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Research Article

Use of Zero-crossings Segmentation for Track Quality Assessment

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Abstract: This study concerns track quality assessment of standard-gauge railways in the context of the Hungarian railway system. Data gathered by multipurpose track recording vehicles matched the EN 13,848 requirements. Track Quality Index (TQI) measurement systems (The Federal Railroad Administration (FRA), the Netherlands', and the Chinese TQI) are considered where three types of predetermined segment techniques: separate, moving, and Zero-crossings segmentation are employed. The importance of track segmentation in quality assessment, which affects maintenance planning, is shown by key findings. For heterogeneous data, the TQIs might be deceptive, highlighting the need for alternatives. The robustness of the Zero-crossings method makes it possible to analyze deterioration factors in great detail and in some efficient way. Longer analytical segments and smoothing of the data improved precision. Based on empirical data, we advise considering a Zero-crossings strategy for precise and efficient track-quality evaluations. With the help of this study, track quality can be better evaluated for train systems.

Keywords: *Track Quality Indices, Track geometry, Signal processing, Zero-crossing, Empirical Mode Decomposition, FRA Geometry TQI, Netherlands TQI, Chinese TQI*

I. INTRODUCTION

In the era of high-speed railway systems, the railway track is considered a main pillar for safety and train punctuality. Using total quality management in railway maintenance has led practitioners to find better ways to manage railway assets more efficiently and cost-effectively [4, 6, 20]. Predicting degradation plays a pivotal role in formulating inspection and maintenance strategies. Monitoring the condition of railway tracks is essential to uphold the efficiency of infrastructure assets [22]. When a geometric track indicator approaches the established legal limit, it signifies the necessity for maintenance intervention. These actions are undertaken to minimize or prevent potential failures, ensuring the restoration of any malfunctioning railway components to an operational condition.

Railway track geometry includes 4 main parameters: 1) Longitudinal level: the concept refers to how much the running table level differs from a smoothed vertical position (reference line) within specific wavelength ranges. 2) Alignment: the concept pertains to how much the rail deviates laterally from a smoothed reference line within specific wavelength ranges. 3) Track gauge: the closest distance between the inner edges of the rail heads, measured slightly below the rail surface within a range of 0–14 mm. 4) Cross level: difference in the height of the adjacent running tables. For more details, the reader refers to [2, 6, 10]. In addition sensitive wavelengths of the track, irregularities have been considered by [7].

The track is divided into segments to evaluate railway track conditions based on track geometry, and the quality is assessed for each segment. Track Quality Indices summarize this assessment (TQI), which are preferred methods for comprehensively evaluating railway track conditions. TQIs are valuable for assessing track performance, planning interventions, and comparing track performance before and after modifications. Two decades ago, [11] identified that the segmentation approach used for TQI calculations is characterized as linear track geometry measurements with consistent attributes related to factors influencing track geometry degradation.

Paper [13] used simulated results to show that various TQIs are specified for track segments of varying lengths, typically categorized as 3–25 meters, 25–70 meters, and 70–200 meters in length. The 200-meter long segment is the most commonly employed, although in certain instances, a specific track or even the entire network is assessed using just a single TQI value [23]. Recently, two approaches have been proposed to define the railway track segments, where both approaches have generated variable segment lengths along the railway track. The first approach relied on the specific type of track construction in use [12] and the second was based on the horizontal elements of track alignment (straight, curve, and curve with transition curve segments) [28]. Additionally, more recent research highlights the importance of considering not only technical factors but also economic and operational aspects when deciding on track segment lengths for maintenance purposes [21]. Although emerging technical factors and economic and operational aspects become crucial when deciding on track segment lengths, the statistical properties of the collected measurements should be treated carefully. The need to evaluate railway track quality to plan repairs is emphasized in [26], with a focus on the objective of preserving stable track geometry. The paper looked at the efficiency of remedial maintenance and the rates of track deterioration on a regional railroad. Also, to identify critical elements for sustainable development, [5] investigated actual measurement data of six geometric parameters of continuously welded rail (CWR). According to their results, vertical irregularities are important in the vertical plane (V-plane), but the track gauge gradient and horizontal irregularities are crucial in the horizontal plane (H-plane). These factors become more intense, particularly in curved sections, necessitating more frequent maintenance. In light of the increasing importance of rail as a sustainable mass transit alternative, the study findings offer a foundation for efficiently regulating the life cycle of CWR to advance sustainability.

Zero-crossings is a powerful tool for analyzing time series data, it can be used to characterize oscillatory patterns, extract useful information about the signal, and develop signal processing applications [3, 15]. Besides that, it can be used for non-Gaussian mixtures and products of Gaussian processes as well. Based on the information gathered by the authors, it can be deduced that there exists no substantial contribution aimed at improving railway track segmentation based on Zero-crossings.

This research aims to propose the Zero-crossings methodology as a possible way of railway track segmentation, evaluating the overall quality of individual track segments, and establishing management criteria based on the proposed approach. Time series and signal processing techniques will be applied since the measurements are very similar in nature to observations in time. The rest of the article is organized as follows. The materials and methods are introduced in Section II, and the results of the Hungarian State Railway are summarized in Section III, a track section of 5,900 meters serves as an example for illustration of our work, without keep mentioning it. Then, in Section IV, the results have been discussed thoroughly. Finally, Section V gives the main conclusions.

II. METHODOLOGY

Various countries have made efforts to customize their version of the TQI. For instance, in China, the TQI is based on the standard deviations of 7 types of track measurements. In the United States, the ratio of traced space curve length to track segment length is used. Polish J-synthetic coefficient based on standard deviation is used to assess the Polish Railways. India has its track geometry index formula, which focuses on standard deviations of geometry parameters over 200-meter segments. A detailed discussion of some approaches is shown in the following subsections.

1. FRA Geometry TQI

Federal Railroad Administration developed a length-based method to calculate the TQI_F of a given segment of the data for gauge, alignment, and longitudinal level, say [6]. Let x_k denote the sampling points and y_k the measurements. The formula of TQI_F is the following

$$TQI_F = 10^6\left(\frac{\ell_s}{\ell_0} - 1\right), \tag{1}$$

where ℓ denotes the theoretical length (in mm), in particular $\ell_0 = \sum_{k=1}^{n_0} \Delta x_k$, and ℓ_s is the traced length of the space curve of a track segment including n_0 measurements, i.e. $\ell_s = \sum_{k=1}^{n_0} \sqrt{\Delta y_k^2 + \Delta x_k^2}$. Here Δy and Δx are the differences between two consecutive measurements in the sample space, respectively. We consider equidistant measurements where $\Delta x_k = h$ therefore

$$TQI_F = 10^6\left(\frac{1}{n_0}\sum_{k=1}^{n_0}\sqrt{\left(\frac{\Delta y_k}{h}\right)^2 + 1} - 1\right).$$

Some other railway administrations use TQI which combines two or more geometrical parameters into a single measure of ride quality.

