



COMPARATIVE ANALYSIS OF TRACK QUALITY INDEX CALCULATION METHODOLOGIES USING REAL GEOMETRY DATA

Ivona NEDEVSKA TRAJKOVA¹ [0000-0002-0407-4846]

Zlatko ZAFIROVSKI² [0000-0003-2099-0710]

Jelena DIMITRIJEVIC³ [0009-0006-7158-0737]

Nenad PETRESKI⁴

Abstract – In modern railway systems, maintaining a high track quality is a key prerequisite for safe and efficient railway traffic operations. The Track Quality Index (TQI) serves as a quantitative indicator reflecting the technical and geometric properties of the track, forming the foundation for maintenance planning and intervention activities. This paper presents a comparative analysis of several TQI calculation methods to determine their advantages, limitations, and applicability across various contexts of railway infrastructure. The research evaluates three widely used methods for determining the track quality index: the Polish quality indicator (*J*), the multi-parameter unified index, and the percentage-based index. For the purpose of this analysis, all three methods were applied to a specific 5-kilometer railway section, utilizing available track geometry measurement data (longitudinal profile, gauge, alignment, and twist). The results demonstrate that while all three approaches show a high correlation in the overall assessment, they exhibit varying sensitivity to specific types of defects. The weighted-factor method (unified index) allows for a more precise identification of critical track locations, whereas the standard deviation-based approach is easier to apply and interpret but proves less informative in complex geometric deformation scenarios. The statistical approach provides a solid foundation for automated analysis, though it requires precise calibration of threshold values according to national or operator standards. The study concludes that there is no universally superior method for calculating the track quality index; rather, the selection of an appropriate methodology should depend on specific infrastructure management goals, data availability, and the required balance between accuracy and simplicity. The combined use of multiple methods is recommended for long-term planning, alongside the future development of a hybrid index that integrates the strengths of existing approaches for real-time track condition assessment.

Keywords – Track quality, Track Quality Index (TQI), Railway infrastructure, Track geometry, Track maintenance.

1. INTRODUCTION

The railway track represents a complex dynamic system subjected to stochastic and cyclic loading conditions. Under the continuous action of wheel-rail interaction forces, compounded by environmental factors and the natural consolidation of the ballast bed, progressive degradation of the designed track superstructure geometry occurs [1]. If left uncorrected, these deformations evolve into geometric defects that severely compromise traffic safety, accelerate rolling stock wear, and degrade passenger ride comfort [2].

To manage infrastructure budgets efficiently, modern railway infrastructure managers utilize automated monitoring systems, such as track recording cars, to calculate various quality indices [3]. However, a single, universally accepted index does not exist in global engineering practice. Different railway administrations apply mathematical models with varying sensitivities to local irregularities versus systemic track degradation [4]. This paper aims to address this gap in the comparative literature by parallel testing three established methodologies on a specific Montenegrin railway

¹ Faculty of Civil Engineering, Ss. Cyril and Methodius University in Skopje, 1000 Skopje, North Macedonia; nedevska@gf.ukim.edu.mk

² Faculty of Civil Engineering, Ss. Cyril and Methodius University in Skopje, 1000 Skopje, North Macedonia; zafirovski@gf.ukim.edu.mk

³ Faculty of Civil Engineering and Architecture, University of Niš, 18000 Niš, Serbia; jelena.dimitrijevic@gaf.ni.ac.rs

⁴ PE Macedonian Railways Infrastructure, 1000 Skopje, North Macedonia; nenadpetreski19@gmail.com

section characterized by demanding operational conditions.

2. PREVIOUS RESEARCH

The evaluation of track geometry quality using composite metrics has been a major focus of railway infrastructure research over the past few decades. Various international railway administrations have developed distinct mathematical formulations for Track Quality Indices (TQIs) to move away from evaluating isolated geometric defects toward a holistic assessment of track sections [5].

Early research primarily focused on using individual standard deviations of geometric parameters over specified segment lengths (typically 100 m to 200 m) to characterize track quality, as outlined in the historical development of the EN 13848 series [6]. Literature indicates that while standard deviation is an excellent indicator of systemic track degradation, its sensitivity varies significantly depending on whether the analyzed section is a straight track or a sharp curve [7].

Recent comparative studies have increasingly emphasized the limitations of relying on a single, local TQI methodology. Researchers have pointed out that different TQI formulations weight geometric parameters differently; for instance, some models place higher mathematical weight on vertical irregularities (longitudinal level), while others emphasize lateral deviations (alignment) [8]. Comparative analyses in European light rail and heavy rail systems demonstrate that applying different TQI models to the same dataset can lead to contrasting maintenance priorities. This variation underscores the necessity of testing and calibrating multiple established methodologies on specific corridor sections that exhibit complex operational and spatial constraints before selecting a definitive management metric.

