuration:	2'Bo'+Bo'2'
Track gauge:	1 435 mm
Total length:	53 652 mm
Minimum curve radius:	150 m
Empty weight:	112 500 kg
Wheel diameter:	850 mm
Maximum speed:	160 km/h

Table 2

Technical Specifications of the MEAS EGCS-A2-5-/C Transducer [25]

MEAS EGCS-A2-5-/C	
Parameters	Up to 4000 [Hz]
Mechanical Features	
Sensor Base Material	Anodized Aluminum
Sensor Axes	Single-axis
Sensor Weight	50 g [1.75 oz]
Mechanical Attachment	
Mounting Type	Screw
Operating Conditions	
Operating Temperature Range	−40°C to 120°C
Other Features	
Sensitivity	5 [mV/g]
Nonlinearity	±1 [%FSO]

Table 3

Technical Specifications of the MEAS EGCS3-A Transducer [26]

MEAS EGCS3-A	
Parameters	Up to 4000 [Hz]
Mechanical Features	
Sensor Base Material	Anodized Aluminum
Sensor Axes	Triaxis
Sensor Weight	50 g [1.75 oz]
Mechanical Attachment	
Mounting Type	Screw
Operating Conditions	
Operating Temperature Range	−40°C to 120°C
Other Features	
Sensitivity	5 [mV/g]
Nonlinearity	±1 [%FSO]

Fig. 7. Piezoelectric transducer MEAS EGCS-A2-5-/C [25]

Fig. 8. Piezoelectric transducer MEAS EGCS3-A [26]

[8] Based on the DTR of the vehicle DP-560.00.

Table 2 and 3. Technical specifications of piezoelectric transducers used for vibration measurement are provided in detail, ensuring high sensitivity and accuracy. Diagnostic data were collected and analyzed using LabVIEW[9] software, enabling real-time monitoring and detailed evaluation of both track conditions and passenger comfort [32].

4.3. Localization of Measurement Points

The precise placement of measurement points was crucial for obtaining high-quality, reliable results. Piezoelectric sensors were strategically mounted at two locations:

1. **Bogie frame** (Fig. 9): This location captured track-generated vibrations, especially at wheel-rail contact points, to assess the technical condition of the tracks, including microcracks and deformations.
2. **Vehicle floor** (Fig. 10): This point measured vibrations impacting passenger comfort, evaluating the effectiveness of vibration damping systems.

These locations addressed different diagnostic needs track condition evaluation versus passenger experience ensuring a comprehensive study. Proper placement also facilitated data comparison across varying track sections, yielding an integrated assessment of technical conditions and travel quality.

Strategically distributing the sensors enabled representative results and a thorough understanding of both infrastructure conditions and operational quality under diverse scenarios.

Fig. 9. Measurement point 1 localized on the train bogie [photo: A. Łomżyńska]

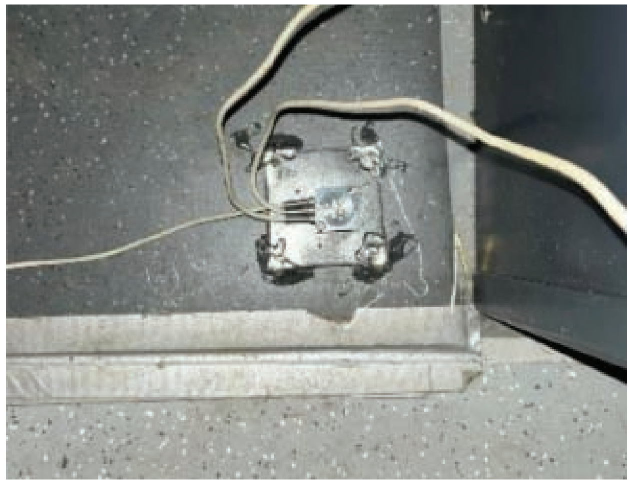

Fig. 10. Measurement point 2 localized on the train floor [photo: A. Łomżyńska]

Strategically distributing the sensors enabled representative results and a thorough understanding of both infrastructure conditions and operational quality under diverse scenarios.

5. Data analysis

The recorded vibration acceleration values for the vertical Z-direction (on the vehicle's floor and bogie) during the object's operation at a speed of $v = 10\,\text{km/h}$ on a railway siding were subjected to further analysis. Initially, the amplitude values of the time-domain signals were compared to establish preliminary differences. These waveforms are presented in Figures 11 and 12.

