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Influence of the Analytical Segment Length on the Tram Track Quality Assessment

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Abstract: In the track quality analysis, numerical values representing the relative condition of track geometry called track quality indices (TQIs) are calculated along a specific track segment. Segments are defined as linear track geometry datasets with the homogeneous characteristics of factors affecting geometry degradation. The 200m-long analytical segment is used most often on intercity conventional and high-speed rail networks. However, in the case of the small urban rail networks, the homogeneity of track-geometry degradation influential factors is very low. This segment length is usually too long for efficient track maintenance or reconstruction with minimal disruption of the urban traffic. This paper explores the effect of reducing the analytical segment length in the condition assessment of the tram network in the City of Osijek, Croatia. The research had two main objectives: (1) to assess the narrow-gauge tram-track geometry quality through the application of the established synthesized TQIs, and (2) to analyze how a change in the analytical segment length affects this assessment. Two synthesized track quality indices—one based on a weighted value and the other on a standard deviation of measured track geometry parameters—were calculated for the 27.5 km of tracks on consecutive 200-, 100-, 50-, and 25 m long analytical segments. The comparative analysis of the TQIs' calculation results showed that the reduction in the segment length increased the resolution of the track quality analysis in both cases, while the index based on a weighted value of geometry deviations proved less sensitive to this reduction. These results contribute to further segmentation process establishment and TQIs implementation on tram infrastructure.

Keywords: tram-track geometry; track quality indices; segment length

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1. Introduction

A prerequisite for safe and reliable rail system operation is an adequate assessment of rail-track quality based on the detected track geometry deviations or irregularities. Longitudinal level, horizontal alignment, gauge, cross-level, and twist are the five track geometry parameters used to effectively describe the track condition [1]. Track quality is defined by calculating the track quality index (TQI) on both high-speed and conventional standard gauge rail-track systems. This numerical value represents the relative condition of the abovementioned track geometries [2] over a track segment of a specific length.

Segments on which the TQIs are calculated are defined as linear track geometry datasets with homogeneous characteristics of track-geometry degradation influential factors [3]. These factors can be classified into three groups: influential factors of designed alignment; influential factors of track structure; and influential factors of rail traffic [4]. The degradation of the track geometry is primarily due to the action of dynamic vehicle loads caused by irregularities on the contact surface of the wheels and rails or in the horizontal track alignment. Higher track-exploitation intensity and the speed of rail vehicles result in a higher degradation rate [5,6]. In terms of structure, using rails with a higher steel hardness and its elastic fastening can slow down the degradation process [7,8]. The design of the horizontal track alignment also has a significant effect, especially the track curvature—the degradation of the track geometry on horizontal curves is faster than on the straight parts of the route [9–11]. In addition, one must not ignore the elements that could influence the overall track geometry condition on a segment, such as switches, stops, bridges, or level crossings.

According to [3], the first studies of the conventional track geometry degradation analyses began during the 1980s and 1990s, when the track data availability, especially in a digital format suitable for thorough analysis, was very modest. Historically, the data were collected with track-recording cars, which produced statistically processed data (e.g., standard deviations) for fixed 100 m, 200 m, or 1 km long segments. This "fixed segment" was too rigid to demonstrate the actual degradation of the geometry along the track. Consequently, more sophisticated segmentation processes were developed. Today, track-recording cars can collect and store high-resolution track data, ensuring that identified individual segments behave as uniformly as possible throughout the track exploitation process.

There are different procedures for TQI calculation adopted in railway systems around the world. Most of them use longitudinal level and horizontal alignment at least to represent the condition of the track [12]. TQIs calculated on segmented rail networks can be sorted into two main categories: (1) objective or single TQIs, which are expressed separately for each geometry parameter; and (2) artificial or synthetic TQIs, which combine and merge different track geometry parameters into a single index [13,14]. The main difference between them is the base on which the TQI is calculated: as a standard deviation, an average value, or a weighted value over a track segment [15]. Once calculated, TQIs are compared to maximum permitted values, most often depending on the rail line speed, and then the decision on track maintenance is made.