2. Netherlands Track Quality Index

The Netherlands Q index proposes a more universal form of quality index across different classes of railway tracks [16], [23]. This index considers the standard deviation of a particular quality parameter for a specific track segment. It compares it to the 80% quantile of the standard deviations of that parameter across all track segments. The Q index spans from 0 to 10. A higher Q index indicates improved track quality for a 200-meter track segment

$$TQI_N = 10 * 0.675^{\sigma_k/\sigma_{80,\bullet}}. \qquad (2)$$

Where σ_k is the standard deviation for the quality parameter, and $\sigma_{80,\bullet}$ represents 80^{th} percentile of standard deviations of all segments in the maintenance section ranging from 5 to 10 km.

3. Chinese Track Quality Index

Chinese national railroads use the sum of standard deviations σ_k of seven quality parameters to assess the overall track quality of a track segment [8]. It is calculated by

$$TQI_C = \sum_{k=1}^{7} \sigma_k. \qquad (3)$$

Two possible lengths of the overall track quality assessment are 200 m and 500 m. The first is applied to conventional railway lines and the second is usually applied to high-speed railroads. The segment is considered worse in the overall track quality as the TQI_C value increases.

4. European Standard EN 13848-5

European Standard is also monitoring the railway track geometry. Longitudinal level, alignment, and gauge are the key track geometry parameters that one evaluates. The mean value determines gauge irregularities over a 100-meter segment while longitudinal level and alignment are assessed by analyzing the standard deviation of irregularities in a 200-meter segment. European Standard provides the permissible thresholds for geometry parameters [1, 4, 10]. The permissible thresholds are given in **Table 1**.

5. Zero-crossings approach

In the literature, the most straightforward procedure of track segmentation is to divide the whole railway track into equally-length segments. The length is usually chosen according to the train's speed, either 200 m or 500 m [23, 27]. However, although the fixed segment length is easier to construct and measure the railway efficiency sometimes it might be misleading where the measurements in the same segment might be heterogeneous. Recently, [18] investigated the impact of changing the segment length to assess railway track quality. They evaluated analytical segments of various lengths, including 200 meters, 100 meters, 50 meters, and 25 meters. The comparative assessment of the calculations for TQIs revealed that decreasing the segment length led to an enhancement in the resolution of the track quality analysis. [21] used the linear regression function and demonstrated its aptness in characterizing track quality between two tamping tasks and exhibited superior accuracy in forecasting future track quality.

Our approach is based on the idea that two consecutive zero observations define the most important changes in the railway track. Since the distortion is restarting from zero at each time. The Zero-crossings in a series of measurements are the points where the signal changes from positive to negative or vice versa. **Fig. 1** illustrates the idea of Zero-crossings as the blue dots show the point where the sign has been changed. The signal crosses the zero line (red) at the blue points. Zero-crossings are a powerful tool for analyzing a series of data, they can be used to characterize oscillatory patterns in time series data in particular providing a robust approach to the detection of periodic autocorrelation, [19]. It gives useful information about the signal and base for signal processing applications [15, 24]. It is worth noting that the lengths of zero-crossing segments are not fixed and the data included in different segments can be considered independent.

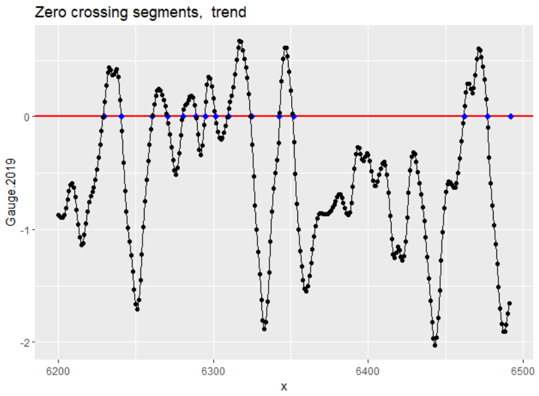

Figure 1. *Example for zero-crossings of the denoised (by EMD) Gauge 2019 (mm) in terms of measurement numbers.*

Zero-crossings method

Consider that we have data sampled over time or space, let $X_s, (s = 1, 2, \ldots, N)$ denote the corresponding stochastic series. We define zero-crossings for observations in equidistant distances. Let the associated (to X_s) clipped binary series Y_s

Table 1. *Difference limit between the specified gauge and mean gauge over 100 m segment (in mm)*

	Mean Gauge threshold			Standard deviation threshold	
Speed (km/h)	Safety limits	Intervention limits	Alert limit	Longitudinal level	Alignment
80-120	[-7, +27]	[-6, +25]	[-5, +22]	1.8-2.7	1.2-1.5
120-160	[-5, +20]	[-4, +18]	[-3, +16]	1.4-2.4	1.0-1.3
160-220	[-5, +20]	[-4, +18]	[-3, +16]	1.2-1.9	0.8-1.1
220-300	[-5, +20]	[-4, +18]	[-3, +16]	1.0-1.5	0.7-1.0

defined by

$$Y_s = \begin{cases} 1, & X_s \geq 0, \\ 0, & X_s < 0, \end{cases} \qquad s = 1, 2, \ldots, N,$$

and let d_s be the indicator function at distance s

$$d_s = (Y_s - Y_{s-1})^2, \quad s \geq 2$$

Now, d_s is 0 or 1. When $d_s = 1$ we say that a zero-crossing occurs at distance s. The number of zero-crossings in $X_1, X_2, \ldots X_N$ is denoted by D_X and is defined by the sum

$$D_X = \sum_{s=2}^{N} d_s.$$

The expected number of zero-crossings D_X per unit distance can be calculated for a Gaussian stationary series by the formula

$$\mathrm{E} D_X = \frac{N-1}{\pi} \arccos \rho_1, \tag{4}$$

where ρ_1 is the autocorrelation of X_s at lag 1, see [14]. It will be clear later that the assumption of zero mean and Gaussian stationarity does not fulfill our data nevertheless the formula (4) provides some basic information.

