Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 6.6
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.6.6

Localized Substructure Assessment in Railway Turnouts Based on Wavelength-Filtered RMS Indicators

T. Koch

Institute of Railway Engineering and Transport Economics, University of Technology, Graz, Austria

Abstract

This paper investigates the applicability of track geometry–based indicators for the assessment of substructure-related degradation in railway turnouts. While spectral analysis methods such as power spectral density have shown promising results for extended plain line sections, their application to turnouts is limited by the required analysis window length and the resulting influence of adjacent track sections. To address this limitation, a localized indicator based on the root mean square value of the longitudinal level signal is proposed. Prior to its computation, the signal is filtered to isolate long-wavelength components associated with substructure behaviour. The indicator is evaluated using repeated track geometry measurements from selected turnouts and is assessed through both cross-sectional comparisons and temporal analyses in relation to maintenance interventions. The results indicate that the filtered root mean square value is sensitive to substructure-related changes while showing limited response to ballast-related maintenance activities. This suggests that the proposed approach provides a suitable diagnostic support tool for turnout-scale substructure assessment based on existing track geometry data.

Keywords: railway infrastructure, substructure condition, railway turnouts, track geometry, longitudinal level, root mean square, wavelength filtering, maintenance assessment

1 Introduction

The primary function of the subgrade within the overall track system is to transmit and distribute the loads generated by railway traffic into the ground [1]. If the subgrade is undersized or becomes damaged due to increasing traffic loads, this typically results in costly consequences and can cause not only damage to the embankment itself but also to superstructure components such as sleepers, ballast, and rails [1]. In addition to rising maintenance costs, increasing traffic volumes also reduce the time available for maintenance activities. Consequently, modern maintenance management must aim for optimal life cycle management by carrying out maintenance interventions and track renewals at the most suitable point in time while minimising disruptions to railway operations [2].

To support such strategies, it is essential to assess the condition of the subgrade in a non-destructive, objective and reproducible manner, ideally using data that can be collected with minimal interference to railway operations. Direct investigation methods such as ground-penetrating radar (GPR) allow conclusions to be drawn about subgrade composition and condition [3]. However, their application is often limited by high operational effort, restricted spatial and temporal availability, and the lack of long-term historical datasets [4].

As an alternative, track geometry measurement data offer an indirect but widely available data source for subgrade condition assessment. Track geometry recording vehicles operate regularly across the railway network and provide long-term, repeatable measurements under operational conditions [5]. As a result, geometry data have been increasingly investigated for detecting degradation processes and evaluating the effectiveness of maintenance measures.

A key challenge in using track geometry data for subgrade assessment lies in separating the influence of different track components. Previous studies have shown that subgrade-related effects are primarily reflected in long-wavelength components of the longitudinal level signal, whereas short- and medium-wavelength components are more strongly influenced by ballast condition and superstructure behaviour [6]. Based on this assumption, spectral analysis methods, in particular power spectral density (PSD) approaches, have been proposed to evaluate subgrade-related characteristics on open track sections [7].

While PSD-based methods have demonstrated promising results for the open track, their applicability to short structural elements remains limited. Railway turnouts represent a particularly critical case due to their complex geometry, movable parts and discontinuities in the track support structure, which lead to higher failure rates and maintenance demands compared with plain line track [8]. At the same time, their spatial extent is typically limited to a few tens of meters, which poses a fundamental challenge for spectral analysis techniques that require comparatively long analysis windows to achieve sufficient frequency resolution.

In practice, the required window lengths lead to a mixing of turnout-related signal characteristics with adjacent open track sections, thereby reducing the interpretability of PSD-based indicators at the turnout scale. This highlights the need for alternative approaches that retain sensitivity to subgrade-related wavelength components while enabling localized evaluation within the geometric boundaries of individual turnouts.