In addition to different calculation approaches, different TQIs are expressed for different track segment lengths, usually 3–25, 25–70, and 70–200m long [16]. The 200m long segment is used most often, but in some cases, a particular track or entire network is evaluated based on only one TQI value [14]. Recent studies of tram track quality used different techniques for determining the track segment: based on the type of track construction [17] or based on the horizontal elements of track alignment (straight, curve, and curve with transition curve segments) [18]. Both approaches resulted in segments of variable length along the network. Newer studies have suggested that the decision on track segment length needs to be based not only on the track technical parameters but also on the economic and operational aspects of track maintenance [19].

Many cities worldwide that have retained the traditional tram systems dating back to before the First World War are trying to upgrade their maintenance procedures by introducing TQIs. However, they are facing several problems. The main one is documenting the tram infrastructure in digital databases, which is the prerequisite for any effective track segmentation, geometry evaluation, and maintenance planning. In addition, the actual knowledge of the track condition is limited to a small number of maintenance employees, and most of them do not have any tools for collecting, systemizing, and integrating the data covering the design, construction, operation, and further maintenance of the tracks. Such data could be stored in databases which would provide data for conducting the assessment of the track quality and maintenance needs [20,21]. Operators of most European urban rail systems carry out the track geometry quality assessment based on controlling the individual measured values of track geometry parameters concerning the permissible values prescribed by internal regulations [22]. Such is the case with tram operators in the Republic of Croatia, ZET in the City of Zagreb, and GPP in the City of Osijek. Both operators control the quality of the tram track by using the same internal regulations, where only the most significant permissible deviations of track geometry parameters immediately after track construction and before reconstruction are defined [23].

Applying the best practices of the track quality evaluation established for classic ballasted rail on tram networks would be most desirable. However, the procedures described in the literature [13–15,24] cannot be applied to tram tracks. The main reason for this is the questionable cost-effectiveness of procuring sophisticated track-recording cars for small tram networks consisting of only a few tens of kilometers of tracks. If the measurements are executed with manual tools, such as measuring rods or by manually operated track geometry trolleys, i.e., in unloaded track conditions, the maximum permitted values of the TQIs cannot be utilized. The other reasons are significant differences in track design requirements and exploitation conditions (the track location, geometry design parameters, construction elements, vehicles, and traffic characteristics) between the tram and conventional ballasted rail tracks [22], defined as the critical geometry degradation influential factors [5,6]. These differences are primarily the consequence of small distances between the tram tracks and the surrounding facilities and requirements for the rational use of urban traffic areas. These requirements often include narrow-gauge tracks, tight horizontal curves of only 18(20) meters' radius, and a lack of transition curves and cant.

For this reason, the tram vehicles are of smaller dimensions and weight (the tram axle load is usually twice as small) and with different undercarriages than conventional trains. The latter is particularly pronounced in the case of modern low-floor trams. The differences are also reflected in the tram traffic-flow characteristics given the movement priority and speed. Tram speed is low and very variable along the route due to the small stop distance. Such distances usually vary from 250 to 500 (800) meters, and include crossings where tram vehicles do not have priority to pass. Additionally, due to a lack of space in the densely built-up urban centers, trams often must share the lanes with road vehicles and therefore adjust (primarily reduce) their speed [25].

For the same reason, the tram tracks' superstructure is often built on continuously reinforced concrete slabs, with continuously welded grooved rails enclosed in pavement construction [26]. The tram networks are usually upgraded over long periods, so the homogeneity of the geometry degradation influential parameters along the tram tracks is very low. In addition, they are deeply rooted in the urban fabric, which complicates track geometry measurement, maintenance, and reconstruction, especially in large tram–road intersection zones. This concludes that due to the differences in the track geometry data collection process, track design, and operational requirements of conventional and tram tracks and vehicles, the track quality analysis of narrow-gauge tram networks should be performed on shorter analytical segments [14], by using a holistic TQI calculation approach with adjusted limit values.

The research presented in this paper had two main objectives: (1) to assess the narrow-gauge tram-track geometry quality through the application of established synthesized TQI by using geometry measurements collected in unloaded track conditions; and (2) to analyze how a change in the analytical segment length affects the track geometry assessment. The research was conducted using tram network data (alignment, structure, and exploitation conditions) and five geometry parameter values measured by a trolley, manually operated along the 27.5 km of tram tracks in the City of Osijek. To avoid possible misconceptions, two different synthesized TQIs established for conventional rail systems—one based on a weighted value and the other based on standard deviation—were calculated on consecutive 200-, 100-, 50- and 25m long analytical tram-track segments. The conducted comparative analysis of the TQIs calculation results demonstrated and quantified the effectiveness of the analyzed segmentation concepts in the tram-track quality assessment and provided further insights for establishing TQIs implementation at a broader scale by the owners of tram infrastructure.

