



## COMPARATIVE ANALYSIS OF STANDARDIZED AND COUNTRY-SPECIFIC METHODS FOR CALCULATING THE TRACK QUALITY INDEX (TQI)

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### Abstract

The Track Quality Index (TQI) is essential for evaluating track geometry quality in railways, influencing maintenance decisions to ensure safety and performance. While most European countries adhere to the European framework (EN 13848-6+A1:2021) for TQI assessment, few apply the same unaltered methods regarding weights, segment lengths, and thresholds. The paper analyzes TQI frameworks across various European countries, highlighting key geometric parameters, threshold values, and their effects on maintenance. The case study focuses on a Romanian railway section, noting that while TQI is calculated, the standardization of its thresholds is still in progress. The study advocates for a uniform calculation methodology for TQI across Europe to enhance interoperability and maintenance strategies per the EN 13848-6+A1:2021 standard.

*Keywords: track quality index (TQI), track geometry, maintenance decision support, track condition monitoring, geometric irregularities*

### 1 Introduction

Rail infrastructure is a critical component of rail transport. To ensure optimal economic efficiency, railway infrastructure must comply with specific fundamental requirements. These requirements are directly aligned with the four key principles that underpin rail transport: safety, comfort, sustainability, and cost efficiency. Infrastructure quality assessment is an essential technical and strategic requirement to ensure the long-term safety, efficiency, and sustainability of the rail transport system. Most railway infrastructure administrations spend a significant part of their budget on routine and periodic maintenance activities. This cost can even reach 70% of the total lifecycle cost of a railway [1]. Therefore, accurately evaluating the quality of railway lines is essential for prioritizing maintenance work and optimizing resource allocation within a railway network. Track Quality Indices (TQIs) are used in most European countries as standardized indicators for monitoring the condition of railway infrastructure and guiding maintenance strategies. According to the European regulatory framework for track quality assessment EN 13848-6+A1, the quality of the track geometry can be characterized for different TQI depending on the purpose pursued. The most common TQI used by European rail networks is the standard deviation and the combined standard deviation of individual geometric parameters [2]. The standard also indicates possible cases where these indices could be applied – high-level maintenance strategies, acceptance of work that influences the geometry of the track, maintenance works – through statistics based on average, maximum, or percentile values of a TQI distribution. Even if the European regulatory framework is a common one, national implementations differ.

The difference does not necessarily lie in the calculation mode, since in most cases the standard deviation is used as the calculation mode on a 200 m long segment of railway, but rather in the assembly mode of the combined TQI index (components and weighting coefficients) and the limit values adopted [3]. For example, the assessment of the quality of the Romanian railway is conducted according to Instruction 329 and Ministerial Order no. 2256/27.11.2006. The two regulations specify individual tolerances and classify deviations for each geometric parameter of the track based on track category. However, this classification does not consider individual quality indices (TQI) for each geometric parameter or their combined effect through summation. The risk levels are classified based on scores that reflect the severity of local defects for each geometric parameter of the measured trajectory [4, 5]. A higher score indicates a greater safety risk to the railway line. In Romania, this evaluation system is operational and well-regulated; however, it should be noted that it is oriented toward corrective maintenance focused on local defects rather than providing a comprehensive overview of the track's overall condition. The purpose of the study is to compare several methods for assessing the condition of the track using measured geometric parameters. This assessment considers the methodology for calculating the TQI indices applicable in Poland, the Netherlands, and Romania, as well as the method described in EN 13848-6+A1:2021. It is important to note that Romania's current regulations do not provide for specific limit values for TQI.

## 2 Tack geometry quality (TQI)

### 2.1 Assessment – general considerations

To ensure safe and cost-effective rail traffic, it is crucial to standardize how track geometry quality is assessed, focusing on both the track and the vehicles [2]. Numerous studies have evaluated railway degradation and optimized maintenance, ranging from simple single-component models to comprehensive predictive models. These models classify degradation into two main types: structural damage and geometrical degradation [6]. Geometrical degradation refers to the assessment of railway track conditions based on measured geometric parameters. In this process, the railway line is divided into several sections, typically 200 meters in length. For each section, standard deviations are calculated for various geometric parameters. These values are then combined using weighting coefficients that reflect the significance of each parameter in the overall evaluation, resulting in an overview of the quality of the examined sections. The geometric parameters considered generally include gauge, longitudinal level and alignment on both rails, cant, and twist. The assessment of track quality should take into account the principles of track-vehicle interaction. A vehicle's response to track defects of the same amplitude can vary depending on their wavelengths. In our study, the wavelength ranges selected for the evaluation of the geometric track parameters were chosen to reflect as accurately as possible the vehicle behavior on the assessed section.