The objective of this study is therefore to investigate the potential of a localized, wavelength-filtered root mean square (RMS) indicator derived from longitudinal level measurements for turnout-scale subgrade assessment. Spectral analysis methods are used as a conceptual and comparative reference to motivate wavelength selection and to illustrate the limitations of PSD-based approaches when applied to short structural elements. The proposed RMS-based indicator aims to provide a practical and interpretable measure that can be derived from standard track geometry data and integrated into existing maintenance management frameworks.

2 Methods

This section describes the data sources and methodological framework used in this study to assess substructure-related behaviour in railway turnouts based on track geometry measurements. The approach combines conceptual spectral considerations with a localized, spatial-domain indicator derived from longitudinal level data.

2.1 Data Sources and Measurement System

The analysis is based on longitudinal level measurements acquired by track geometry recording vehicles operating on the Austrian railway network. Depending on track classification and operational importance, these measurements are carried out repeatedly over time, providing multiple measurement runs for the same infrastructure elements. The longitudinal level signal is recorded with a spatial sampling interval of 0.25 m and can be acquired at operational speeds of up to 250 km/h [5]. This enables the evaluation of both spatial signal characteristics and their temporal development under real operating conditions.

For the present study, all available measurement runs covering the selected turnouts were extracted. The data were aligned to a common spatial reference system to ensure consistency between repeated measurements.

2.2 Conceptual Background and Wavelength Selection

Based on established track dynamics concepts, subgrade-related behaviour is primarily associated with long-wavelength components of the longitudinal level signal, whereas short- and medium-wavelength components are more strongly influenced by ballast condition, sleeper support and superstructure irregularities [6,9]. This relationship has motivated the use of spectral analysis methods for separating wavelength-dependent effects in track geometry data.

PSD analysis provides a systematic framework for investigating the distribution of signal energy across different wavelength ranges. By transforming the longitudinal level signal into the frequency domain, the contribution of individual wavelength components to the overall signal variance can be quantified [10]. A previous study applied PSD-based indicators to longitudinal level measurements to assess subgrade-related degradation on extended open track sections, focusing on wavelength ranges commonly associated with subgrade behaviour, such as the D2 range between approximately 25 m and 70 m [7].

A fundamental characteristic of PSD-based methods is the requirement for sufficiently long spatial analysis windows to achieve adequate frequency resolution. In practice, the window length must exceed the longest wavelength of interest and typically involves overlapping segments [10], resulting in required window lengths on the order of 140 m for a maximum wavelength of 70 m. Figure 1 illustrates the calculation process from a selected track section, through the longitudinal level signal, to the resulting PSD.

