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# FROM TRACK GEOMETRY TO SUBSOIL: A SIGNAL PROCESSING APPROACH TO SUBSTRUCTURE CONDITION ASSESSMENT

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## Abstract

With increasing traffic loads and simultaneously decreasing maintenance time windows, a precise and preferably non-destructive assessment of the condition of track components is becoming ever more important. The substructure in particular poses a major challenge, as it is difficult to access during regular operation for inspection or maintenance. Existing methods such as ground-penetrating radar (GPR) can provide complementary information but require additional measurement campaigns, offer limited historical data and comparatively low detection speeds. In contrast, the track recording car has been collecting standardized longitudinal level data over decades and across entire networks, offering a unique potential for data-driven assessment. Building on the assumption found in the literature that the D2 ($\lambda$ = 25–70 m) longitudinal level signal contains information related to the subsoil, this study evaluates whether this signal can reliably indicate substructure condition. For this purpose, a Power Spectral Density (PSD) analysis was applied to the D2 longitudinal level signal ($\lambda$ = 25–70 m), decomposing it into different wavelength ranges. To reference good and poor substructure conditions, track sections immediately before and after substructure rehabilitation interventions were compared. The database for this investigation is based on historical data from the track recording cars of the Austrian Federal Railways (ÖBB). The results show that those interventions lead to a uniform reduction in PSD values across all analysed track sections, particularly in the longest wavelength ranges ($\lambda > \sim 35$ m), while shorter wavelengths ($\lambda < \sim 35$ m) exhibit less consistent changes. Furthermore, the shorter wavelength ranges appear sensitive to the condition of the ballast layer, suggesting that the currently assumed 25–70 m range could be further refined. These findings indicate that long wavelengths in the longitudinal signal indeed describe the subsoil. The results provide a methodological basis for the future development of a substructure quality index to support predictive, data-driven maintenance management.

*Keywords: subsoil, predictive maintenance, railway, longitudinal level signal, power spectral density*

## 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.

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This means carrying out maintenance interventions and track renewals at the most suitable point in time while minimizing disruptions to railway operations [2]. Therefore, it is essential to assess the condition of the subgrade in a non-destructive, objective, reproducible manner and with minimal interference in railway operations. This article provides an assessment of the potential for detecting subgrade damage based on existing data sources.

## 2 Methodology

### 2.1 Non-destructive data generation

Two data sources in particular meet these criteria for assessing subgrade condition: ground-penetrating radar (GPR) and track geometry measurement vehicles. GPR measurements allow direct conclusions to be drawn about the composition of the subgrade [3]. However, a major drawback of GPR is the limited availability of historical data, and its evaluation is both time- and labor-intensive [4]. In contrast, the EM250 track geometry measurement vehicle operates on the Austrian railway network multiple times per year, depending on track classification. As a result, a significantly larger volume of data is available, which is especially advantageous for observing temporal changes. Furthermore, it can perform measurements at speeds of up to 250 km/h and records data at intervals of 25 cm [5]. This provides an objective, non-destructive, and reproducible data basis suitable for research. Although it does not yield direct evaluations of the subgrade condition as GPR does, the track geometry data enables indirect conclusions to be drawn about the condition of the various track components.

### 2.2 The longitudinal level signal for subgrade condition assessment

According to the EU Standard [6] and the research of Landgraf and Hansmann [7], it is possible to differentiate the causes of deviations in the longitudinal level signal based on their wavelength. Indicators of subgrade condition can be detected within the wavelength range between 25 and 70 m (cf. [7]). Traditional quality indices, such as the standard deviation or the root mean square (RMS) value, respond to changes in the amplitude of the longitudinal level signal. However, their explanatory power is limited, as they do not permit valid conclusions regarding changes in the composition of wavelength components. Since the scientific literature indicates that such differentiation between components is possible, a signal-processing methodology is required that is sensitive to variations within wavelength ranges. For this reason, the use of the power spectral density (PSD) as an analytical tool is recommended.

### 2.3 PSD-based signal processing of the longitudinal level signal

The PSD describes how the energy of a signal is distributed across different frequencies (or wavelengths). It is calculated based on the Fast Fourier Transform (FFT), which converts a signal from the spatial domain into the wavelength domain. Since the FFT is applied to a temporally (or spatially) limited signal, this often leads to leakage effects, as the discrete Fourier transform assumes a periodic continuation of the signal segment [8]. To reduce these effects, this study employs the Welch method [9], in which multiple overlapping segments are weighted using a Hanning window and subsequently evaluated. Following common recommendations for spectral analysis, the analysis window should be selected such that it contains at least one period of the longest wavelength under consideration [10]. Given the longest wavelength of 70 m and three windows overlapping by 50%, a window size of 140 m is required. Concretely, 140 m of the longitudinal level signal are considered, and the power spectral density is computed from this segment.