### 2.2 Standardized and national TQI methodologies

#### 2.2.1 Combined standard deviation

The calculation of TQI according to the European standard EN 13848-6+A1 is based on the standard deviation (SD). This SD represents the variation of a signal across a specific section of track, in relation to the average value of that signal in the section being analyzed.

$$SD = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (1)$$

where:

- $n$  – number of measured values
- $x_i$  – the current value of the signal
- $\bar{x}$  – the mean value of the signal.

Standard deviation is typically calculated within the D1 ( $3 \text{ m} < l \leq 25 \text{ m}$ ) or D2 ( $25 \text{ m} < l \leq 70 \text{ m}$ ) wavelength ranges for torsion and the horizontal and vertical positioning of the track. It can also be determined for gauge and cant. The evaluation of overall track geometry quality (CoSD) for a predetermined length section can be assessed through a combination of the weighted standard deviations of individual geometric parameters.

$$CoSD = \sqrt{w_{AL}^2 SD_{AL}^2 + w_G^2 SD_G^2 + w_{CL}^2 SD_{CL}^2 + w_{LL}^2 SD_{LL}^2} \quad (2)$$

where:

$w_i$  – weighting factors for each geometric parameter.

Indices:

AL – position of the track in the horizontal and vertical plane (average of the left and right rails), G – track gauge, CL – cant, LL – longitudinal level (average of the left and right rails).

### 2.2.2 Poland's J coefficient

The J Synthetic Coefficient is an indicator of track quality developed by Polish railways. To calculate this coefficient, four geometric parameters of the line are considered: longitudinal level, alignment, twist, and track gauge.

$$J = \frac{S_z + S_y + S_w + 0,5 \cdot S_e}{3,5} \quad (3)$$

where:  $S_z$ ,  $S_y$ ,  $S_w$  și  $S_e$  represent the standard deviations for longitudinal level, alignment, twist, and gauge.

The method for calculating standard deviation aligns with the European standard.

$$S = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (4)$$

### 2.2.3 Netherlands N Index

The N index is determined separately for each geometric parameter of the track. This calculation takes in consideration the standard deviation of the parameter for 200-meter track segments. Additionally, it takes into account the 80th percentile of standard deviations calculated over a distance of 5 to 10 kilometers of track [7].

$$N = 10 \cdot 0,675^{\sigma_i / \sigma_i^{80}} \quad (5)$$

### 2.2.4 Romanian standard deviation

In Romania, Ministerial Order no. 2256/2006 includes the TQI-Ro calculation method, which is based on the standard deviation (AS) formula. This method applies to the following geometric parameters: gauge, longitudinal level and alignment for both rails, cant, and twist. The relation for calculating the standard deviation is as follows:

$$AS = \sqrt{\frac{1}{(n-1)} \left[ \sum_{i=1}^n (x_i)^2 - \frac{\left( \sum_{i=1}^n x_i \right)^2}{n} \right]} \quad (6)$$

To assess the general quality of the track (TQI-Ro), Romanian regulation stipulates calculating the total of the individual standard deviations of the relevant geometric parameters, excluding any weighting indices.

$$TQI-Ro = \sum AS \quad (7)$$

### 3 Case study

This study is based on track geometry data collected by the EM130 track geometry vehicle over a 5 km section between km 105+400 and km 110+400 on Romanian Main Line 300, Track 1, along the Comarnic – Sinaia route. The measurements were conducted between 2016 and 2024, ensuring data consistency by utilizing the same equipment and measurement procedures under identical operating conditions. The route consists of a series of curves interspersed with straight sections. The geometric characteristics of the curves along the route are detailed in table 1. The geometric parameters measured were gauge, elevation, longitudinal level and alignment on both rails, and twist. This data was recorded at regular intervals of 25 cm and exported to an Excel file for further processing and analysis.