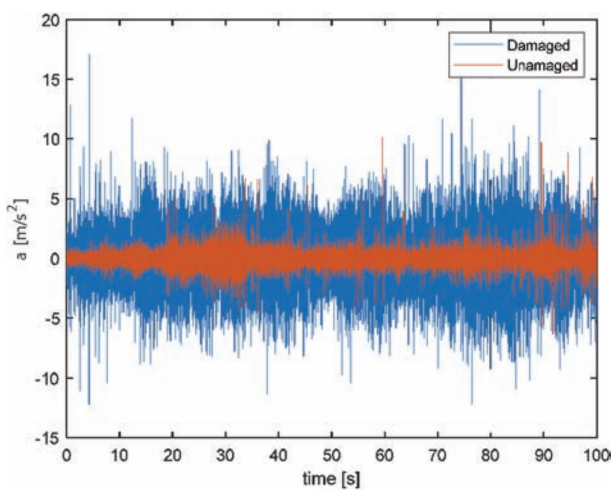

Fig. 11. Comparison of time-domain waveforms for damaged and model tracks in the case of bogie measurements [own elaboration]

[9] LabVIEW (Laboratory Virtual Instrument Engineering Workbench) – a graphical programming environment used in research centers (including CERN and NASA), for industrial testing, and for measuring and analyzing collected data.

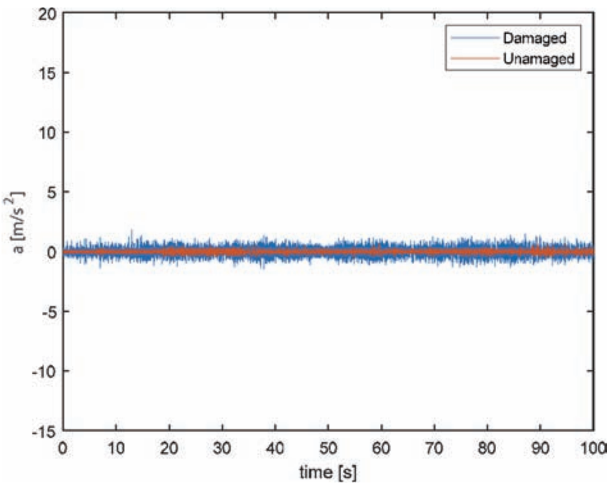

Fig. 12. Comparison of time-domain waveforms for damaged and model tracks in the case of floor measurements [own elaboration]

In Figures 11 and 12, it can be observed that the vibration amplitude values for the signal measured on the floor are comparatively lower than those for the signal measured on the bogie.

The next step of the study involved analysis of dimensional point measures, dimensionless coefficients and kurtosis values for data. They are expressed in the following equations (Equations 1–10):

- Average Amplitude- calculated as the mean value of instantaneous amplitude over a given time. It equally accounts for each amplitude value, providing a general representation of the signal:

$$S_{AVERAGE} = \frac{1}{T}\int_0^T \left|s(t)\right| dt \tag{1}$$

- Root Mean Square Amplitude (RMS) – this is the square root of the average of the squared instantaneous amplitudes. It gives more weight to higher amplitude values, making it proportional to the power of the process and commonly used in diagnostics:

$$S_{RMS} = \sqrt{\frac{1}{T}\int_0^T \left[s(t)\right]^2 dt} \tag{2}$$

- Square Amplitude- this parameter gives greater weight to smaller values of instantaneous amplitude:

$$S_{SQUARE} = \left[\sqrt{\frac{1}{T}\int_0^T \left[s(t)\right]^{\frac{1}{2}} dt}\right]^2 \tag{3}$$

- Peak Amplitude- the highest instantaneous amplitude value in the signal. Useful for analyzing impulsive processes such as clearances or impacts:

$$S_{PEAK} = \left[\sqrt{\frac{1}{T}\int_0^T s(t)^{\infty} dt}\right]^{\frac{1}{\infty}} \tag{4}$$

- Shape Factor- this coefficient represents the ratio of the RMS amplitude to the average amplitude, providing insight into the overall waveform shape and energy distribution relative to its mean:

$$K = \frac{S_{RMS}}{S_{AVERAGE}} \tag{5}$$

- Crest Factor – this measure, defined as the ratio of the peak amplitude to the RMS amplitude, indicates the sharpness of the signal peaks and helps identify impulsive or spiky events in the vibration signal:

$$C = \frac{S_{PEAK}}{S_{RMS}} \tag{6}$$

- Impulse Factor – calculated as the ratio of the peak amplitude to the average amplitude, it highlights the presence of high-intensity, short-duration impulses typical in damaged structures or systems:

$$I = \frac{S_{PEAK}}{S_{AVERAGE}} \tag{7}$$

- Clearance Factor – this coefficient, the ratio of the peak amplitude to the square amplitude, is used to detect mechanical faults by analysing the amplitude variations relative to the waveform's lower energy levels:

$$L = \frac{S_{PEAK}}{S_{SQUARE}} \tag{8}$$

- Peak to peak Range – this measure reflects the difference between the maximum and minimum values of the signal, capturing the range of amplitude fluctuations and providing a direct indicator of signal variability:

$$S_{PK-PK} = \max[s(t)] - \min[s(t)] \tag{9}$$

- Kurtosis – a measure describing the degree of concentration of signal values around the mean. It is used to identify random processes or rare events:

$$\beta = \frac{\frac{1}{T}\int_0^T s(t)^4\,dt}{\left[\frac{1}{T}\int_0^T s(t)^2\,dt\right]^2} \tag{10}$$

where:
T – time interval,
$s(t)$ – instantaneous value of the vibration signal.