2. Materials and Methods

A list of abbreviations, acronyms, and symbols used in the manuscript is given in Appendix A, to make a unified description for the convenience of readers.

2.1. Osijek Tram Network

The tram network in the City of Osijek consists of 30 km of narrow-gauge tram tracks 1000 mm wide (including tracks inside the depot). The length of the operational part of the tram track is 27.5 km. A GIS database containing the tram-track geometry data, type of track construction, and exploitation period, i.e., cumulative track exploitation intensity in millions of gross tonnes (MGT), for each meter along the tram tracks was created for the investigation based on the data provided from the track manager GPP Osijek. Figures 1 and 2 show graphic excerpts from the database.

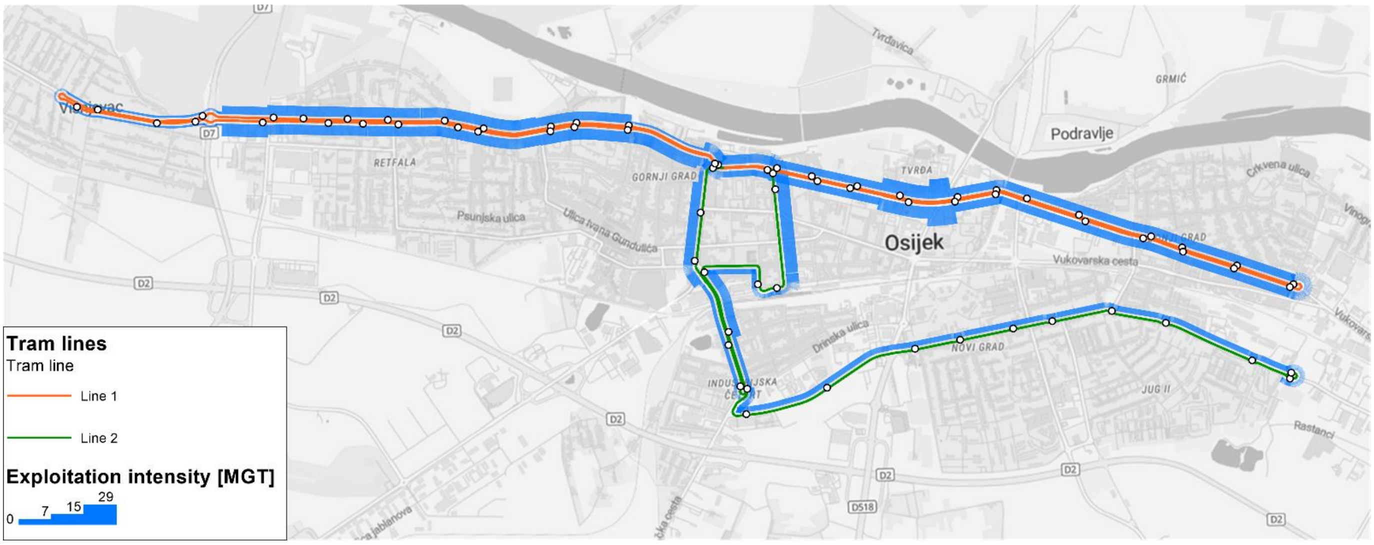

Figure 1. The City of Osijek tram lines 1 and 2 and cumulative track exploitation intensity.