**Table 1** Curves geometrical characteristics

Curve	Starting chainage [km]	Radius [m]	Cant [mm]	Transition curve length – enter [m]	Circular Length [m]	Transition curve length – exit [m]
C-01	105+950	3870	10	40	380	50
C-02	106+900	1790	10	40	80	87
C-03	107+720	590	130	100	280	87
C-04	108+435	450	130	85	70	58
C-05	108+731	435	85	75	75	63
C-06	109+087	405	95	53	70	54
C-07	109+580	910	45	40	60	35
C-08	109+908	400	95	90	120	72
C-09	110+235	465	115	100	70	85

The geometric data included both deterministic elements, like curve geometry and level differences, and stochastic data about track conditions. Two cases were analyzed based on the impact of defects on vehicle behavior. In both, cant and twist were examined in the D1 wavelength domain using a low-pass filter of  $l = 7.5$  m. For alignment and longitudinal level, a wavelength of  $l = 20$  m was used in the first case, while  $l = 50$  m was applied in the second case for the D2 domain. Data pre-processing involved a  $l = 1$  m filter to remove measurement errors, with a moving average method used for different wavelength filters. The TQI calculation was performed using the four methodologies outlined above, and the track quality indicators were derived from a statistical analysis of irregularities across predefined track segments of 200 meters.

For all geometric parameters, except for the gauge, the irregularities were determined by calculating the difference between the filtered value (low-pass filter) and the peak value.

## 4 Results

Based on the conducted calculations, it was found that the individual standard deviations for each studied parameter do not significantly differ among three of the four methodologies. The exception is the N index used by the Netherlands. Differences arise when evaluating the overall quality of the track through the calculation of a combined TQI, as each railway administration applies different weighting factors. Figure 1 illustrates these discrepancies based on measurements taken in 2024. Notably, the Romanian method does not provide any weighting factors; instead, the combined TQI-Ro value is obtained by simply summing the individual standard deviations of each parameter. In figure 2, the variation of the combined TQI-Ro over four years is presented, while figure 3 illustrates the variation of the Synthetic Coefficient J. Both graphs clearly indicate that the maximum values of these indices occur along the same 200-meter track segments; however, they are displayed on different scales due to the weighting factors applied to the Synthetic Coefficient J. The localized increases in the combined TQIs are attributed to gauge variations, as shown by the gray line in figures 2 and 3, which represents the standard deviation of this geometric parameter.

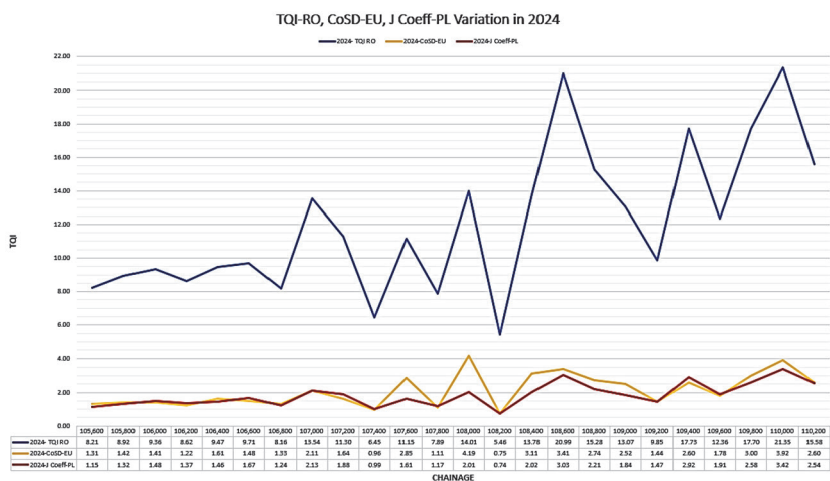


Figure 1 Comparison of TQI-Ro, CoSD-Eu, and J Coeff-PL for the same track section measured in 2024

This study not only conducts a comparative evaluation of methodologies for calculating the Track Quality Index (TQI) but also explores the relationship between TQI-Ro and the local defect scoring system currently in use. To achieve this, a local defects assessment was conducted on the same 200-meter-long segments, and a total score was calculated for each segment. The goal was to assess whether the combined TQI-Ro aligns with the prioritization logic currently used in maintenance practices. While some correlation between the two metrics can be observed in certain analyzed track segments, as illustrated in figure 4, it's important to note that the defect scoring system relies on local levels of exceedance. In contrast, TQI-Ro is a continuous statistical measure. As the calculations demonstrate, a perfect linear correlation between these two indicators cannot be expected.

