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In-Situ Track Ballast Condition Assessment during Tamping Operations: Correlation with Established Geotechnical Methods

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ABSTRACT: Effective evaluation of railway ballast condition is essential for maintaining track stability and safety. This study introduces a novel approach for assessing ballast condition through in-situ data collected during tamping machine operations. The data was analyzed to evaluate key ballast properties such as ballast fouling and structural integrity. The results were then compared with established geotechnical assessment methods, including sieve analysis, ballast Fouling Index and the Ballast Breakage Index revealing a high level of correlation and validating the tamping-based evaluation technique. Building on these insights, a ballast condition determination method was developed and integrated into the tamping machine, enabling real-time assessment during maintenance activities. This innovation reduces reliance on traditional, labor-intensive evaluation techniques while improving operational efficiency. Advanced signal processing and machine learning algorithms were utilized to enhance the precision and reliability of ballast condition classification, merging maintenance and diagnostic capabilities into a unified process. The study underscores the practical benefits of this approach, including cost-effectiveness, time savings, and streamlined maintenance workflows. This integrated solution marks a significant advancement in railway asset management, offering a proactive, data-driven tool for sustaining track infrastructure.

KEYWORDS: Track tamping, Ballast condition determination, Sieve analysis, Fouling index

1 INTRODUCTION

Ballast plays a crucial role in railway tracks by providing stability, distributing loads, and ensuring drainage. Over time, wear and contamination—commonly referred to as *ballast fouling*—degrade ballast condition. Fouling, caused by particle breakdown and infiltration of fines, reduces drainage and load-bearing capacity, impacting both track performance and tamping operations and shortening track maintenance cycles. Tamping operation should therefore be adjusted to the current ballast condition to achieve optimal results.

Current ballast assessment methods include visual inspections, ground penetrating radar, fractal analyses and laboratory testing. While laboratory methods give detailed results, they are expensive and not suited for continuous monitoring.

This paper presents a novel method that uses tamping machine sensor system to assess ballast condition in real time. The introduced Ballast Coefficient β_{Ballast} offers a practical tool for condition monitoring. Additionally, β_{Ballast} is compared with established geotechnical methods like sieve analysis and fouling indices to validate its effectiveness.

2 TAMPING MACHINE-BASED BALLAST CONDITION ASSESSMENT

During tamping operations, the tamping tines directly engage with the ballast between the sleepers. This interaction offers a valuable opportunity to reliably assess sleeper-specific ballast condition across the entire tamped section. By leveraging the data generated from this interaction, it becomes possible to evaluate ballast condition without the need for costly and time-consuming additional machine deployments or sample collection, transforming the tamping machine from a maintenance tool into an effective, in-situ sensor for ballast condition assessment. (Offenbacher et al., 2021; Barbir et al., 2018).

2.1 *Experimental approach & Methodology*

Building on the idea of using the tamping machine itself as a measurement instrument, a state-of-the-art Universal Tamping Machine (Unimat 09-4x4/4S E³) was transformed into a high-precision measurement platform through the integration of an advanced sensor system (Figure 1) (Koczwara and Offenbacher, 2025). Installed directly within the tamping unit, the sensors continuously record the real-time mechanical interaction between the tines and the ballast bed during every tamping process.

Among others, the system incorporated strain gauges embedded in the tines for accurate measurement of vertical and lateral forces, hydraulic pressure sensors as an independent channel for force verification, and depth sensors to track vertical motion—enabling precise calculation of penetration velocity and acceleration. Sampling at 1 kHz ensures that both the quasi-static, slower squeezing motion of the tamping arms, as well as the high-frequency tamping tine oscillations (35–45 Hz) are captured in detail (Offenbacher, 2025, Barbir, 2022). In addition to the sensor data, also operational parameters and settings have been recorded. Each tamping cycle generated approximately 600,000 data points per sleeper, creating a comprehensive dataset describing this interaction throughout the process.