Table 2 shows that although the formula (4) is not applicable precisely there is some clear connection between the observed number of zero crossings *nZC* and the theoretical values *nZCth* of it. The column *nZC*/*nZCth* points out the dependence on the mean μ, since the zero mean is assumed for the formula (4). After we have centered the series column $nZC0^*$ became really close to theoretical values, see column *%nZC0*/*nZCth*. Nevertheless, we are interested in the zero-crossing segments of the non-centered data and use the formula (4) for the orientation of the investigation.

6. EMD and trend

We consider the Empirical Mode Decomposition (EMD) as a possible tool for preliminary transformations for non-stationary, non-Gaussian data, moreover which is not smooth enough. EMD is a data-driven auto-adaptive method, which decomposes signals into components referred to as Intrinsic Mode Functions (IMF) and a residual. IMFs are satisfying the following conditions: (i) In the whole dataset, the number of extrema and the number of zero crossings must either equal or differ by at most one; (ii) at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero, [9]. The construction of IMFs is not unique. In our calculations, we apply the R package Rlibeemd using the so-called sifting process method, see [9], [17]. One of the advantages of EMD is that the modes (IMFs) are orthogonal. The sum of all modes and the remaining residual resemble the original signal. The IMFs fluctuated around zero. The only non-zero mean component is the remaining residual. An IMF represents a simple oscillatory mode. It has been noticed [25] that the frequency bandwidths tend to reduce as the number of IMFs increases.

We are interested in the decomposition of a signal into a possible continuous deterministic trend and an additive noise since the result of the changes of the railway track should be a smooth signal i.e. there are no sudden changes except the noise of the measurement. The trend can serve as the nonlinear smooth signal and the additive noise as the stationary Gaussian process. The separation of the signal to the trend and noise has been considered by [29]. The methodology is the following: consider the correlations of the marginal Hilbert spectrum for two consecutive IMFs then starting from the first IMF $u_1(t)$, check step by step if the modulus of correlation is smaller than an ε (typically $\varepsilon = 0.2$). The separation before and after that stopping order p_0 say, provides the decomposition of the signal into noise which is the sum of IMFs: $W(t) = \sum_{k \leq n_0} u_k(t)$ and the trend $X(t) - W(t)$. In our case, we have $p_0 = 2$ for Gauge 2019. One observes that the outliers are included in the noise but the residual, which is considered a nonlinear trend.

Fig. 3 shows an example where the observation X_{13710} has neighbors with significantly different values. Therefore it should be considered to be an outlier. The trend (EMD residual) smooths the observations.

III. RESULTS

A formal analysis has been conducted to compare the effectiveness of segmentation by Zero-crossings

Table 2. *Number of zero crossing segments for data Gauge 2019, in mm.*

Type	Year	nZC^*	$nZCth^*$	$\% \, nZC/nZCth$	μ	$nZC0^*$	$\% \, nZC0/nZCth$
Gauge	2017	1245	1892	66	-1.13	1794	95
	2018	1553	1930	80	-0.76	1812	94
	2019	1528	1893	81	-0.73	1782	94
	2020	1387	1805	77	-0.96	1748	97
Left	2017	1398	1619	86	-0.45	1598	99
	2018	1506	1568	96	0.43	1634	104
	2019	1369	1523	90	-0.50	1565	103
	2020	1515	1529	99	-0.42	1575	103
Right	2017	1604	1634	98	-0.30	1686	103
	2018	1327	1578	84	0.57	1575	100
	2019	1517	1528	99	-0.32	1531	100
	2020	1471	1531	96	-0.33	1561	102

**We have denoted the number of zero crossings segments of the data: nZC, estimated by the formula (4): $nZCth$, percentage: $nZC/nZCth$, mean: μ, in mm, number of zero crossing segments for centered data: $nZC0^*$, percentage: $\%nZC0/nZCth$.*

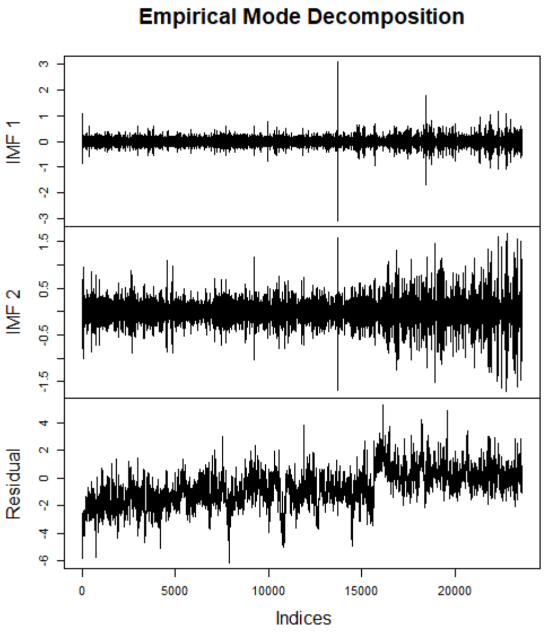

Figure 2. *EMD, data Gauge 2019, in mm.*

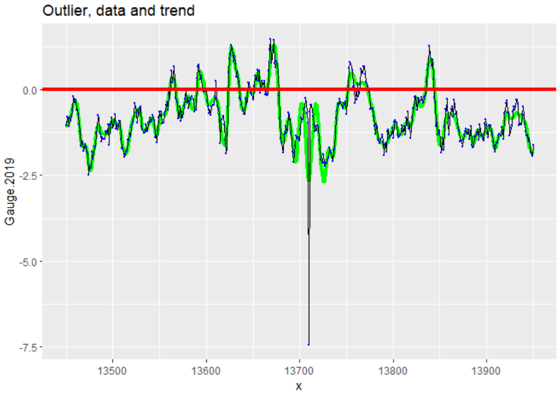

Figure 3. *Data Gauge 2019, in mm,(black) and trend, i.e. denoised data generated by EMD (green). Outlier: $X_{13710} = -7.43$ in between $X_{13709} = -0.97$, and $X_{13711} = -0.65$, (indices denote the measurement numbers).*

and fixed-length segmentation. MÁV CRTI Ltd. (Hungarian State Railways Central Track Inspection Ltd., Budapest, Hungary) provided a local gauge narrowing fault dataset obtained from their measurements by a versatile Track Recording Vehicle (TRV). The TRV operated at an average speed of 160 km/h, and track irregularity data was meticulously sampled at 0.25-meter intervals along the railway track. We have considered the dataset comprised four years, from 2017 to 2020, and was sourced from diverse segments of railway lines in Hungary. We consider a specific choice of a track section spanning measurements including a chain 5,900 m. The primary focus of the inquiry is on specific track geometry parameters, including measurements of the track gauge (mm) and alignment (mm) of both the right and left rails. The surveyed railway maintains straight-line geometry within each year.