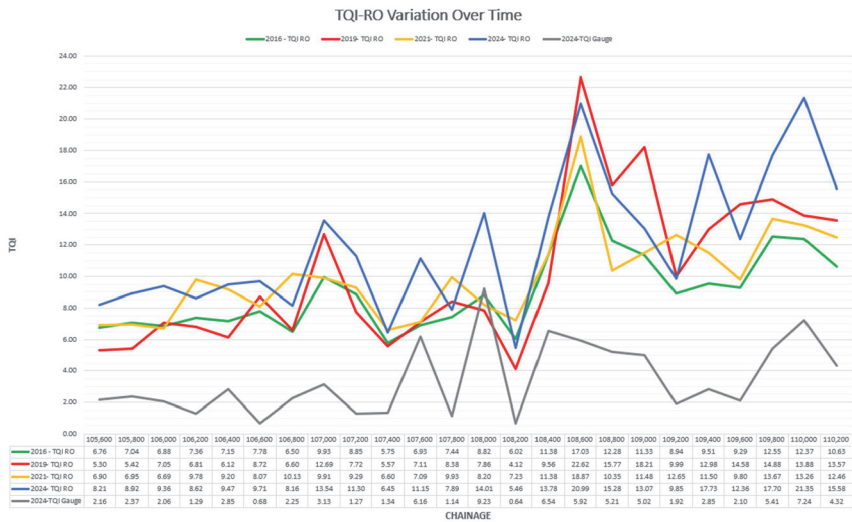


Figure 2 The combined variation of TQI-Ro and the impact of the gauge standard deviation on the results

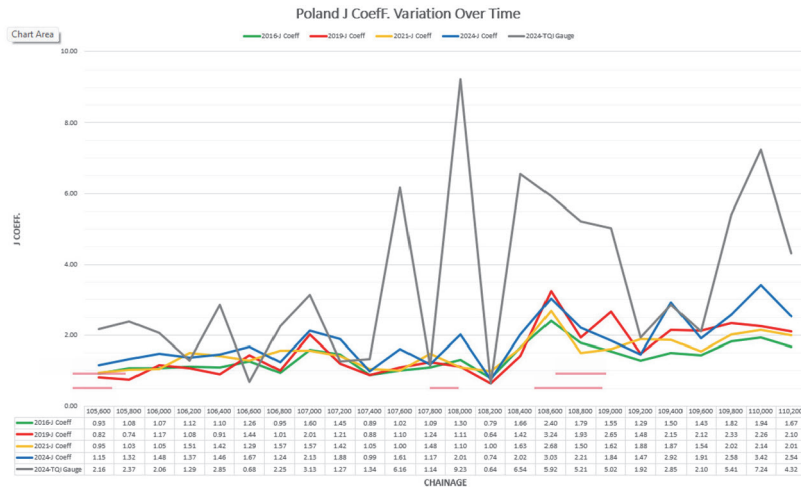


Figure 3 Poland's J Synthetic Coefficient variation and the influence of the gauge standard deviation

The study goes beyond simply comparing methodologies; it also explores the potential of using combined TQI values as long-term performance indicators for maintenance. Rather than relying solely on average TQI values, the study evaluates statistics based on the 70th, 80th, and 90th percentiles. This evaluation helps identify the proportion of segments that exhibit high levels of degradation, as illustrated in figure 5. This approach enables verification of critical sections and supports strategic maintenance planning by quantifying the share of rail lines that exceed predefined intervention thresholds. These thresholds are established based on the financial capacity of each administration to conduct maintenance work [8].