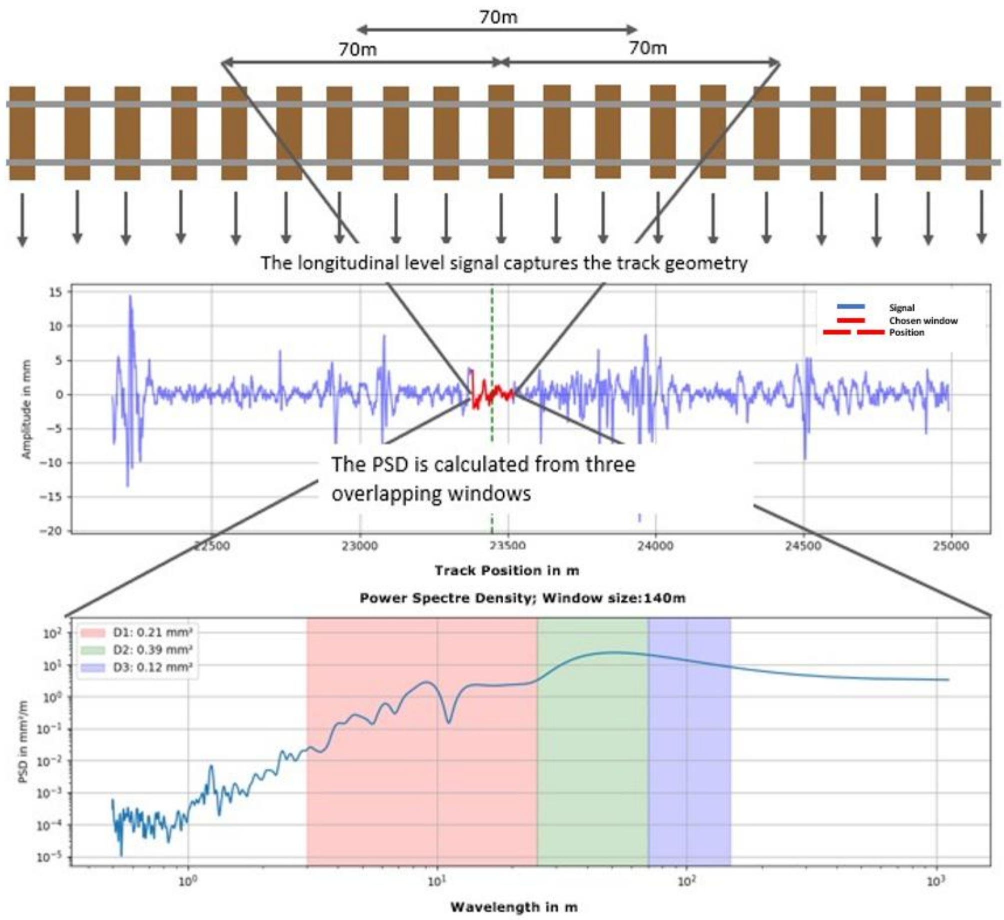

Figure 1: Process from the longitudinal level signal to PSD values.

Integrating the resulting PSD over a specified wavelength range yields the proportion of signal variance attributable to that range, i.e. the contribution of the corresponding wavelength components to the deviation of the original longitudinal level signal. While this approach is well suited for extended open track sections, it poses inherent limitations when analysing short structural elements. Consequently, the analysis windows required for spectral estimation inevitably extend beyond the turnout boundaries. This leads to a mixing of turnout-related signal characteristics with those of the surrounding track, which limits the interpretability of PSD-based indicators at turnout scale.

This methodological limitation is illustrated in Figure 2, which compares the RMS values (Calculated from the longitudinal D2 Signal) derived for three adjacent spatial domains: the turnout area itself and the track sections located immediately before and after the turnout. These neighbouring sections fall within the spatial extent that would be captured by a typical PSD analysis window centred at the turnout midpoint, even though they are not part of the turnout structure.

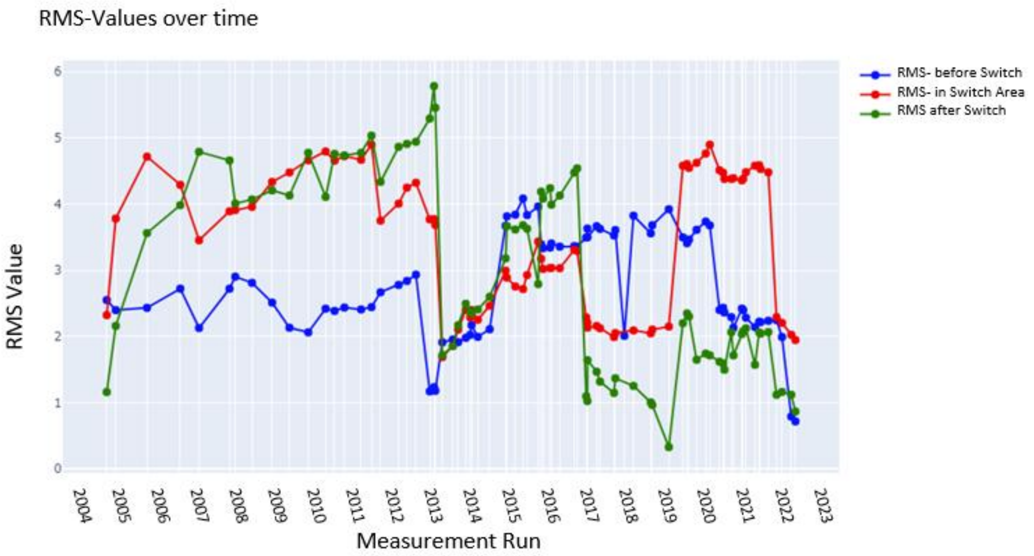

Figure 2: Temporal evolution of RMS values before, within and after the turnout.