1. Basic statistics

The primary objective of our statistical methodology is to examine and elucidate the location and variability characteristics of our railway dataset and to assess and describe the skewness and kurtosis parameters.

Table 3 provides a summary of the statistical data related to track gauge measurements and left and right rail alignments, and categorizes the defined railway sections by years. The results of the Hungarian railway measurements meet or exceed the established EU benchmarks, as stated in [2], which are consistent with EU standards. The statistical

Table 3. *Summary statistics of the railway geometrical parameters, including gauge (mm), left, and right alignments (mm), were measured over a period of four years.*

Type	Year	Mean	Var	Corr. matrix				Min	Max	Skewness	Kurtosis
				2017	2018	2019	2020				
Gauge	2017	-1.13	1.58	1.00	0.46	0.52	0.58	-6.70	4.86	-0.04	0.87
	2018	-0.76	1.60	0.46	1.00	0.51	0.51	-6.06	5.02	0.05	0.59
	2019	-0.73	1.68	0.52	0.51	1.00	0.63	-6.03	5.18	0.05	0.65
	2020	-0.96	1.81	0.58	0.51	0.63	1.00	-6.79	4.91	0.01	0.76
Left	2017	-0.45	1.61	1.00	0.02	-0.05	-0.02	-5.92	4.74	-0.05	0.59
	2018	0.43	1.72	0.02	1.00	-0.16	0.07	-5.05	5.57	-0.03	0.58
	2019	-0.50	1.96	-0.05	-0.16	1.00	-0.12	-6.42	5.21	-0.07	0.69
	2020	-0.42	1.88	-0.02	0.07	-0.12	1.00	-6.95	7.51	-0.04	1.41
Right	2017	-0.30	1.32	1.00	-0.00	0.02	0.04	-7.63	4.48	-0.08	0.90
	2018	0.57	1.45	-0.00	1.00	-0.19	0.03	-6.86	5.57	-0.09	0.77
	2019	-0.32	1.66	0.02	-0.19	1.00	-0.14	-7.72	6.01	-0.09	0.85
	2020	-0.33	1.61	0.04	0.03	-0.14	1.00	-6.78	7.90	0.01	1.37

properties of the gauge look different from those of alignments. The correlation matrix shows that the dependence during the years does not change too much. The skewness of every variable is small it refers to the symmetry of the distributions. All kurtosis suggests the non-normality of the variables. **Fig. 4** illustrates in agreement with **Table 3** (non-zero positive kurtosis values) that the distributions of data exhibit a greater degree of peakedness than a normal distribution should. We note that all the above statistical statements should be tested, here we spare some room not to do so. The autocorrelation function (ACF) analysis revealed nonstationarity within the data, see **Fig. 5**.

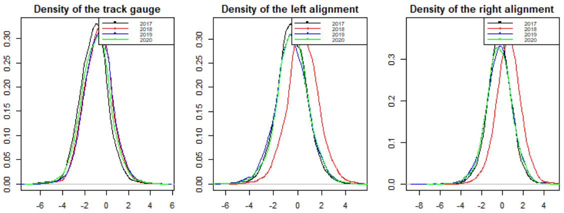

Figure 4. *The distribution of the Hungarian railway track geometry measurements over the different years.*

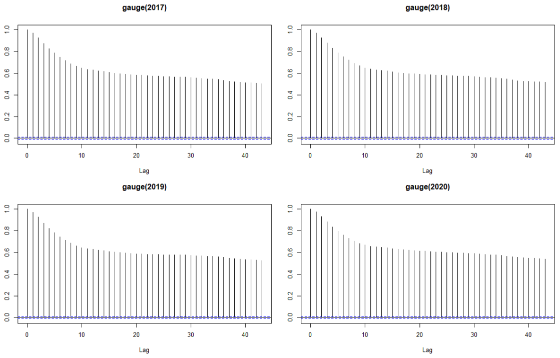

Figure 5. *ACF plots for the gauge measurements.*

As it has been shown trimming necessarily follows from the smoothness of the rail track but it should not affect the mean, say. The EMD method provides the trend (nonlinear) which can be used for smoothing the data. Another simpler method is the moving average of consecutive values. **Fig. 6** implies that although the trend is smoother nevertheless the moving averages of three consecutive values (MA3) do the job as well. Therefore from now on we shall use MA3 smoothed data for our analysis.

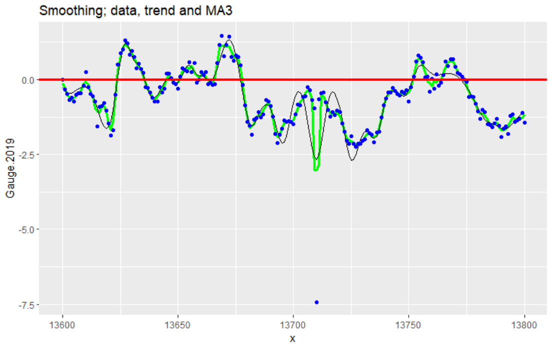

Figure 6. *Data Gauge 2019, in mm: data (blue dots), EMD trend (black), and smoothed data by MA3 (green), by observation numbers.*

We note an additional property of the measurements arising from the railway track which is the reversibility i.e. the signal is invariant under reversing the starting and ending point of the process. It also reserves some methodologies for the future.

2. TQI for quality assessment

This study aims to evaluate the effectiveness of the TQI techniques when applied to the data from the Hungarian railway system by considering various segment-length strategies. Now we are given the array of railway track quality assessment methodologies introduced in Section II. To this end, two distinct segment lengths, 100 and 200 meters, are employed by the guidelines provided by the Federal Railroad Administration for calculating TQI_F. Moreover, both the discrete segmentation approach (i.e., split the entire length of the railroad track into equal L_0 distances) and the continuous moving segmentation approach (i.e., use a moving window of size L_0, recursively selecting segments of length L_0 from the whole railway track) were utilized to select the segment measurements.