3. TRACK GEOMETRY PARAMETERS AND NORMATIVE FRAMEWORK

In accordance with the EN 13848 standard series [9] and the TSI Regulation No. 1299/2014 [10], track quality is determined by five primary geometric parameters requiring continuous measurement and analysis:

- Track Gauge (G): The minimum distance between the inner running faces of the two rails, measured 14 mm below the running surface.
- Longitudinal Level (z_p): The vertical deviations of the longitudinal rail profile from its design geometry along both rails.
- Alignment (y_p): The horizontal (lateral) deviations of the rail running line relative to its design alignment.
- Cross Level (h): The height difference between the left and right rail heads, which is critical for balancing centrifugal forces in curves.
- Twist (v): The algebraic difference between two cross levels measured over a specific base (1 to 5 m), acting as a safety-critical parameter for derailment

prevention.

The EN 13848-5 standard establishes three strictly defined deviation limits for each parameter, depending on the operational speed class [11]:

- Alert Limit (AL): Defines thresholds where standard operational values are exceeded, utilized for scheduling routine maintenance.
- Intervention Limit (IL): Indicates conditions that affect ride comfort and accelerate component wear, requiring mandatory maintenance planning.
- Immediate Action Limit (IAL): The critical safety threshold regarding derailment risk, necessitating immediate technical repair or train speed restrictions [12].

4. MATHEMATICAL FORMULATIONS OF TRACK QUALITY INDICES (TQIS)

To transform raw, high-frequency spatial measurements from track recording cars into actionable infrastructure management data, composite indicators are required. This section presents the formal mathematical frameworks of the three compared methodologies, detailing how discrete geometry deviations are aggregated into unified indexes.

4.1. The Polish Quality Indicator (J)

The Polish methodology employs a multi-parameter composite index calculated based on the standard deviations (σ) of four fundamental track geometry parameters over a standardized section length [13]. The mathematical formulation is defined as follows:

$$J = \frac{\sigma_z + \sigma_y + \sigma_w + 0.5 * \sigma_e}{3.5} \quad (1)$$

where:

- σ_z is the mean value of the standard deviations of the longitudinal level measured on both rails,
- σ_y is the mean value of the standard deviations of the alignment measured on both rails,
- σ_w is the standard deviation of the track twist,
- σ_e is the standard deviation of the track gauge.

Tab. 1. Classification of track quality based on the Polish J indicator

Track Qual. Class	Threshold Range	Maintenance Implications and Actions
Excellent	$J < 1$	Stable track geometry; no intervention required.
Good	$1 \leq J < 2$	Standard condition; routine monitoring.
Satisfactory	$2 \leq J < 3$	Acceptable state; baseline maintenance scheduling.
Poor	$3 \leq J < 4$	Accelerated degradation; triggers priority remediation planning.
Very Poor	$J \geq 4$	Critical state; necessitates immediate corrective action.

The denominator (3.5) acts as a normalization constant derived from empirical operational thresholds. Based on the calculated J value, the track quality is categorized into five distinct structural condition classes, as defined in Table 1.

4.2. Multi-Parameter Unified Combined Index (CI)

A known limitation of traditional standard deviation aggregates is their inability to compensate for the different physical units and nominal boundaries of distinct geometric parameters. The Unified Combined Index (CI) addresses this by introducing a normative normalization technique [14], where each parameter's standard deviation (σ_i) is scaled directly against its maximum allowable tolerance threshold (T_i) specified by the EN 13848-5 standard for the line's corresponding speed class:

$$CI = \sum_{i=1}^n \frac{\sigma_i}{T_i} \quad (2)$$

where

- σ_i represents the standard deviation of parameter i ,
- T_i denotes the normative EN 13848-5 boundary limit (such as the Alert Limit or Intervention Limit) for that specific parameter, and
- n is the total number of evaluated geometry metrics ($n=5$).

This dimensionless formulation mathematically benchmarks localized track degradation directly against regulatory European reference framework constraints.

4.3. Percentage Track Quality Index (PTQI)

In contrast to variance-based indicators (σ) that focus on average defect amplitudes, the Percentage Track Quality Index (PTQI) evaluates the continuous spatial frequency of geometric non-conformities [15]. It operates fundamentally as a spatial binary filter that quantifies the exact proportion of discrete measurement coordinates where the geometry violates predefined structural tolerances over the entire length of the segment:

$$PTQI = \left(\frac{N_{exceed}}{N_{total}} \right) * 100\% \quad (3)$$

where:

- N_{exceed} represents the total number of discrete sampling points along the track segment where at least one geometric parameter simultaneously violates the normative tolerance limit (AL or IL),
- N_{total} is the cumulative number of discrete spatial matrix points generated during the recording run.

A PTQI value approaching 100% indicates near-absolute spatial degradation along the route, demonstrating that geometric anomalies are continuous throughout the asset's length, irrespective of whether individual peak amplitudes are localized or systemic.