Figure 1 illustrates the calculation process from the selected track section, through the longitudinal level signal, to the power spectral density.

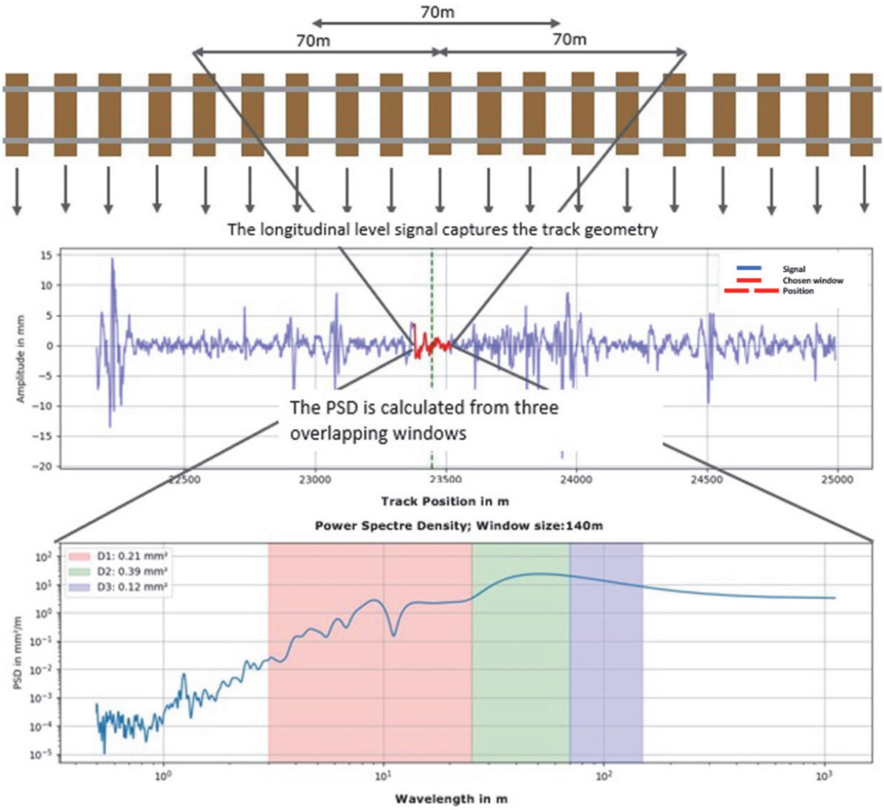

**Figure 1** Process from the longitudinal Signal to PSD Values

Integrating the resulting power spectral density over a specified wavelength range yields the proportion of signal variance attributable to that range – in other words, how much this wavelength range contributes to the deviation in the original longitudinal level signal. The wavelength range $\lambda_0$ (25–70 m) was subdivided into five subranges ($\lambda_1$–$\lambda_5$: 25–30 m, 30–40 m, 40–50 m, 50–60 m, and 60–70 m). To obtain an overview of the subgrade quality along a track section, the PSD with its 140-metre influence window is computed every 5 meters along the route. This approach results in the formation of a metric referred to as the “floating PSD”, which enables a continuous representation of the condition, analogous to moving quality indicators such as the standard deviation. Figure 2 shows the floating PSD for the specific wavelength range $\lambda_0$.

The figure shows that the track section at 8.6 km exhibits a high energy contribution from the wavelength range of 25–70 m. An increased contribution can also be observed between 8.75 - 8.8 km. This indicates that these parts of the track section contain particularly high energy within this wavelength range. For an adequate interpretation of the calculated values, a reference is required. These interventions are performed using the so-called *Aushubmaschine* (AHM), where AHM denotes an excavation-based track subgrade rehabilitation machine. Accordingly, a suboptimal subgrade condition is assumed prior to the intervention, whereas the condition after the intervention is expected to correspond to an ideal state.