The adoption of these two lengths ensures the availability of at least one zero-crossing segment for comparative analysis. The resulting calculations are presented in **Tables 4, 5** and **6**, which provide the top five maximum TQI_Fs values using discrete segmentation ($L_0 = 400$ and 800) and discrete-moving segmentation approaches, respectively. From now on L_0 denotes the number of measurements included in segments.

Table 4 presents an array of distinct railway track segments, accompanied by their respective TQI_F values spanning 2017, 2018, 2019, and 2020. The table evaluates three critical railway track geometry parameters: Gauge, Left alignment, and Right alignment. Within the table, the "Segment" column specifies the particular section of the railway track under scrutiny, with the numbers in parentheses designating the commencement observation points for these segments.

It is essential to note that lower TQI_F values indicate improved track conditions, whereas elevated values may suggest potential issues or track degradation, as established by [6]. Examining the results, a discernible trend emerged, wherein the track gauge consistently exhibited the highest TQI_F values, particularly in 2019, followed by 2017 and 2020. In contrast, the TQI_Fs for the left and right alignments consistently registered lower values when compared to the gauge. Consequently, it is apparent that the gauge parameter exhibits heightened sensitivity to railway degradation, necessitating periodic decision-making in the context of track maintenance and management. A graphical summary of the calculated TQI_Fs employing the distinct segmentation approach is shown in **Fig. 7**. One can read from **Fig. 7** the yearly change in the quality of TQI_F .

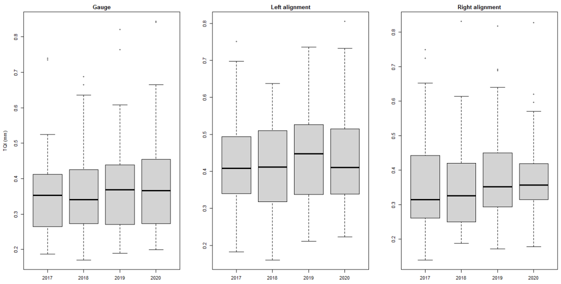

Figure 7. *Summary plot of TQI_F values per segment of the track geometry parameters. ($L_0 = 400$)*

Using a formal tone, the authors report that their findings in **Table 6** support the conclusions drawn from their earlier analysis using the distinct segmentation approach. The track gauge consistently exhibited the highest TQI values, with notable prominence in 2019. To further elucidate the factors contributing to the elevated TQI_Fs observed in 2019, the authors conducted a deeper investigation and found that certain measurements deviated significantly from the expected pattern. For example, measurement number 13710 registered a value of -7.43, **Fig. 3**. Given the continuous nature of the observations, outliers in TQI_F values can potentially introduce misleading interpretations without smoothing the data. Segment no. 17 with $L_0 = 800$ (200m) and measurements $X_{13601:14400}$ includes 32 zero-crossing segments and one of them has a larger length than 25 m with TQI_F value 0.0632. At the same time, the TQI_F value of this segment is 1.5305 and the TQI_F value for the same segment of the trend is 0.1693, **Fig. 6**.

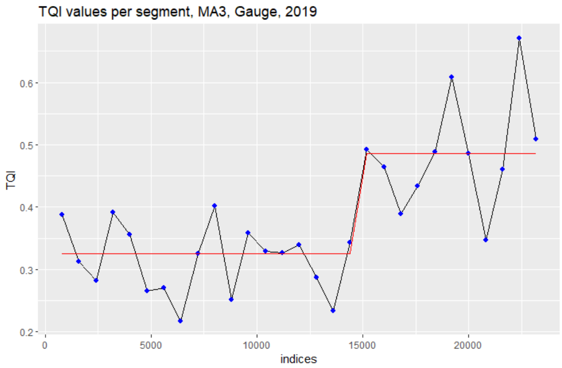

Figure 8. *TQI_F Variations for the Track Gauge with change point detection (red), MA3, by 200 m in the Year 2019, indices refer to the measurement numbers.*

IV. DISCUSSION

The aforementioned section highlights the significance of theoretical segment length on the computed TQI, resulting from diverse TQI methodologies. The following subsections will discuss the findings in detail.

1. Federal Railroad Administration, TQI_F

To evaluate the efficacy of the FRA TQI under various segmentation approaches, **Tables 4** through **7**, along with **Fig. 7**, provide insights into its

Table 4. *Maximum TQIs for the associated segments for the railway geometrical parameters with length 100 m, $L_0 = 400$.*

		2017		2018		2019		2020	
		Segment	TQI_F	Segment	TQI_F	Segment	TQI_F	Segment	TQI_F
Gauge	1	47 (18401)	0.74	55 (21601)	0.69	55 (21601)	0.82	55 (21601)	0.84
	2	55 (21601)	0.73	46 (18001)	0.66	47 (18401)	0.76	47 (18401)	0.84
	3	46 (18001)	0.52	57 (22401)	0.64	49 (19201)	0.61	57 (22401)	0.66
	4	38 (14801)	0.52	47 (18401)	0.54	57 (22401)	0.59	49 (19201)	0.60
	5	49 (19201)	0.52	44 (17201)	0.53	54 (21201)	0.56	56 (22001)	0.60
Left	1	39 (15201)	0.75	11 (4001)	0.64	39 (15201)	0.74	39 (15201)	0.80
	2	19 (7201)	0.70	19 (7201)	0.64	20 (7601)	0.68	31 (12001)	0.73
	3	20 (7601)	0.70	38 (14801)	0.63	31 (12001)	0.67	20 (7601)	0.72
	4	11 (4001)	0.64	44 (17201)	0.62	44 (17201)	0.65	19 (7201)	0.67
	5	56 (22001)	0.63	7 (2401)	0.58	19 (7201)	0.63	37 (14401)	0.65
Right	1	56 (22001)	0.75	39 (15201)	0.83	39 (15201)	0.82	39 (15201)	0.83
	2	39 (15201)	0.72	55 (21601)	0.61	47 (18401)	0.69	30 (11601)	0.62
	3	54 (21201)	0.65	52 (20401)	0.61	54 (21201)	0.69	47 (18401)	0.60
	4	47 (18401)	0.65	56 (22001)	0.58	56 (22001)	0.64	54 (21201)	0.57
	5	52 (20401)	0.62	54 (21201)	0.57	52 (20401)	0.63	31 (12001)	0.54

**The term "Segment" refers to the section of the railroad track with length L_0 that contains the measurements in the order beginning with the measurement in the bracket.*

Table 5. *Maximum TQIs for the associated segments for the railway geometrical parameters with length 200 m, $L_0 = 800$.*