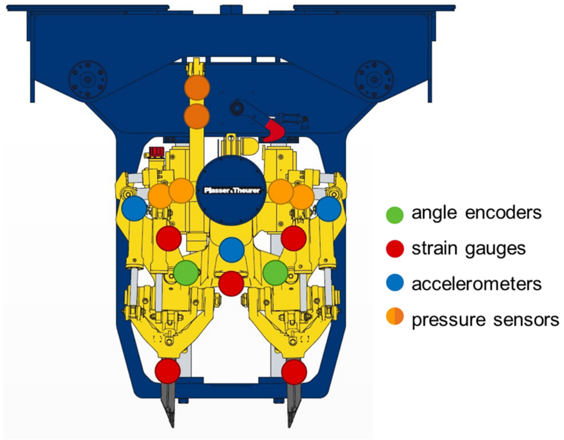


Figure 1: Schematic representation of the sensor setup (Koczwara and Offenbacher, 2025)

2.2 *Ballast Coefficient*

The recorded high-resolution dataset enabled the extraction of multiple parameters characterizing the interaction between the tamping tines and the ballast bed—such as penetration energy, maximum horizontal and vertical forces, and detailed loading–unloading response curves. Comparative analysis of these parameters highlighted one as the most effective indicator of ballast condition: the Ballast Coefficient β_{Ballast}. This coefficient is defined as the ratio between the maximum vertical penetration force $F_{\max}$ and the maximum penetration velocity $v_{\max}$ (Offenbacher, 2025). In practical terms, it represents the ballast's resistance to tine penetration: higher β_{Ballast} values are typically associated with fouled ballast, while lower values point to cleaner, more permeable aggregate. The unit of β_{Ballast} is Ns/m, which is dimensionally equivalent to a mechanical damping coefficient. To accurately represent the ballast condition independent of tamping machine parameters, the raw β_{Ballast} values were normalized. These adjustments compensated for operational factors such as tamping depth and lifting height of the track panel. For example, greater lifting values produce larger voids beneath the sleeper, lowering penetration resistance and thus reducing β_{Ballast}. On the other hand, deeper tamping increases contact friction and stress, potentially artificially increasing the coefficient. These effects were filtered out using statistical correction models derived from extensive field trials (Offenbacher, 2025). Following correction, the β_{Ballast} values were grouped into four ballast condition classes, from Class I (clean) to Class IV (heavily fouled) (Koczwara and Offenbacher, 2025). This classification converted raw sensor data into practical insights for track engineers. To validate the reliability of the β_{Ballast} values, they were compared with established laboratory and field methods, which will be covered in the following sections.

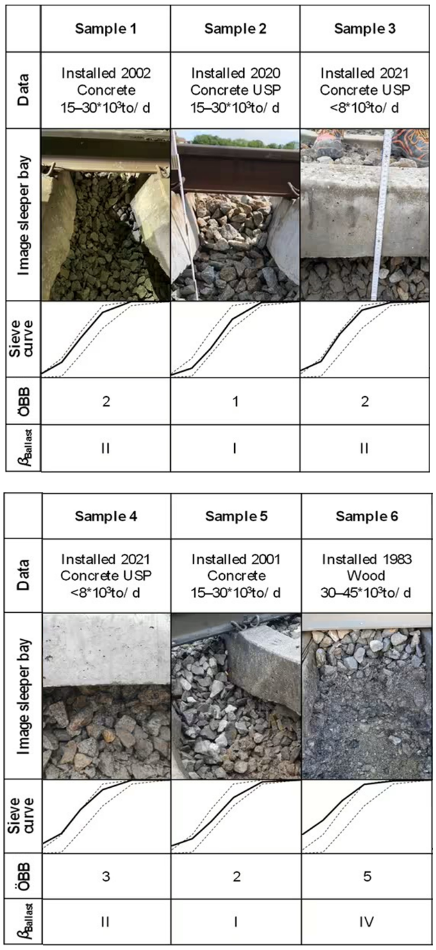
3 CORRELATION AND COMPARISON WITH ESTABLISHED GEOTECHNICAL ASSESSMENT METHODS

A detailed validation study was performed to evaluate the accuracy of the Ballast Coefficient. Various methods were applied to analyze ballast samples collected from the same track locations where the sensor-derived β_{Ballast} values were obtained, allowing for a comprehensive comparison between several approaches.