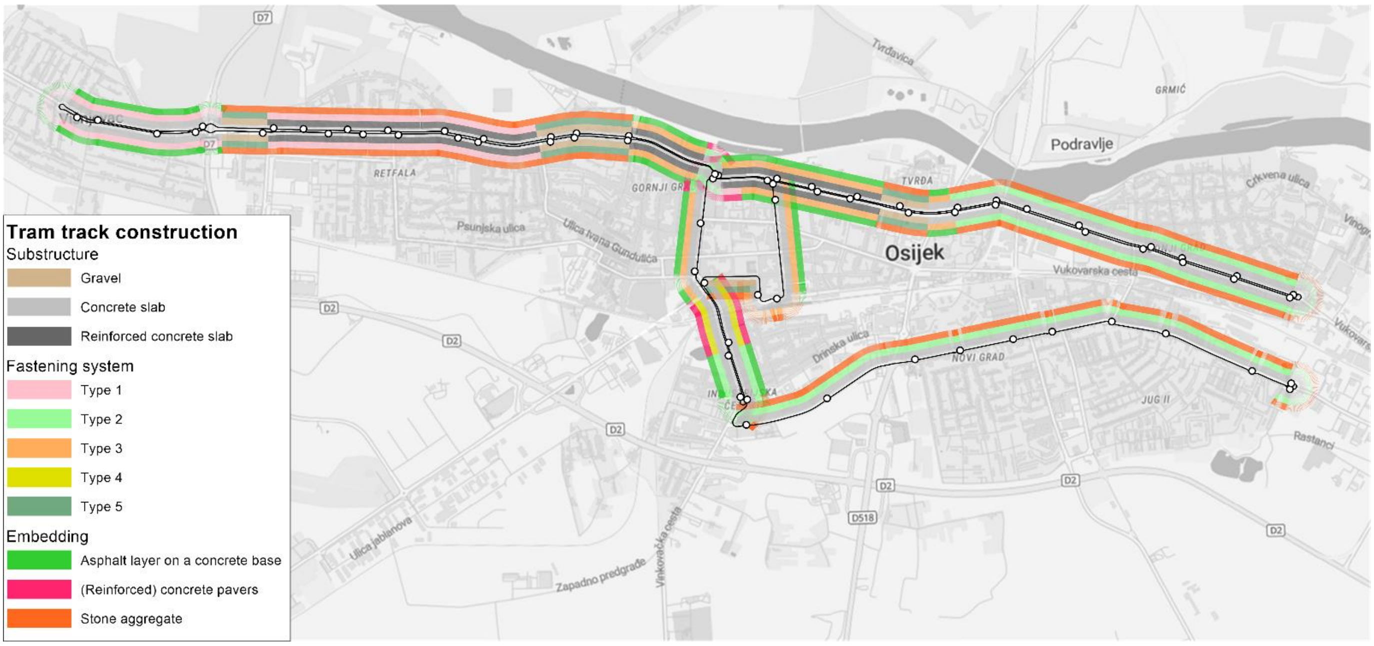

Figure 2. The City of Osijek tram-track construction elements.

The tram transport is organized into two tram lines, Line 1, which connects the eastern and western settlements with the city center, marked orange in Figure 1, and circular Line 2, which connects the southern settlements with the city center, marked green. Passengers are exchanged at 72 stops, on average 400 m apart. The fleet consists of 26 vehicles, operating with an average speed of up to 15 km/h. An average annual exploitation intensity calculated based on the timetables and tram characteristics amounts to 1,0 million gross tons per year (MGT/year) for tram Line 1 and 0,5 MGT/year for tram Line 2. Almost

80% of the tram track has been (re)constructed in the last 15 years, while parts of the track are older than 35 years.

The tram-track structure, shown in Figure 2, consists of the substructure (supporting base), and the superstructure comprises continuously welded rails, switches, and crossings, a rail fastening system, and a paving system embedding the rails (Figure 2). On 87% of tracks, the substructure is a continuous (reinforced) concrete slab. The rest of the tracks are constructed as "floating", laid on a substructure of crushed stone. For rail fastenings, five different systems are used: discrete double-elastic (types 1 and 2); discrete single-elastic (type 3); and continuously embedded rail by elastomeric pads (type 4); or by stone aggregate (type 5). On 65% of the network, tram tracks are constructed as part of the road surface, closed with reinforced concrete or concrete pavers, stone cubes, or an asphalt layer on a concrete base. Along the separate tram tracks, the rails are enclosed with stone aggregate.

2.2. Track Geometry Data Collection

Before track geometry data acquisition, the tram tracks in the City of Osijek were divided into sections. This was performed in two steps. In the first step, the direction of tram traffic was considered. Then, an additional division was made due to the lines' specific track layout and organization. As a result, the network was divided into three sections: Lines L1 and L2A are part of the double-track tram network, while L2B is part of the single-track tram network with passing loops at tram stops.