		2017		2018		2019		2020	
		Segment	TQI_F	Segment	TQI_F	Segment	TQI_F	Segment	TQI_F
Gauge	1	28 (21601)	0.61	28 (21601)	0.60	28 (21601)	0.67	28 (21601)	0.72
	2	24 (18401)	0.55	29 (22401)	0.58	24 (18401)	0.61	24 (18401)	0.65
	3	23 (17601)	0.51	23 (17601)	0.54	29 (22401)	0.51	29 (22401)	0.54
	4	19 (14401)	0.47	24 (18401)	0.50	19 (14401)	0.49	23 (17601)	0.51
	5	20 (15201)	0.46	19 (14401)	0.47	23 (17601)	0.49	19 (14401)	0.51
Left	1	10 (7201)	0.70	10 (7201)	0.61	10 (7201)	0.65	10 (7201)	0.70
	2	20 (15201)	0.62	19 (14401)	0.58	20 (15201)	0.63	20 (15201)	0.66
	3	6 (4001)	0.61	5 (3201)	0.56	6 (4001)	0.59	19 (14401)	0.61
	4	19 (14401)	0.57	28 (21601)	0.53	5 (3201)	0.58	6 (4001)	0.59
	5	28 (21601)	0.54	6 (4001)	0.53	19 (14401)	0.57	16 (12001)	0.54
Right	1	28 (21601)	0.64	28 (21601)	0.60	28 (21601)	0.64	20 (15201)	0.66
	2	20 (15201)	0.61	20 (15201)	0.54	20 (15201)	0.62	28 (21601)	0.48
	3	27 (20801)	0.57	27 (20801)	0.53	24 (18401)	0.59	24 (18401)	0.47
	4	24 (18401)	0.55	24 (18401)	0.51	27 (20801)	0.58	15 (11201)	0.47
	5	26 (20001)	0.48	23 (17601)	0.49	26 (20001)	0.50	27 (20801)	0.46

**The term "Segment" refers to the section of the railroad track with length L_0 that contains the measurements in the order beginning with the measurement in the bracket.*

performance. These findings underscore the effectiveness and reliability of the approach across diverse segmentation scenarios.

Tables 4, 5 and **6** provide valuable insights into the vulnerability of the Federal Railroad Administration approach when applied in conjunction with the distinct and moving segmentation methods. These findings underscore its susceptibility to influence by outliers, consequently yielding potentially misleading Track Quality Index (TQI) values. A notable illustration of this susceptibility was observed in the context of track gauge measurements in 2019, where the presence of a few outliers had a considerable impact. This is evident when comparing the moving TQI_F values for the gauge measurements in 2019 with their trimmed counterparts (the trimmed counterpart is derived from the original measurements after applying the moving average, MA3, method).

Furthermore, **Table 6** highlights the maximum TQI_F values obtained using the moving segmentation approach under the different lengths ($L_0 = 400$ and 800). Notably, these segments exhibit a con-

Table 6. *Maximum moving TQIs for the associated segments for the railway geometrical parameters with lengths 100 m and 200 m.*

		$L_0 = 400$		$L_0 = 800$	
	Year	segment*	max	segment	max
Gauge	2017	18281	0.79	22797	0.65
	2018	23170	0.86	22692	0.67
	2019	21497	0.86	21501	0.71
	2020	18252	0.88	21521	0.75
Left	2017	7380	0.83	7182	0.71
	2018	7264	0.80	7022	0.68
	2019	7346	0.86	7120	0.71
	2020	7363	0.90	7158	0.74
Right	2017	15302	0.87	15030	0.69
	2018	15182	0.85	14910	0.68
	2019	15243	0.91	14979	0.74
	2020	15250	0.96	15007	0.77

**Segment represents the part of the railway track that contains the sequence of measurements starting with the given observation of length L_0.*

Table 7. *TQI_F values under Zero-crossings segmentation with number of measurements exceeding the lengths of 25 m and 50 m.*

		$L_0 = 100$			$L_0 = 200$		
Parameter	Year	Segment	Start at	TQI_F	Segment	Start at	TQI
Gauge	2017	87	7622	0.59	313	15318	0.46
	2018	578	17593	0.79	3	411	0.36
	2019	504	16415	0.71	642	18082	0.39
	2020	373	14468	0.52	413	15287	0.51
Left	2017	324	5583	0.11			
	2018	1205	22253	0.36			
	2019	421	7939	0.30			
	2020	1185	22167	0.47			
Right	2017	1306	22187	0.23			
	2018	1073	22254	0.28			
	2019	1213	22128	0.28			
	2020	734	14425	0.26			

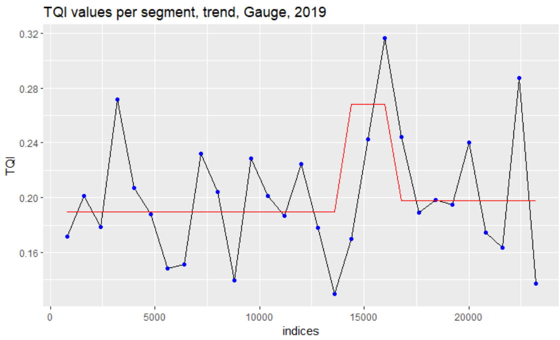

Figure 9. *TQI_F Variations for the Trend of Track Gauge with change point detection (red) by 200 m in the Year 2019, indices refer to the measurement numbers.*

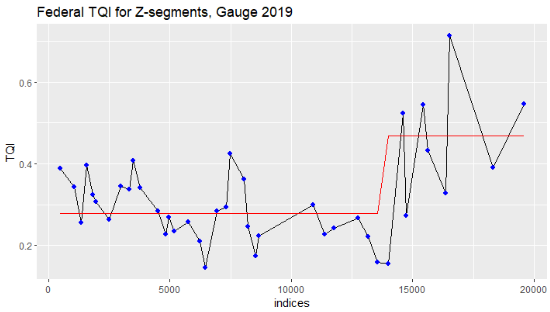

Figure 10. *TQI_F Variations for Z-segments with lengths greater than 25 m of Track Gauge (mm) in the Year 2019, and change point detection (red), indices refer to the measurement numbers.*

secutive pattern, with the difference between them typically amounting to a single measurement. Consequently, it is apparent that the distinct segmentation approach represents a special case within the framework of the moving segmentation approach, wherein the maximum TQI_F value achieved under the distinct segmentation approach does not surpass the TQI_F values obtained through the moving segmentation approach.