3.1 *Sieve analysis*

For the purpose of this study, ballast samples were collected from six locations where tamping operations were conducted and the Ballast Coefficient was determined (Figure 2) (Koczwara and Offenbacher, 2025). At each site, two excavation points were selected, and from each point, samples were taken from both the upper ballast layer (above the sleeper base) and the lower layer (extending down to the formation). These samples were analyzed in accredited laboratories to evaluate grain size distribution and fouling levels (Klotzinger, 2007; Indraratna et al., 2011). Experienced track engineers from Austrian Federal Railways (ÖBB) also assessed the ballast condition at each location using a five-point grading scale (1 = excellent, 5 = poor), based on the laboratory results. These expert assessments served as a qualitative benchmark to compare against the β_{Ballast}-based classifications.

To establish a correlation, the average β_{Ballast} value was calculated for each location, using ten consecutive sleepers centered around the sampling points. These values were then categorized into four ballast condition classes and compared with the expert evaluations. The results (Figure 2) demonstrate a strong correspondence between the β_{Ballast} classifications and the expert assessments, with minor discrepancies attributed to sampling variability or localized ballast differences. (Koczwara and Offenbacher, 2025)



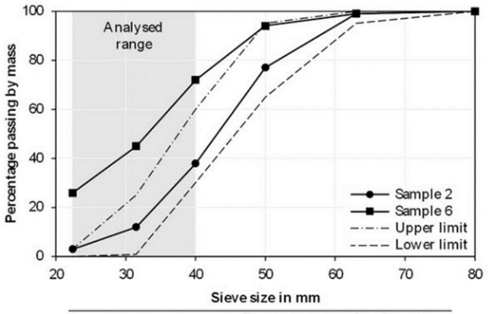
	Sample 1	Sample 2	Sample 3
Data	Installed 2002 Concrete 15–30*$10^3$to/ d	Installed 2020 Concrete USP 15–30*$10^3$to/ d	Installed 2021 Concrete USP <8*$10^3$to/ d
ÖBB	2	1	2
β_{Ballast}	II	I	II

	Sample 4	Sample 5	Sample 6
Data	Installed 2021 Concrete USP <8*$10^3$to/ d	Installed 2001 Concrete 15–30*$10^3$to/ d	Installed 1983 Wood 30–45*$10^3$to/ d
ÖBB	3	2	5
β_{Ballast}	II	I	IV

Figure 2: Comparison of the ÖBB expert assessments with the condition classes of the Ballast Coefficient. (adapted from Koczwara and Offenbacher, 2025)

3.2 *Weighted Sieve Passing index*

To quantify the link between laboratory results and machine-derived measurements, a dedicated fouling metric was introduced. (Offenbacher, 2025)



Sieve size in mm	Percentage passing by mass Sample 2	Percentage passing by mass Sample 6
80	100	100
63	99	99
50	77	94
40	38	72
31.5	12	45
22.4	3 ∑	26 ∑
Sum:	**53**	**143**

Figure 3: Particle size distribution of ballast samples for clean ballast (Sample 2) and heavily contaminated ballast (Sample 6). and the weighted sieve passing index values for the three smallest opening widths. (Koczwara and Offenbacher, 2025)

It was calculated as the weighted sum of the mass percentages passing through the three smallest sieve sizes (22.4 mm, 31.5 mm, and 40 mm), giving greater emphasis to the proportion of fine particles—a key indicator of ballast fouling (Figure 3).

Statistical analysis showed a strong relationship between this laboratory-derived metric and the β_{Ballast} values for the lower ballast layer, with a Pearson correlation coefficient of 0.89 ($p = 0.007$) (Offenbacher, 2025). This high correlation provides clear evidence that the tamping machine-based coefficient reliably represents the actual physical condition of the ballast.