Track geometry irregularities were measured in November 2016 by manually operated trolley TET-1000 (Figure 3) that meets the requirements of the European Standard EN 13848-4, addressing manual and lightweight devices for track geometry measurements [27]. This is a device for the manual continuous measurement of track geometry whose structure consists of transverse and longitudinal beams, supported by three rollers, and the control unit with memory (data logger). Measurement elements include a distance counter, an inductive linear displacement sensor for measuring track gauge as well as vertical and horizontal track irregularities, and an electronic clinometer (inclination needle) for measuring the cant. Track twist is calculated during measurements as the algebraic difference between two consecutive cant values 10 m apart (5 m in front and behind the measurement cross section) [28].

Figure 3. TET-1000 trolley.

The measurements were recorded with a 1.0 m resolution, as a function of track chainage. During measurements, each of the track measuring profiles was assigned with the value (signal) of the five track geometry parameters and track chainage. For the measured data processing and analysis, after data transfer from the TET-1000 logger to the personal computer, conversion to Excel format was performed by specialized Track Gauge software. The data were georeferenced along track sections and structured into the created

GIS database. The distribution of the geometry data collected along 27,520 measurement points is shown in Figure 4. An example of a graphical representation of the track gauge values along the tracks expressed as relative values to the regular track width, i.e., gauge deviations, is shown in Figure 5.

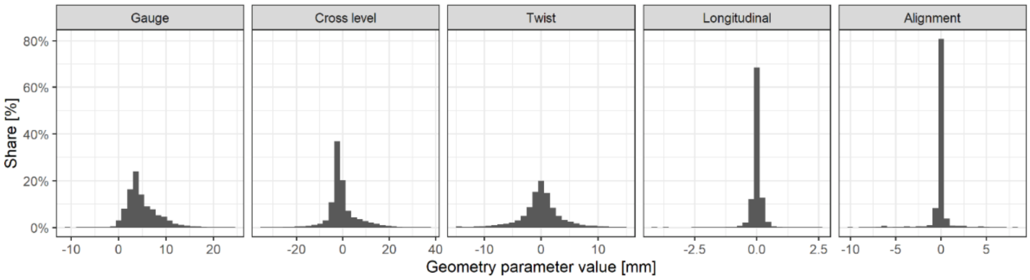

Figure 4. Measured track geometry irregularities histograms.

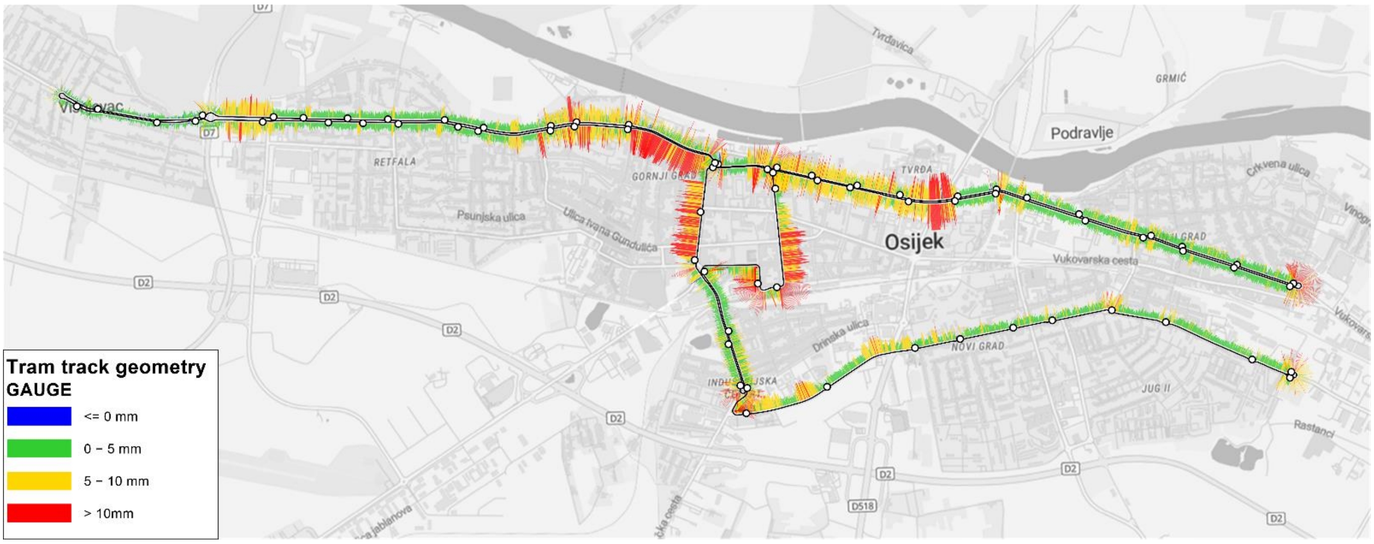

Figure 5. Tram track gauge parameter values.