Table 8. *Minimum Netherlands Q indices with lengths 100 m and 200 m.*

		$L_0 = 400$						$L_0 = 800$					
		Gauge		Left		Right		Gauge		Left		Right	
Year		Segm.	TQI_N	Segm.	TQI_N	Segm.	TQI_N	Segm.	TQI_N	Segm.	TQI_N	Segm.	TQI_N
	1	28 (10801)	5.45	56 (22001)	5.75	56 (22001)	5.11	20 (15201)	6.06	28 (21601)	6.28	28 (21601)	5.65
	2	50 (19601)	5.86	37 (14401)	5.89	54 (21201)	6.11	14 (10401)	6.30	19 (14401)	6.31	27 (20801)	6.21
2017	3	32 (12401)	5.93	39 (15201)	6.31	39 (15201)	6.30	10 (7201)	6.37	16 (12001)	6.32	20 (15201)	6.47
	4	20 (7601)	5.94	32 (12401)	6.39	52 (20401)	6.31	19 (14401)	6.47	20 (15201)	6.53	26 (20001)	6.54
	5	40 (15601)	6.06	31 (12001)	6.45	53 (20801)	6.40	25 (19201)	6.66	6 (4001)	6.70	24 (18401)	6.54
	1	27 (10401)	5.95	56 (22001)	5.69	56 (22001)	5.29	20 (15201)	5.52	28 (21601)	6.09	28 (21601)	5.66
	2	49 (19201)	5.95	34 (13201)	6.17	34 (13201)	6.12	10 (7201)	6.18	14 (10401)	6.29	27 (20801)	6.42
2018	3	32 (12401)	6.14	36 (14001)	6.28	55 (21601)	6.22	14 (10401)	6.29	16 (12001)	6.48	26 (20001)	6.58
	4	20 (7601)	6.20	27 (10401)	6.32	53 (20801)	6.33	16 (12001)	6.40	18 (13601)	6.60	14 (10401)	6.64
	5	9 (3201)	6.24	49 (19201)	6.42	52 (20401)	6.42	19 (14401)	6.44	17 (12801)	6.61	17 (12801)	6.68
	1	27 (10401)	5.88	56 (22001)	5.61	56 (22001)	5.26	20 (15201)	5.89	28 (21601)	6.12	28 (21601)	5.73
	2	49 (19201)	6.03	34 (13201)	5.85	34 (13201)	5.87	14 (10401)	6.27	14 (10401)	6.19	27 (20801)	6.36
2019	3	32 (12401)	6.08	27 (10401)	6.04	54 (21201)	6.18	10 (7201)	6.42	16 (12001)	6.43	14 (10401)	6.47
	4	20 (7601)	6.18	37 (14401)	6.14	27 (10401)	6.36	19 (14401)	6.53	17 (12801)	6.45	17 (12801)	6.49
	5	28 (10801)	6.28	31 (12001)	6.34	55 (21601)	6.54	16 (12001)	6.60	19 (14401)	6.65	26 (20001)	6.54
	1	32 (12401)	6.00	34 (13201)	5.17	34 (13201)	5.05	20 (15201)	5.88	17 (12801)	5.98	17 (12801)	5.94
	2	27 (10401)	6.08	27 (10401)	5.84	56 (22001)	6.03	14 (10401)	6.38	14 (10401)	6.15	14 (10401)	6.33
2020	3	20 (7601)	6.17	37 (14401)	6.22	27 (10401)	6.08	10 (7201)	6.51	16 (12001)	6.35	28 (21601)	6.58
	4	28 (10801)	6.23	31 (12001)	6.26	25 (9601)	6.23	19 (14401)	6.68	10 (7201)	6.58	10 (7201)	6.59
	5	46 (18001)	6.27	20 (7601)	6.27	20 (7601)	6.38	23 (17601)	6.68	18 (13601)	6.66	16 (12001)	6.67

**The term "Segm." refers to the section of the railroad track with length L_0 that contains the measurements in the order beginning with the measurement in the bracket.*

Table 9. *Netherlands Q indices under Zero-crossings segmentation*

		with length more than 25 m			with length more than 50 m		
Parameter		Segment	start at	TQI_N	Segment	start at	TQI_N
Gauge	2017	183	10762	5.30	183	10762	5.51
	2018	712	19429	5.63	145	7653	5.61
	2019	728	19495	5.76	159	7727	6.04
	2020	25	3336	5.83	25	3336	6.09
Left	2017	324	5583	6.75			
	2018	1205	22253	6.41			
	2019	421	7939	6.50			
	2020	1185	22167	6.09			
Right	2017	1306	22187	6.75			
	2018	1073	22254	5.30			
	2019	1213	22128	6.39			
	2020	1165	22177	6.53			

In contrast, the Zero-crossings segmentation approach exploits the intrinsic structure of railway track measurements by modeling them as a signal process. Acknowledging its theoretical advantages, the amalgamation of the FRA approach within a Zero-crossings segmentation framework highlights augmented resilience, as presented in **Table 7**. Additionally, it is evident that the sensitivity of the FRA approach, when applied across the three segmentation methodologies, is significantly influenced by the choice of length (L_0) and the number of measurements utilized in the distinct, moving, and Zero-crossings segmentation approaches, respectively. Formula (1) shows that FRA TQI for a segment can be separated by the zero-crossings segmentation inside the formula (1), hence the TQI_F calculated by the zero-crossings provides finer results for further actions. One can compare the TQI_F values considering the plots: **Fig. 8** and **Fig. 9** and **Fig. 10** . We have identified the segments in the x-axis by the indices of their ending points. Notice that Z-segments show up not equidistantly, the reason is that not all segments are considered and the segment lengths are different. We have analyzed the quality of the segments using change points in the mean detection as well. In this way, not only

Table 10. *Maximum Chinese* TQI_C *with lengths* $L_0 = 400$ *and* 800.