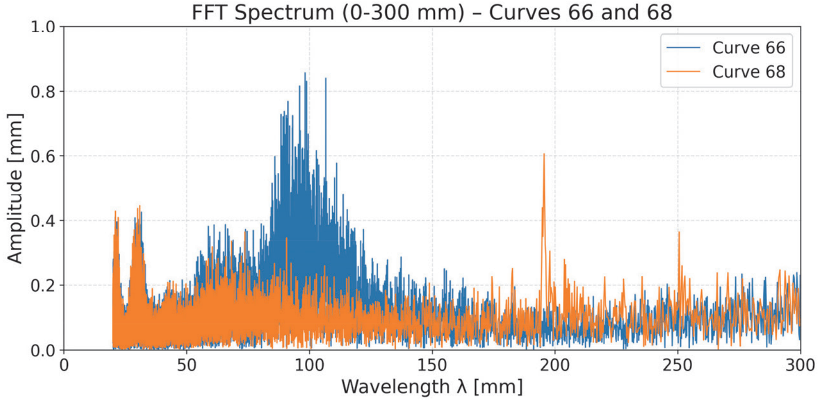

**Figure 2** Floating PSD

# 3 Analysis

## 3.1 Influence of subgrade rehabilitation on the long-wavelength portion of the longitudinal level signal

In a first step, within each track section affected by an AHM intervention, the area with the highest floating-PSD values prior to the intervention is identified. For this area, the integrated energy beneath the floating PSD is calculated and compared with the same area after the AHM intervention. The analyzed "poor sections" contain at least three floating-PSD points, meaning they cover a minimum distance of 150 meters. To ensure comparability between sections of different lengths, the integrated values are normalized by dividing the distance between points. For the 51 investigated sections, figure 3 shows an exemplary boxplot for the wavelength range $\lambda_4$.

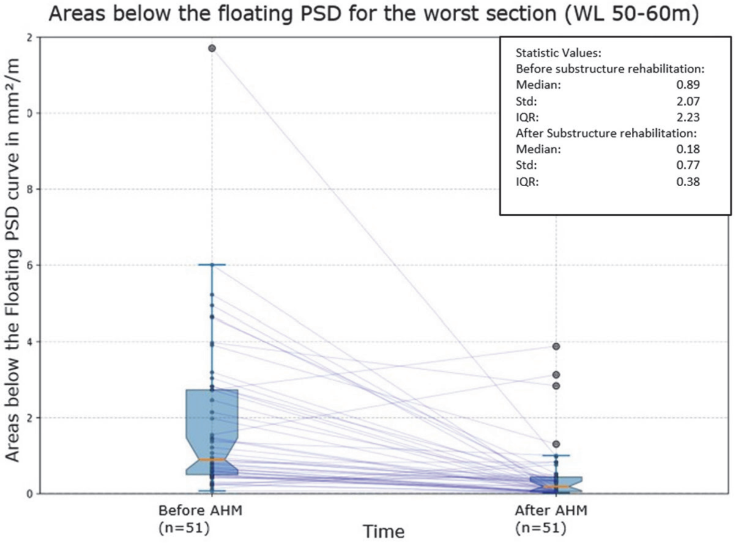

**Figure 3** PSD values ($\lambda_5$) before and after an AHM intervention

The boxplot in figure 3 illustrates a comparison of the "integrated energy per meter" values before and after an AHM intervention, where each point represents one track section. The results demonstrate that subgrade rehabilitation leads to a substantial reduction in PSD values. Since the boxplot notches do not overlap, this improvement is also statistically significant. Sections with particularly high initial values exhibit the strongest improvements, while areas with already low values may, in isolated cases, show slight deterioration. Overall, AHM interventions homogenize previously highly heterogeneous track sections and lead to a good, consistent condition – although this is not achieved without exception.

## 3.2 Analysis of the interquartile range

Comparing statistical metrics across wavelength ranges is particularly insightful when considering the interquartile range (IQR) (table 1). The relative IQR shown represents the dispersion of PSD values between the investigated track sections relative to the respective median of all sections within a wavelength range. Due to the smaller bandwidth of 5 meters compared to 10 meters, the value for the 25–30 m range was multiplied by 2. Using the relative IQR makes it possible to evaluate how homogeneous the floating-PSD values of the different rehabilitated sections are in relation to each other.

**Table 1** Interquartile range of all sections before and after an AHM intervention

| | **Before AHM** | **After AHM** |
|---|---|---|
| | **Rel. IQR [mm²/m]** | |
| $\lambda_0$ 25-70 | 1.92 | 2.32 |
| $\lambda_1$ 25-30 Factor 2 | 1.49 | 2.00 |
| $\lambda_2$ 30-40 | 1.63 | 2.28 |
| $\lambda_3$ 40-50 | 2.32 | 2.36 |
| $\lambda_4$ 50-60 | 2.51 | 2.11 |
| $\lambda_5$ 60-70 | 2.12 | 1.86 |

Before the AHM intervention, the long-wavelength ranges ($\lambda_4$, $\lambda_5$) in particular exhibit the greatest variability between sections, indicating a high degree of inhomogeneity. After subgrade rehabilitation, this dispersion decreases significantly, whereas in the short-wavelength ranges ($\lambda_1$, $\lambda_2$) a slight increase in variability can be observed. This suggests that the AHM measures primarily led to a homogenization of track quality in the long-wavelength ranges. It should be noted, however, that the influence of accompanying measures affecting the ballast bed has not yet been evaluated separately. Building on these findings, the behavior of the short- and long-wavelength ranges ($\lambda_1$, $\lambda_2$ vs. $\lambda_4$, $\lambda_5$) was therefore analyzed in greater detail.