5. CASE STUDY AND DATA PREPARATION

5.1. Description of the Analyzed Railway Section and Data Acquisition

The empirical evaluation of the three TQI methodologies is conducted using real-world track geometry data obtained from a specific section of the Vrbnica–Bar railway line in Montenegro. The analyzed corridor is located between km 38+570 and km 39+000, comprising a total length of 430 meters. This particular section faces demanding operational environments and significant geometric challenges. To evaluate the track quality over time, historical geometry datasets from two distinct measurement years—2022 and 2024—are utilized. The track geometry during both measurement campaigns was recorded using the same specialized Sever 1435 track recording car. Using the exact same diagnostic vehicle ensures that the spatial resolution, sensor filtering, and baseline measurement conditions are fully identical, providing a mathematically robust and highly comparable temporal framework for analysis.

5.2. Data Structuring and Matrix Formulation

The raw geometric signals recorded by the Sever 1435 car along the analyzed 430-meter section are structured into a continuous spatial dataset. For the mathematical calculation of the indices, the dataset captures four primary geometric parameters: track gauge (G), longitudinal level (z_p), alignment (y_p), and track twist (v). To perform the parallel evaluation, the discrete measurement points from both 2022 and 2024 are processed through the mathematical filters of the Polish Quality Indicator (J), the Unified Combined Index (CI), and the Percentage Track Quality Index ($PTQI$). This structured approach ensures that all three models are evaluated against the exact same spatial matrix across both historical years, allowing for a direct and objective comparative analysis of their calculation sensitivities.

6. RESULTS AND DISCUSSION

The mathematical processing of the geometry datasets recorded by the Sever 1435 track recording car yielded distinct numerical trends for each of the three evaluated TQI models. The aggregated calculation results for both historical periods are systematized in Table 2.

Tab. 2. Comparison of TQI Results for 2022 and 2024

Evaluated Index / Parameter	Year 2022	Year 2024	Qualitative Condition Assessment
Polish Indicator (J)	4.64	4.34	Degraded State (Class V to Class IV)
Unified Combined Index (CI)	15.11	6.36	Significant Deviations (Poor Condition)
Percentage TQI ($PTQI$)	99.61%	99.69%	Critical Spatial Degradation (>99%)

6.1. Analysis of the Divergence Phenomenon and Model Sensitivity

A detailed analysis of the results uncovers a highly compelling engineering and mathematical phenomenon: a clear divergence in index behavior between the two observed timelines. The variance-based metrics—namely the Polish Indicator (J) and the Unified Combined Index (CI)—both exhibited a numeric reduction, signaling an apparent improvement in track geometry quality. The J value shifted downward from Class V (Critical) toward the upper boundary of Class IV (Poor), while the CI index dropped sharply from 15.11 to 6.36. Mathematically, this behavior is strictly governed by the nature of standard deviation (σ). If localized maintenance interventions or spot repairs were executed on the section between 2022 and 2024 to eliminate a few extreme isolated defects (peak amplitudes), the standard deviation decreases drastically. Consequently, these two indices reflect an overall reduction in peak variance, suggesting a better asset condition. Conversely, the Percentage Track Quality Index (PTQI) did not follow this improving trend; instead, it registered a slight marginal increase from 99.61% to 99.69%. This contrasting behavior highlights the structural nature of the PTQI as a spatial binary filter. Even though isolated maintenance might have successfully capped the maximum peak amplitudes (thereby dropping the CI and J values), nearly every single discrete sampling point along the 430-meter section on the 25 cm grid still violates the regulatory EN tolerances (AL or IL boundaries). This proves that variance-based indices (J and CI) can inadvertently mask systemic wear if isolated severe defects are repaired, whereas the percentage-based methodology (PTQI) remains highly resilient against localized data shifts, providing an objective representation of continuous, systemic track superstructure degradation.

7. CONCLUSION

This paper presented a comparative evaluation of three distinct Track Quality Index (TQI) methodologies: the Polish Indicator (\$J\$), the Unified Combined Index (\$CI\$), and the Percentage Track Quality Index (\$PTQI\$). These models were applied to real-world track geometry data from a 430-meter section of the Vrbnica–Bar railway line in Montenegro. The analyzed datasets were recorded across two distinct timelines, 2022 and 2024, utilizing the same Sever 1435 track recording car. The analytical results demonstrate a significant divergence in index behavior, highlighting the unique mathematical sensitivities of each model:

- The variance-based metrics (J and CI) exhibited a numerical reduction, implying a false or localized improvement in track quality due to their extreme sensitivity to the suppression of peak amplitudes via isolated spot repairs.
- The spatial frequency metric (PTQI) remained stagnant in a critical zone (>99%), acting as a robust

binary filter that successfully captured continuous, systemic geometric degradation across the entire asset length.

Ultimately, the study underscores that no single index can universally address all infrastructure asset management requirements. While variance-based indicators are highly effective for high-speed lines where passenger comfort depends on capping amplitude spikes, the percentage-based approach (PTQI) provides an invaluable and objective tool for conventional and highly stressed corridors, ensuring that systemic structural wear is not masked by localized maintenance interventions.

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