		$L_0 = 400$		$L_0 = 800$	
Year		Segment	TQI_C	Segment	TQI_C
2017	1	47(18401)	1.95	28(21601)	1.80
	2	39(15201)	1.94	20(15201)	1.69
	3	56(22001)	1.87	24(18401)	1.61
	4	55(21601)	1.72	27(20801)	1.44
	5	54(21201)	1.56	10(7201)	1.43
2018	6	55(21601)	1.85	28(21601)	1.73
	7	39(15201)	1.83	24(18401)	1.50
	8	46(18001)	1.63	22(16801)	1.45
	9	56(22001)	1.62	19(14401)	1.44
	10	7(2401)	1.59	20(15201)	1.43
2019	11	47(18401)	2.08	28(21601)	1.87
	12	39(15201)	2.00	24(18401)	1.76
	13	55(21601)	1.97	20(15201)	1.72
	14	56(22001)	1.76	27(20801)	1.56
	15	54(21201)	1.76	22(16801)	1.45
2020	16	39(15201)	2.11	20(15201)	1.82
	17	47(18401)	1.98	28(21601)	1.65
	18	55(21601)	1.79	24(18401)	1.58
	19	31(12001)	1.57	19(14401)	1.53
	20	49(19201)	1.54	10(7201)	1.50

**The term "Segment" refers to the section of the railroad track with length L_0 that contains the measurements in the order beginning with the measurement in the bracket. .*

the places of the maximum values but the significant changes in the mean can be recognized. All three methods provide the same results, in particular, **Fig. 8** and **10** are very similar.

2. Netherlands Q index

Nevertheless, it is important to note that the Netherlands Q index was originally formulated for assessing the quality of 200-meter segments within maintenance sections spanning distances of 5 km to 10 km. To evaluate the quality of Hungarian railway track geometry, lengths of 100 m and 200 m were adopted for the application of the Netherlands Q index.

The numerical findings presented in **Table 8** indicate a notably high level of quality within the Hungarian railway system, with an average score of 80% relative to the maximum achievable quality. Furthermore, these results highlight the resilience of the Netherlands Q indices across multiple years as the methodology effectively mitigated the influence of outliers. Interestingly, the minimum TQI_N values were obtained from disparate and distinct segments; however, the method exhibited relatively low variation among these segments. Additionally, the outcomes underscore the minimal impact of theoretical length on Netherlands Q indices.

Conversely, the approach exhibited a marginally increased track gauge quality level when utilizing a Zero-crossings segmentation approach with a theoretical length of 200 m as the benchmark for segment consideration. Nevertheless, the methodology demonstrated consistent quality levels over the years and exhibited greater resilience to the influence of outliers. Additionally, it should be noted that the quality of the left and right alignments was comparatively same as the results obtained through the distinct/moving segmentation approach, as shown in **Table 9**.

3. Chinese TQI

The primary objective of the Chinese Track Quality Index (TQI_C) approach within the context of high-speed railways is to evaluate the overall quality of track segments. **Table 10** presents the computed TQI_C values for the Hungarian railway. We used three instead of seven quality parameters because only the gauge and left and right alignments were available in our datasets. Notably, the method exhibited increased variability between segments as the theoretical length decreased. Conversely, greater theoretical lengths resulted in reduced TQI variability among the segments. Furthermore, the adoption of higher theoretical lengths yielded more stable TQI values throughout this study.

Although both the FRA and Netherlands Q index approaches yielded exceptional TQI values when applied within the Zero-crossings segmentation framework, it is essential to note that the adoption of the Zero-crossings segmentation approach is not feasible for the Chinese TQI_C. This limitation arises from the fact that, for the same sequence of measurements, distinct Zero-crossings segments are obtained for various railway geometric parameters, rendering it impractical for uniform application.

V. CONCLUSION

The current TQI methodologies are predominantly designed to assess the quality of track geometry in the context of standard-gauge railways, encompassing both high-speed and broadband rail networks. These methodologies hinge on track geometry data collected under loaded track conditions by employing a versatile multifunctional TRV. The track geometry parameters extracted from the TRV measurements on the Hungarian railway align with the criteria stipulated in the EN 13,848 series.

The evaluation of track geometry quality entails the computation of the TQI within a predetermined segment characterized by specified dimensions. In the context of assessing the Hungarian railway system, a range of metrics, including the FRA's TQI, Netherlands' Q index, and Chinese TQI, have been utilized. Diverse segmentation techniques encompassing Distinct, Moving, and Zero-crossings approaches have been investigated.

The primary objective of this study was to address these questions by conducting a comprehensive track quality assessment of the Hungarian railway system employing three fundamentally distinct TQI measures. Based on the acquired results and ensuing discussion, the following conclusions can be drawn.

- Track segmentation plays a pivotal role in the assessment of railway track quality by facilitating the analysis of deviations and irregularities in track geometry. In addition, it has significant implications for strategic planning related to maintenance and reconstruction efforts on railway tracks.
- The FRA's TQI may occasionally yield misleading quality assessments when applied to heterogeneous railway measurements.
- The utilization of the Zero-crossings segmentation approach demonstrates enhanced stability and robustness compared to distinct or moving length segmentation methods. It is evident that a thorough analysis of the factors contributing to the heterogeneity of railway track geometry degradation cannot be adequately accomplished through an examination of fixed-length track segments.
- Increasing the length of the analytical segment enhances the precision of the analysis concerning railway track geometry quality.
- The Netherlands Q index and Chinese TQI exhibit greater resilience to outliers and consistently provide more stable results over the four years.

In conclusion, based on the theoretical advantages of the Zero-crossings segmentation method and the empirical results obtained from the Hungarian railway track, it is recommended that professionals give due consideration to implementing the Zero-crossings approach over more conventional methods.

VI. LIMITATIONS OF THE STUDY

This study undertook some evaluations of three TQI methods for measuring track quality, despite the existence of over ten other techniques within the broader domain of track quality evaluation. The selection of these specific methods was intentional and based on the observation that many of the reviewed techniques required access to a more sophisticated track-geometry dataset, which can be challenging to obtain due to its complex nature. This often requires specialized track geometry measurement vehicles or dedicated equipment for data collection.

NOMENCLATURE

ρ	The autocorrelation, unitless.
L_0	The number of measurements by segments.
TQI_C	Chinese Track Quality Index, mm.
TQI_F	Federal Railroad Administration Track Quality Index, unitless.
TQI_N	Netherlands Track Quality Index, unitless.
ACF	The autocorrelation function.
CWR	Continuously welded rail.
E	Expected value of a random variable, in unite of a random variable.
EMD	Empirical Mode Decomposition.

IMF	Intrinsic Mode Functions.
MA3	Moving averages of three consecutive values.
TQI	Track Quality Index, unitless.
Var	Variance of a random variable, in square unit of a random variable.

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AUTHOR CONTRIBUTIONS

A. Dawod: Writing the manuscript, Writing the code, Theoretical analysis.

G. Terdik: Conceptualization, writing the code, Review and editing. Supervision.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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