The comparison highlights that the RMS values of the adjacent track sections may exhibit distinct behaviour compared to the turnout area. This indicates that signal characteristics originating outside the turnout can substantially influence indicators derived from window-based spectral analysis. As a result, PSD-based approaches are prone to mixing turnout-related behaviour with that of neighbouring open track sections, which limits their interpretability for localized substructure assessment.

Although these limitations prevent the direct application of PSD-based indicators for localized turnout assessment, the underlying spectral considerations remain relevant. Previous spectral analyses have indicated that wavelength components below approximately 30 m may still be influenced by ballast-related behaviour [7].

To reduce the influence of ballast-related components and to focus on subgrade-dominated behaviour, the present study therefore restricts the analysis to the longer wavelength range between 40 m and 70 m.

Rather than applying PSD-based indicators directly at the turnout scale, spectral considerations are used here as a conceptual basis for selecting an appropriate wavelength range. This wavelength selection forms the foundation for the localized RMS–based indicator introduced in the following section.

2.3 Root mean square Value

To enable a localized assessment of subgrade-related behaviour at the turnout scale, an RMS–based indicator derived from the longitudinal level signal is proposed. In contrast to spectral metrics, the RMS value can be computed directly in the spatial domain and therefore allows evaluation within the geometric boundaries of short structural elements such as turnouts.

The RMS value is defined as

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \tag{1}$$

where N denotes the number of measurement points within the evaluation domain and x_i represents the individual longitudinal level deviations. Due to its quadratic weighting, the RMS metric is particularly sensitive to larger deviations [11].

However, when applied to the unfiltered longitudinal level signal, the RMS value reflects the combined influence of multiple track components, including ballast condition and short-wavelength irregularities. To preserve sensitivity to subgrade-related behaviour while maintaining local spatial resolution, the longitudinal level signal is filtered prior to RMS computation.

Based on the spectral considerations outlined in Section 2.2, a bandpass filter is applied to isolate the wavelength range between 40 m and 70 m. This range is assumed to be predominantly influenced by subgrade behaviour, while minimising contributions from ballast-related effects. A fourth-order Butterworth bandpass filter is selected due to its smooth frequency response, numerical stability and suitability for application to relatively short signal segments [12].

The target wavelength range is converted into the corresponding spatial frequency band using the spatial sampling interval of the measurement system. To reduce boundary effects during filtering, the longitudinal level signal is extended by mirror-padding prior to filtering and subsequently truncated to the original signal length.

Following filtering, the RMS value is computed exclusively within the geometric boundaries of each turnout, defined by the official turnout start and end. This localized evaluation ensures that the resulting indicator reflects turnout-specific behaviour and avoids contamination from adjacent open track sections.

The resulting filtered RMS value is considered a candidate indicator for turnout-scale subgrade assessment. Its performance and robustness are evaluated in the following section through comparison with PSD-based metrics and unfiltered RMS values.

2.4 Experimental Design and Evaluation Setup

To evaluate the suitability of the proposed filtered RMS indicator for turnout-scale subgrade assessment, a structured experimental design was defined. The analysis focuses on a comparison between turnouts with documented substructure-related deficiencies and reference turnouts with comparable operational characteristics.

For each turnout, the evaluation domain was restricted to the geometric turnout area, defined by the official turnout start and end chainages provided in the infrastructure inventory. All RMS-based indicators were computed exclusively within these boundaries to ensure a localized assessment and to avoid interference from adjacent open track sections.

For PSD-based reference indicators, an analysis window centred at the geometric midpoint of the turnout was defined. The window length was selected according to the requirements described in Section 2.2, ensuring coverage of the longest wavelength component under consideration.