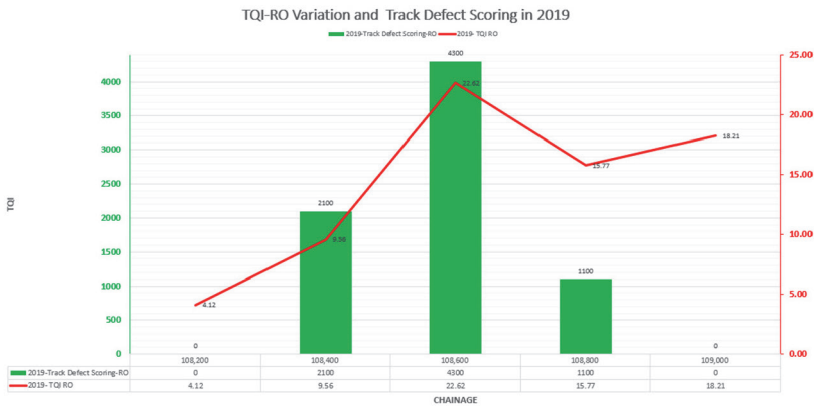


Figure 4 Correlation between TQI-Ro and the local defect scoring system

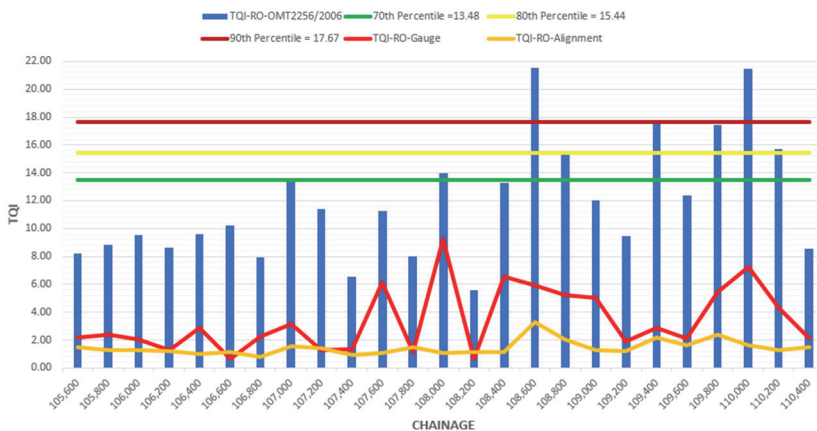


Figure 5 Using TQI-RO as a KPI in long-term maintenance strategies, TQI-RO according to OMT 2256/2006

The percentiles of the combined TQI serve as an effective performance metric for maintenance management, particularly when identifying sections that may be damaged. However, to determine the appropriate types of interventions, it is essential to analyze the individual quality indices related to each geometric parameter. By breaking down the overall TQI into its parameter-specific components, we can pinpoint the primary degradation mechanisms and support more targeted maintenance actions. Figure 5 illustrates that the overall increase in combined TQI-Ro values is primarily due to components related to track gauge and twist, which are crucial indicators for determining the required maintenance work.

## 5 Conclusion

This study conducted a comparative analysis of standardized and national methodologies for calculating TQI. While all the methods discussed are based on the calculation of the standard deviation of the track's geometric parameters, they differ significantly in their structural combinations. This leads to variations in their sensitivity and affects how maintenance work is prioritized. The correlation between TQI-Ro and the current defect scoring system is not necessarily linear, however, the combined TQI demonstrates significant increases in areas where the defect scores are high.

The research emphasizes not only the comparison of methodologies but also the strategic advantages of using combined TQI values assessed through percentile-based statistics. Additionally, it underscores the importance of analyzing individual track geometry indices alongside the combined TQI values to identify the main degradation mechanisms and to aid in selecting the most suitable maintenance strategies.

Future research should enhance this analysis by examining various railway networks with respect to track condition, traffic levels, and maintenance practices, incorporating longer observation periods and more frequent measurements. Additionally, further studies are needed to refine the weighting strategies used to combine individual standard deviations, as this can significantly impact the prioritization of maintenance work. Finally, harmonizing the definitions of cut-off thresholds for TQI remains a significant challenge. Future comparative studies should aim to establish benchmarks that improve interoperability and consistency in European railway track quality assessment practices.

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