## 3.3 Development of PSD values over time

The temporal evolution of PSD values was examined at a specific track point. While tamping operations performed by the so-called *Maschineller Durcharbeitungszug* (MDZ), i.e. a mechanized track maintenance and tamping train, reduced the previously rising PSD, only the subgrade rehabilitation measures led to a sustained improvement. To analyze the influence of individual wavelength ranges, their relative contribution to the total signal $\lambda_0$ (25–70 m) was compared over time. The results show that the short-wave ranges 25–30 m ($\lambda_1$) and 30–40 m ($\lambda_2$), as well as the long-wave ranges 50–60 m ($\lambda_4$) and 60–70 m ($\lambda_5$), evolve almost in parallel. This indicates that each pair of ranges behaves coherently and can be considered jointly. Moreover, both range pairs respond similarly to maintenance interventions.

These observations suggest that $\lambda_1$+$\lambda_2$ and $\lambda_4$+$\lambda_5$ represent consistent subgroups of the total wavelength spectrum, supporting their combined interpretation in subsequent analyses. The question arises whether the $\lambda_1$+$\lambda_2$ range may still contain an influence from the overlying ballast bed. For this reason, a section was examined where a pronounced whitening of the ballast indicated a visually poor ballast condition. Indeed, at that point in time, a strong response in the $\lambda_1$ range and a somewhat weaker response in the $\lambda_2$ range can be observed, as shown in the following figure 4.

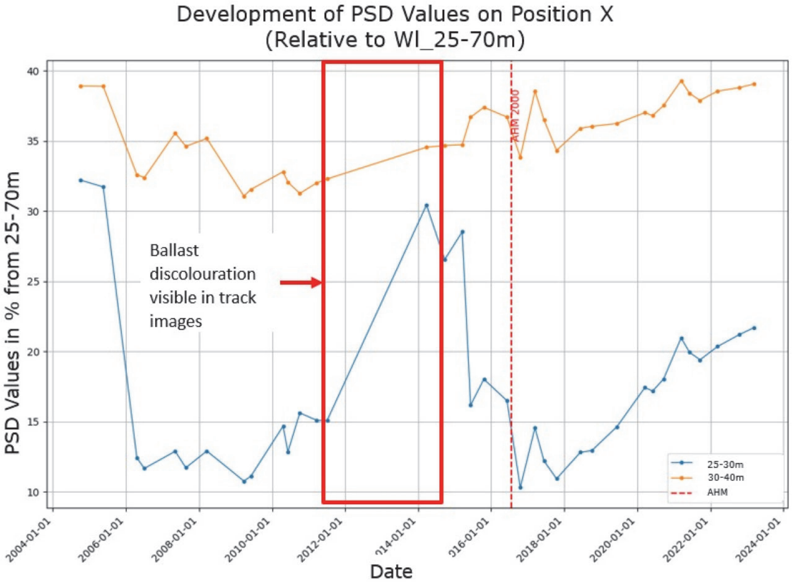

**Figure 4** Influence of degraded ballast condition on the $\lambda_1$ wavelength range

Figure 4 visualizes the relative share of energy in the $\lambda_1$ and $\lambda_2$ ranges with respect to the total signal $\lambda_0$. Over the years, both lines run largely parallel to one another. In the red highlighted section, the ballast discoloration was identified. Here, the $\lambda_1$ range responds strongly. This observation suggests that influences of the ballast can also be found in the D2 range, and that the previously assumed separation of wavelength ranges D1 and D2 for subgrade assessment should be further refined. Building on these initial insights, further research will aim to develop a reliable quality index for subgrade assessment that explicitly accounts for the different wavelength ranges.

## 4 Conclusion

The present study demonstrates that an in-depth analysis using the PSD provides a viable approach for assessing subgrade conditions. By computing a floating PSD over 140 m track segments and analyzing defined wavelength ranges, it was shown that subgrade rehabilitation measures lead to a significant homogenization of track sections, particularly in the long-wavelength ranges ($\lambda_4$ and $\lambda_5$), while short-wavelength ranges ($\lambda_1$ and $\lambda_2$) show less consistent responses. Although tamping operations temporarily reduce PSD values, they do not result in a lasting improvement. Moreover, the findings indicate that certain short-wavelength ranges (within the $\lambda_0$ = 25–70 m area) are sensitive to the condition of the overlying ballast bed, which calls for a more differentiated interpretation of the wavelength ranges.

Future research should systematically quantify the influence of renewal and maintenance measures affecting the ballast bed in order to separate ballast-related from subgrade-related effects. Building on this foundation, a quality index can be developed that reliably and objectively characterizes the condition of the subgrade.

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