Two primary turnout groups were defined for comparative evaluation:

- **Degraded Substructure Group (Poor Condition)**
  This group comprises turnouts with documented substructure-related deficiencies according to internal infrastructure condition reports and maintenance records provided by the infrastructure manager. These turnouts exhibited persistent geometry irregularities, drainage-related issues or settlement behaviour requiring increased maintenance effort.
- **Reference Group**
  The reference group consists of turnouts without known substructure deficiencies. To minimize the influence of external factors, these turnouts were selected such that traffic load characteristics, track class and operational conditions were comparable to those of the degraded group. It is noted that the reference group may still include turnouts with substructure-related deficiencies.

For each turnout and each available measurement run, the following quality indicators were computed:

- PSD-based indicator for the wavelength range 25–70 m
- PSD-based indicator restricted to the long-wavelength range 40–70 m
- RMS value of the unfiltered longitudinal level signal
- Filtered RMS value for the wavelength range 40–70 m

To reduce the influence of short-term fluctuations, measurement noise and isolated maintenance effects, the indicator values obtained from individual measurement runs were aggregated for each turnout. The final indicator value for a given turnout was calculated as the mean value across all available measurement runs within the observation period.

This aggregation approach preserves systematic differences between turnouts while improving the robustness of the comparison between turnout groups.

The performance of the investigated quality indicators was assessed using two complementary evaluation approaches:

- **Cross-sectional comparison**
  Indicator distributions for the degraded and reference turnout groups were compared to evaluate the separation capability of each metric and its suitability for distinguishing between different substructure conditions.
- **Temporal analysis**
  For selected representative turnouts, time series of RMS-based indicators were analysed in conjunction with recorded maintenance interventions. This analysis aims to assess the robustness of the proposed indicator with respect to ballast-related maintenance activities and long-term degradation processes.

The results of these evaluations are presented in the following section.

3 Results

This section presents the results obtained from the application of the proposed methodology to the selected turnout data.

3.1 Cross-Sectional Comparison of Quality Indicators

The second step of the analysis focuses on the ability of different quality indicators to distinguish between turnouts with documented substructure deficiencies and reference turnouts with comparable loading conditions. For each turnout, indicator values were aggregated across all available measurement runs, and each turnout is represented by a single data point.

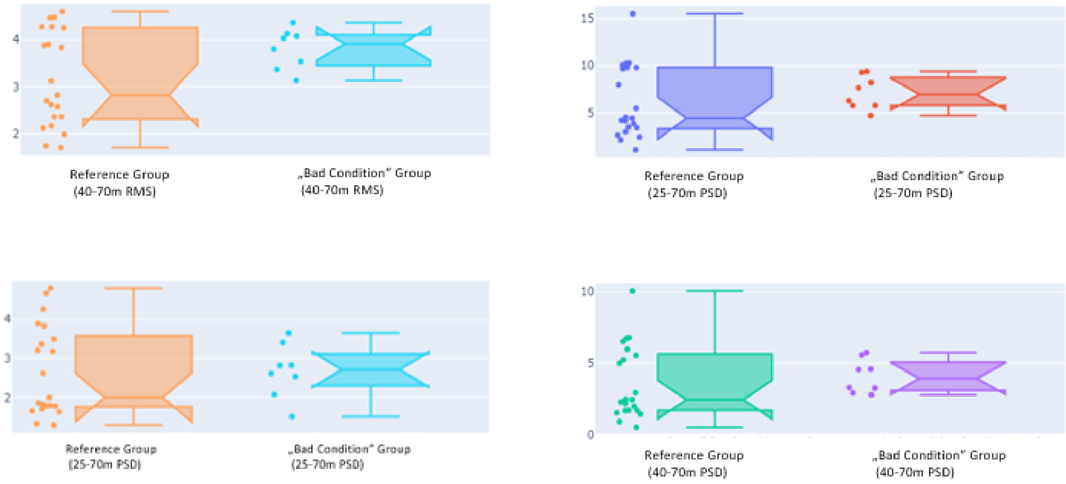

Figure 3: Comparison of quality indicators for degraded and reference turnouts.