The comparison of measuring points for damaged and undamaged tracks revealed distinct differences depending on the measurement location, calculated values for data collected from the bogie is presented in Table 4, and from the floor in Table 5.

The differences between the calculated values for both tracks are visualized separately for dimensional point measures and dimensionless coefficients. The results for bogie are presented in Figures 13 and 14 and in Figures 15 and 16 for the floor.

Table 4

Measurement points for Bogie [own elaboration]

Coeficient	Damaged	Undamaged	Dynamics
$S_{average}$	129 dB	113 dB	9 dB
S_{rms}	126 dB	117 dB	9 dB
S_{sqr}	121 dB	112 dB	9 dB
S_{peak}	145 dB	140 dB	5 dB
$S_{pk\text{-}pk}$	149 dB	144 dB	5 dB
K	1.41	1.43	–1%
C	8.57	14.90	–42%
I	12.11	21.45	–44%
L	15.66	26.61	–41%
Kurtosis	5.25	10.83	–52%

[Own elaboration].

As can be observed the difference between the three measures (i.e. $S_{average,}$ $S_{rms,}$ S_{sqr}) exceeds 6 dB, while the difference between the remaining measures ($S_{peak,}$ $S_{pk\text{-}pk}$) approaches 6 dB. This indicates a change in the technical condition of the vehicle.

Dimensionless coefficients such as the crest factor (C), impulse factor (I), and clearance factor (L) displayed marked reductions in the damaged state, with changes of −42%, −44%, and −41%, respectively. Kurtosis value decreased by 52%, indicating changes in the signal's impulsiveness and energy concentration.

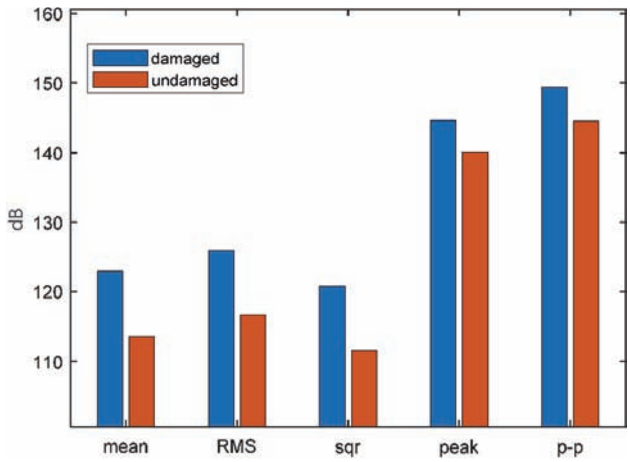

Fig. 13. Comparison of dimensional point measures for damaged and undamaged tracks in the case of bogie measurements [own elaboration]

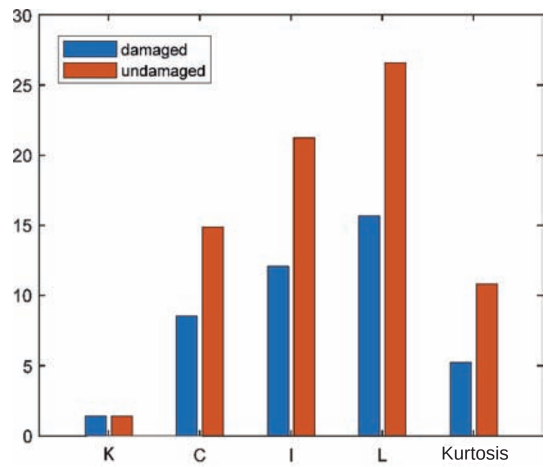

Fig. 14. Comparison of dimensionless coefficients and kurtosis for damaged and undamaged tracks in the case of bogie measurements [own elaboration]

Table 5

Measurement points for Floor

Coeficient	Damaged	Undamaged	Dynamics
$S_{average}$	106 dB	98 dB	8 dB
S_{rms}	109 dB	100 dB	9 dB
S_{sqr}	104 dB	95 dB	9 dB
S_{peak}	125 dB	117 dB	8 dB
$S_{pk\text{-}pk}$	130 dB	123 dB	7 dB
K	1.35	1.38	–2%
C	6.51	6.84	–5%
I	8.83	9.49	–7%
L	11.02	12.32	–11%
Kurtosis	4.27	4.49	–5%

[Own elaboration].