2.3. Selection of the Track-Quality Index

During its 135-year history, the assessment of the tram-track geometry quality in Osijek was based on the control of individually measured values of track geometry concerning the permissible values prescribed by internal regulations of the Zagreb Municipal Transit System [23]. Recently, in parallel with the introduction of information technologies, especially regarding Big Data storage, a state-of-the-art TQI assessment was developed. For this, an overview of established TQIs was performed. As presented in [13–15], different railway infrastructure managers developed their TQI calculations, mainly for standard-gauge ballasted tracks, and established threshold values or allowable limits related to the calculation in question. Figure 6 graphically presents the distribution of TQIs for the method of calculation.

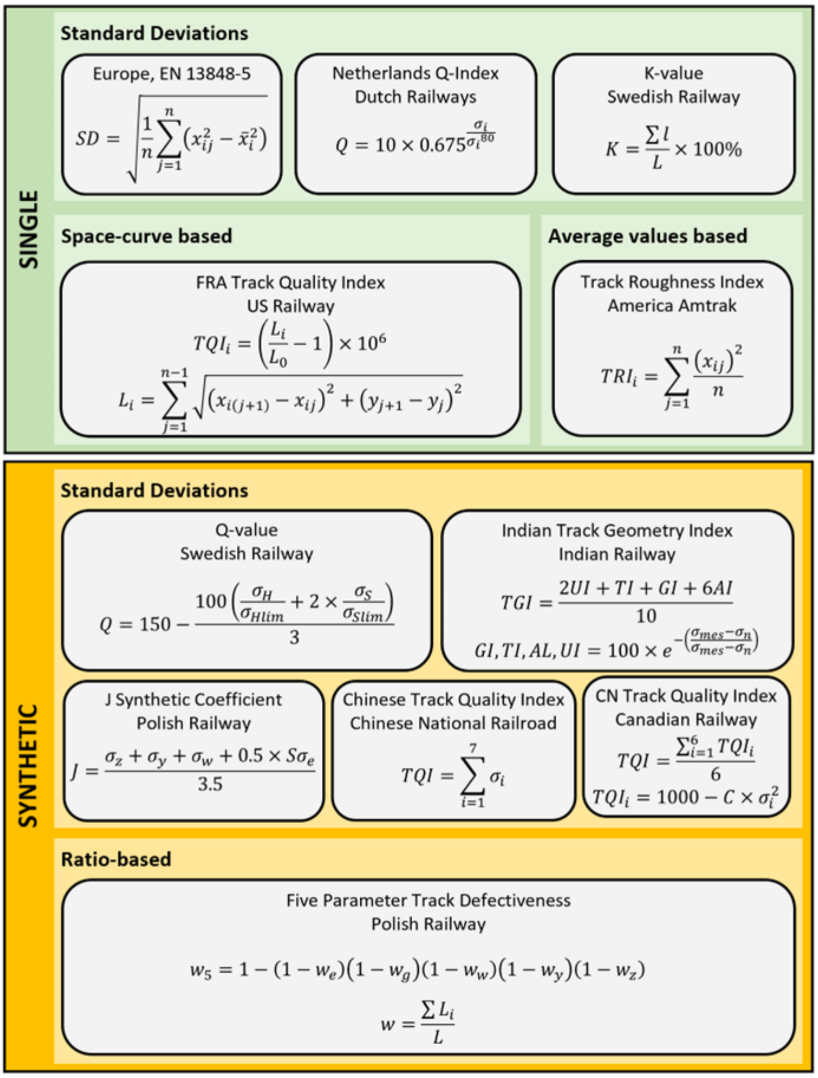

Figure 6. Overview of existing TQIs.