Figure 3 compares the distributions of the investigated indicators for the two turnout groups. All indicators show a tendency toward higher values for turnouts in the degraded substructure group, indicating a general sensitivity to structural deterioration. However, the degree of separation between the two groups differs markedly between the indicators.

The PSD-based indicators, both for the full 25–70 m range and the restricted 40–70 m range, exhibit considerable overlap between degraded and reference turnouts. In particular, the reference group displays a wide spread of values, suggesting that PSD-based metrics are influenced by factors not directly related to turnout substructure condition.

Similarly, the unfiltered RMS values show limited separation between the two groups, reflecting the combined influence of ballast condition, short-wavelength irregularities and substructure effects.

In contrast, the filtered RMS indicator restricted to the 40–70 m wavelength range provides a markedly clearer separation between degraded and reference turnouts. The degraded group consistently exhibits higher filtered RMS values, while the reference group remains more compact with reduced dispersion. This indicates that wavelength filtering substantially improves the specificity of the RMS metric with respect to substructure-related behaviour.

3.2 Temporal behaviour of the Filtered RMS Indicator

To evaluate whether the proposed wavelength-filtered RMS indicator is largely insensitive to superstructure-related maintenance and primarily reflects substructure-related behaviour, its temporal evolution was analysed in relation to recorded maintenance interventions.

As a first step, the response of RMS values to ballast cleaning operations was investigated. Figure 4 shows the temporal evolution of the RMS value computed for the short-wavelength range dominated by superstructure effects RMS_{D1} and the filtered RMS value for the long-wavelength range between 40 m and 70 m RMS_{40-70}. In addition, major maintenance interventions are indicated along the time axis.

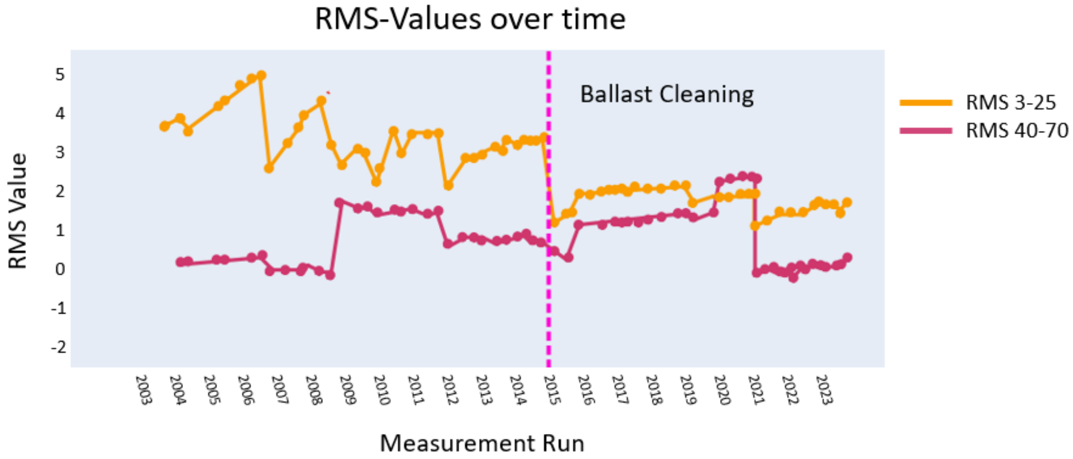

Figure 4: Temporal evolution of RMS_{D1} and RMS_{40-70} with maintenance events.

The ballast cleaning operation carried out in 2014 is clearly reflected in the RMS_{D1}time series, which exhibits a pronounced change following the intervention. In contrast, the RMS_{40-70} values show only minor variations during the same period. This observation supports the assumption that the selected long-wavelength range effectively suppresses ballast-related influences and that the filtered RMS indicator predominantly reflects deeper structural behaviour associated with the subgrade. Similar response patterns were observed at additional track sections, indicating that this behaviour is not limited to a single isolated case.