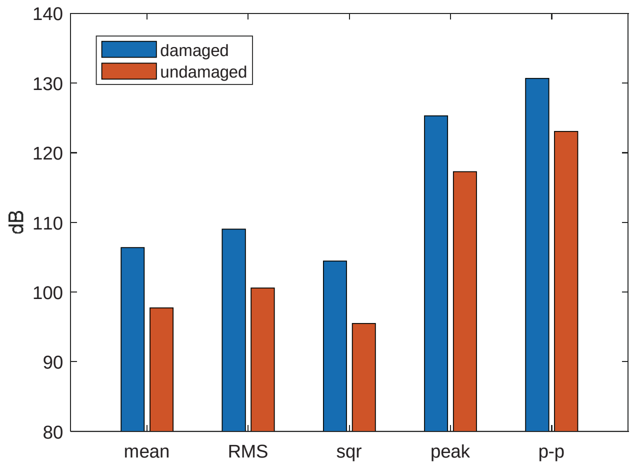

Fig. 15. Comparison of dimensional point measures for damaged and undamaged tracks in the case of floor measurements [own elaboration]

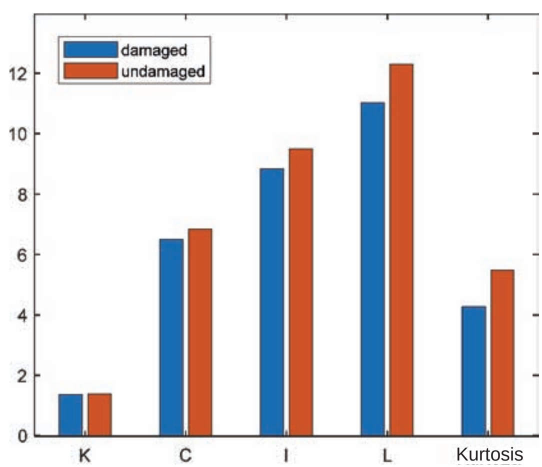

Fig. 16. Comparison of dimensionless coefficients and kurtosis for damaged and undamaged tracks in the case of floor measurements [own elaboration]

A similar situation occurs for the measurement on the floor; however, in this case, the difference across all measures exceeds 6 dB, unequivocally indicating a change in the technical condition of the object.

The comparison of point measures between the bogie and the floor reveals differences in sensitivity to track damage. Both locations exhibit identical increases of in average amplitude, RMS amplitude, and square amplitude, indicating a comparable rise in overall vibration energy levels. However, peak amplitude and peak-to-peak range show larger differences at the floor level (8 dB and 7 dB, respectively) than at the bogie (5 dB for both measures). This suggests that localized impacts and amplitude variability are more pronounced at the floor due to interactions with the vehicle's structural damping system.

The reductions in dimensionless coefficients are more pronounced for the bogie (e.g., Crest Factor: −42%) compared to the floor (e.g., Crest Factor: −5%). This demonstrates that the bogie experiences sharper changes in vibration characteristics, while the floor, due to the damping system, registers smoother variations.

Kurtosis decreases significantly more for the bogie (−52%) than the floor (−5%), reflecting the bogie's heightened sensitivity to rare, high-intensity vibration events in the damaged state. In contrast, the floor measurements show a more uniform vibration energy distribution, likely a result of effective vibration damping. Similarly, dimensionless coefficients, such as crest factor and impulse factor, display greater reductions for the bogie, indicating sharper changes in vibration characteristics compared to the smoother variations seen at the floor level.

5. Conclusions

The conducted research demonstrates that vibration acceleration signals recorded during the operation of railway vehicles offer significant insights into the condition of railway infrastructure. The analysis of both dimensional and dimensionless characteristics revealed clear distinctions between damaged and undamaged track states, underscoring the diagnostic potential of this approach.

Measurements obtained from the sensor mounted on the bogie system showed substantially higher amplitude values for the damaged rail condition, indicating elevated energy levels within the vibration signals. Additionally, reductions in kurtosis and dimensionless coefficients highlighted changes in the impulsive nature of the signal, likely attributable to irregularities in the track or structural components. Comparable trends were observed in signals recorded from a sensor located on the vehicle floor, although the magnitude of changes was less pronounced due to the vibration damping effects of the vehicle's suspension system.

The findings highlight the diagnostic value of vibration signal analysis in the context of railway infrastructure maintenance. Sensors placed on the bogie system, in particular, were shown to be highly effective in detecting early-stage damage, providing a critical advantage in proactive maintenance strategies. The presented data and corresponding visualizations further validate these conclusions, showcasing the effectiveness of the method in identifying and quantifying damage in railway systems.

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