3.3 *Fouling index*

The Fouling Index (FI) is one of the most widely used parameters for classifying ballast condition. Quantification of the fouled ballast for North American railways in terms of the Fouling Index (FI) emphasizes the importance of silt and clay-sized (< 0.075 mm) fouling. The revised approach—compared to the method originally developed for the USA—has been adapted to European conditions by limiting the proportion of fine particles smaller than 22.4 mm to a maximum of 5% of the sample weight. For this reason, a more consistent Fouling Index has been proposed, based on the grain size diameter ratio:

$$FI_D = \frac{D_{90}}{D_{10}} \tag{1}$$

Both D_{90} and D_{10}, which correspond to the grain sizes at which 90% and 10% of the sample weight passes, respectively, can be derived directly from the grain size distribution curve of ballast taken from the track. Moreover, a high D_{90} to D_{10} ratio describes a well-graded material, which indicates reduced permeability and a loss of elasticity in the ballast bed (Barbir, 2022). The table below presents the classification of ballast condition based on the Fouling Index FI_D:

Table 1: Track ballast classification based on the Fouling Index FI_D (Barbir, 2022)

$FI_D = D_{90}/D_{10}$	Classification
< 2.1 and $P_{13.2} \geq 1.5\%$	clean (1)
2.1 to < 4	moderately clean (2)
4 to < 9.5	moderately fouled (3)
9.5 to < 40	fouled (4)
≥ 40, $P_{13.2} \geq 40\%$, $P_{0.075} \geq 5\%$	highly fouled (5)

The application of this approach to verify ballast condition quantification for the six grain size distribution curves (Figure 2) yielded very good results with a high degree of correlation:

Table 2 Comparison of different ballast condition quantification methods (Barbir, 2023)

Ballast sample	No.1	No.2	No.3	No.4	No.5	No.6
ÖBB	2	1	2	3	2	5
β_{Ballast}	2	1	2	2	1	4
FI_D	2	1	2	2	2	3

The only exception was grain size curve No. 6, where the D_{10} value could not be determined due to the very poor ballast condition and therefore had to be estimated.

3.4 *" Grobfaktor" + BBI*

The definition of the "Grobfaktor" (Coarse Grain Factor) originates from the Austrian road construction Standards (RVS 8S.05.11) (Bundesministerium für Verkehr, Innovation und Technologie, 2001). It describes the area located to the left and above the sieve curve. The Coarse Grain Factor decreases as the material becomes finer. According to the RVS, the area is bounded above by the 100% line, on the left by a vertical line at 0.063 mm, and on the bottom-right by the grading curve.

In road construction, potential (and harmful) particle breakage due to compaction is assessed by comparing sieve curves before and after compaction (or before and after a modified Proctor test). When particle breakage occurs, the sieve curve shifts upward to the left, and the Coarse Grain Factor decreases. The difference between the factors is referred to as the "degree of refinement", (in German "Verfeinerungsgrad") for which limit values are defined in road construction. (Barbir, 2023)

The Coarse Grain Factor is also applied in evaluating the abrasiveness of coarse-grained unconsolidated rock. The guideline *"Determination of Abrasiveness of Coarse-Grained Unconsolidated Rock"* issued by the Austrian Society for Construction Technology (Österreichische Bautechnik Vereinigung (ÖBV), 2013) uses the Coarse Grain Factor to assess the breakdown of the original material after an abrasion test.

It therefore appears appropriate to also make such a comparison for the subject area of ballast fouling and assessment of the ballast condition. Due to the very different grain sizes and sieve sets for formation layers and track ballast, it is necessary to slightly modify the definition of the surface area. When testing track ballast, the usual smallest standard sieve has an opening width of 22.4 mm. The area on the left-hand side must therefore be limited to 22.4 mm (track ballast) instead of 0.063 mm (road construction formation layers). Furthermore, following the criterion of the ballast breaking index 'BBI', the difference between the two areas is not calculated, but the difference is related to the total area. (Barbir, 2023)

$$BBI = \frac{A}{A+B} \tag{2}$$

where the parameters A and B are defined in Figure 4.