Although the filtered RMS indicator shows a largely stable behaviour with respect to ballast-related maintenance, occasional discontinuities and step changes can be observed in the time series. These changes do not necessarily indicate a deterioration of the substructure. Instead, they may result from external influences such as local geometry adjustments in adjacent tracks or neighbouring turnouts.

Therefore, an increase in RMS_{40-70} values should not be interpreted in isolation but rather in conjunction with additional contextual information, including maintenance records and spatial correlation with neighbouring track elements.

A recurring pattern can be observed following turnout renewals. In several cases, RMS_{40-70} values change noticeably in the years immediately after renewal before gradually stabilising. This behaviour is plausibly explained by initial settlement and consolidation processes occurring after substructure rehabilitation.

To further illustrate the diagnostic potential of the filtered RMS indicator, a turnout with clearly documented drainage and vegetation problems prior to renewal was examined. Visual inspections of track images revealed extensive vegetation growth and impaired drainage conditions, indicating a severely weakened substructure.

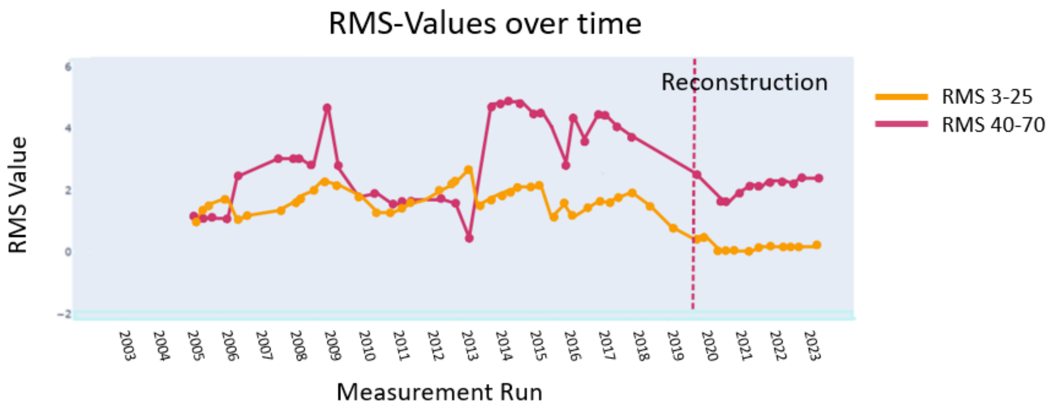

Figure 5: Time series of RMS_{40-70} for a turnout with severely degraded substructure prior to renewal.

Figure 5 shows that, prior to renewal, the RMS_{40-70} values are consistently high and exhibit a markedly irregular temporal evolution. After turnout renewal, the RMS values decrease substantially and show a more stable development over subsequent measurement runs. Comparable behaviour was observed for other turnouts with similar documented substructure deficiencies.

These findings suggest that not only the absolute magnitude of the filtered RMS indicator, but also its temporal stability and variability, contain relevant information for substructure condition assessment.

The temporal analyses indicate that a purely binary classification of substructure condition into “good” and “poor” may be insufficient. Different degradation mechanisms, such as drainage deficiencies, loss of stiffness or progressive settlement, can lead to distinct temporal signatures in the RMS_{40-70} time series.

In particular, a distinction should be made between spatially uneven substructure conditions and ongoing settlement processes, as the latter are typically more critical for the long-term development of track geometry. Future research should therefore focus on developing classification schemes that incorporate both the magnitude and temporal behaviour of the RMS-based indicator to enable a more differentiated assessment of substructure condition.

4 Conclusions and Contributions

This study investigated the potential of using standard track geometry measurements for localized substructure condition assessment in railway turnouts. While PSD–based approaches have previously shown promising results for extended track sections, their applicability to short structural elements is fundamentally limited by the required spatial analysis window.

The primary contribution of this work is the development and evaluation of a localized, wavelength-filtered RMS-based indicator that can be applied directly within the geometric boundaries of turnouts. By restricting the analysis to the long-wavelength range between 40 m and 70 m, the proposed indicator combines local spatial resolution with sensitivity to substructure-related behaviour derived from spectral considerations.

The results demonstrate that PSD-based indicators are strongly influenced by adjacent open track sections when applied at the turnout scale, which significantly reduces their interpretability. In contrast, the filtered RMS indicator enables a clearer differentiation between turnouts with documented substructure deficiencies and reference turnouts with comparable loading conditions. Temporal analyses further indicate that the proposed indicator is largely insensitive to ballast-related maintenance interventions, while remaining responsive to long-term substructure-related degradation processes such as settlement and drainage deficiencies.

From a methodological perspective, this study highlights that the commonly used D2 wavelength range (25–70 m) still contains ballast-related influences and that a further restriction to longer wavelengths improves interpretability for substructure assessment. Rather than proposing a fully standardized quality index, the presented approach should therefore be regarded as a diagnostic support tool that supports relative comparison, anomaly detection and trend analysis for turnout substructure condition.

A remaining limitation is the absence of a clearly defined reference for what constitutes a “good” substructure condition under operational railway conditions. In addition, overlapping maintenance interventions and the indirect observation of substructure behaviour through geometry data complicate the interpretation of absolute indicator values. Future research will therefore focus on further isolating substructure-related effects and on establishing suitable reference conditions for improved interpretability.

Overall, the proposed RMS-based indicator provides a practical and computationally efficient link between spectral knowledge of track behaviour and localized condition assessment at the turnout scale. It represents a methodological step towards data-driven, infrastructure-wide monitoring of substructure condition using existing measurement systems.

Acknowledgements

The author thanks ÖBB Infrastruktur AG for providing the data used in this study.

References

[1] Lichtberger, B.: Handbuch Gleis. DVV Media Group GmbH / Eurailpress, Linz (2010).

[2] Veit, P.: Life Cycle Management der Eisenbahninfrastruktur. WING-Business, 55 (2022), Bd. 2.

[3] Eriksen, A.; Venables B.; Gascoyne J.; Bandyopadhyay, S.: Benefits of High Speed GPR to Manage Trackbed Assets and Renewal Strategies. Zetica Rail, Brisbane (2006).

[4] Landgraf, M.: Einfluss von Unterbau und Wasserwegigkeit auf die Gleislagequalität. AV Akademikerverlag, s.l. (2012).

[5] Hanreich, W.: Moderne Fahrweginspektion mit dem oberbautechnischen Messwagen EM 250. ZEV Rail – Zeitschrift für das gesamte System Bahn, Sonderheft „Fahrwegoptimierung des Rad/ Schiene-Systems“, (2004).

[6] Landgraf, M.: Zustandsbeschreibung des Fahrwegs der Eisenbahn – Von der Messdatenanalyse zum Anlagenmanagement. Technische Universität Graz, Graz (2016).

[7] T. Koch, "Detektion des Unterbauzustands mithilfe des Leistungsdichtespektrums", Master’s thesis, Technische Universität Graz, Austria, 2025.

[8] I. Grossoni, P. Hughes, Y. Bezin, A. Bevan, J. Jaiswal, "Observed failures at railway turnouts: Failure analysis, possible causes and links to current and future research", Engineering Failure Analysis, vol. 119, 104987, 2021, doi:10.1016/j.engfailanal.2020.104987.

[9] Austrian Standards: EN 13848-5 – Track Geometry Quality, Part 5: Geometric Quality Levels. Österreichisches Normungsinstitut, Wien, 2014.

[10] Petre Stoica, Randolph Moses, Spectral Analysis of Signals. Upper Saddle River, New Jersey : Prentice Hall, 2005. 0-13-113956-8.

[11] Kavuncuoğlu, E., Uzunhisarcikli, E., & Barshan, B. (2018). "Digital Signal Processing." Handbook of Signal Processing Systems. DOI: 10.1201/9781420003086-14

[12] Fischer-Cripps, A. C. (2002). "Digital Signal Processing." In The Electronics Companion. Institute of Physics Publishing. DOI: 10.1016/B978-075065720-4/50121-2