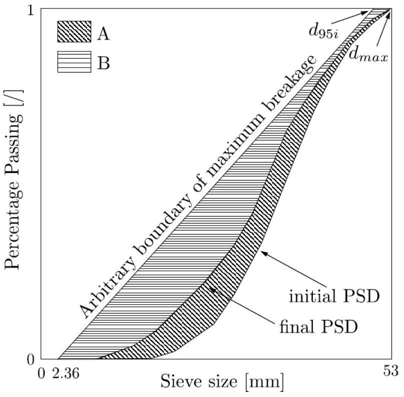


Figure 4: Ballast Breakage Index determination (Indraratna, and Rujikiatkamjorn, 2011)

It is proposed that the lower limit of the particle size distribution curve for track ballast defined by the Austrian Federal Railways be used as the 'initial' PSD. The investigated 6 samples are to be analyzed as the "final" PSD curve.

The following is defined (Figure 5):

- Coarse Grain factor lower limit: G_0
- Coarse Grain factor actual grading curve: G_1
- Coarse Grain factor or BBI: $(G_0-G_1)/G_0$

The theoretical limits of this factor are:

- 0 if the actual sieve curve still corresponds to the initial sieve curve
- 1 if the refinement of the material means that there are only grains below the smallest sieve (22.4 mm).

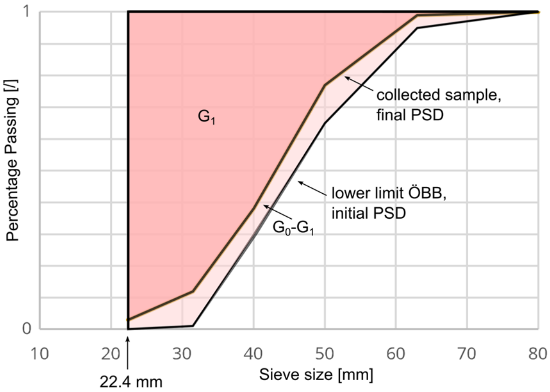


Figure 5: Modified definition of the surface areas for track ballast (Barbir, 2023)

The comparison with the ballast coefficient β_{Ballast} shows very good agreement (regression 0.94). In addition, the proposed factor is based on an evaluation that already exists in geotechnical engineering and is used for similar problems (grain size reduction in abrasiveness tests, compaction, etc.).

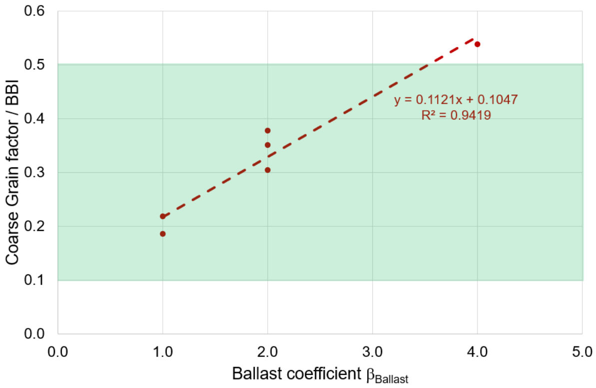


Figure 6: Comparison of the Coarse Grain factor or BBI and the Ballast coefficient for the 6 collected samples (Barbir, 2023)

The area of the factor that is likely to be of practical relevance is shown in green in Figure 6. The most important advantage of this method is that a single parameter describes the entire particle size distribution curve. (Barbir, 2023)

4 CONCLUSIONS

This study introduces and validates the Ballast Coefficient $\beta_{Ballast}$ as a reliable, real-time indicator of railway ballast condition, derived directly from tamping tine–ballast interaction data. Extensive correlation analyses with grain size distribution metrics, Fouling Index, Coarse Grain Factor, and expert evaluations confirmed its strong alignment with traditional laboratory-based assessments. Unlike conventional sampling methods, which are costly and time-consuming, $\beta_{Ballast}$ approach enables continuous monitoring along the entire tamped section without disrupting the regular track maintenance workflow. A successful integration of this methodology into operational tamping machines marks a significant advancement in condition-based track maintenance.

A streamlined sensor configuration—comprising pressure, depth, and angle sensors—was developed for field use, capable of withstanding the harsh environment of long-term railway operations. Real-time data processing onboard the machine allows operators to view ballast condition instantly and provides infrastructure managers with detailed post-operation records. This technology supports adaptive tamping control, enabling automated adjustment of compaction parameters to match local ballast conditions, improving tamping quality and extending the service life of the ballast.

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