As can be seen from Figure 6, the TQIs can be divided primarily by the way of perceiving the track geometry, either as a single-parameter or synthetic one. They also differ according to the formulation of their indicators. Although most procedures associate TQI with standard deviation, specific methods have a different approach and use averaged square measured values per analytical segment; the length of the spatial curve of the measured value; or the ratio of geometric values that exceeded acceptable limits. In addition, there are constant proposals of new TQIs for track quality assessment, such as overall TQI [29], the adaptations of the existing TQIs to urban railway systems such as metro or subway [15], TQI based on track passenger ride comfort [30], tram-track degradation data [31], and Bayesian-based TQI [13].

This research selected the appropriate method for assessing track geometry quality for the Osijek tram network based on the following six criteria. The TQI calculation procedure had to be comprehensive (synthetic) and applicable to low-speed tram tracks. It had to allow the application of local tolerances, the weighting of parameters, and the analytical segment length changes. Most importantly, the method should not require knowledge of the track geometry quality immediately after track construction. Therefore, considering all of the mentioned criteria, it was decided to analyze the applicability of two synthesized TQIs, namely W and J, both developed for the Polish Railway [32].

The synthetic track quality index W is based on the analysis of the total effect of all five measured values of geometry parameters along each segment of the track: track gauge (G); cant (C); twist (T); horizontal (H); and vertical (V) irregularities. Following the European Standard EN 13848-1 addressing characterization of track geometry [33], the geometry parameter cant refers to cross-level, horizontal irregularities refer to horizontal alignment, and vertical irregularities refer to longitudinal level. The W index is a dimensionless calculated value, characteristic for each analytical track segment, determined by the following expression:

$$W = 1 - (1 - W_G)(1 - W_C)(1 - W_T)(1 - W_H)(1 - W_V). \quad (1)$$

The equation treats the deviations of an individual parameter as an independent event where W_G represents the track gauge quality indicator, W_C the rail height ratio quality indicator, W_T the track curvature quality indicator, W_H the horizontal irregularity quality indicator, and W_V the vertical irregularity quality indicator. The following expression defines these individual indicators along a particular analytical segment:

$$W_i = \frac{N_p}{N}, \quad (2)$$

where W_i represents the quality indicator of the observed track geometry parameter along the analytical segment; N represents the total number of measured values of the observed track geometry parameter; and N_p represents the number of measured values of the observed track geometry parameter exceeding a certain tolerance. The track geometry quality is expressed concerning the values of the synthesized track geometry quality index W along the analytical segment, as follows:

- $0.0 \leq W < 0.1$ indicates new or reconstructed track;
- $0.1 \leq W < 0.2$ indicates good quality of track geometry;
- $0.2 \leq W < 0.6$ indicates the satisfactory quality of track geometry;
- $0.6 \leq W \leq 1.0$ indicates poor quality of track geometry.

The synthetic track quality index J provides a quantitative evaluation of the track. The index is based on the standard deviation of four track geometric parameters: longitudinal level (Z), horizontal alignment (Y), twist (W), and gauge (e). The following expression determines it:

$$J = \frac{S_Z + S_Y + S_W + 0.5 S_e}{3.5}, \quad (3)$$

where S_z represents the standard deviation of longitudinal level; S_y represents the standard deviation of horizontal alignment; S_w represents the standard deviation of track twist; and S_e represents the standard deviation of track gauge. The following equation calculates the standard deviation for each measured parameter:

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

where n represents the number of signals registered on the analyzed track section; x_i represents the parameter value at point i; and $\overline{x}$ represents the average signal value. Table 1 presents the specified allowable deviation of the J index given in [32], determining the track condition for the state defined by the track operating as appropriate on one side and the track requiring maintenance on the other.

Table 1. Allowable deviations of the J index depending on speed.

Speed (km/h)	30	40	50	…	90	…	120	…	160	…	200
J index (mm)	12.0	11.0	10.0	…	6.2	…	4.0	…	2.3	…	1.4

2.4. Defining the Geometry Parameters Limit Values

The W index represents the number of exceedances of the allowed tolerances of track geometry parameters on a track segment. If available, these tolerances should be taken from the applicable regulations; otherwise, it is necessary to apply the limits defined by the European Standard EN 13848-5 [34]. As the internal regulations [23] defined only the permissible deviations of track gauge and cross-level immediately after track construction and the gauge values that define the need for track immanent reconstruction, the decision was made to consult the European Standard EN 13848-5, and Deliverable 2.4 of the Urban Rail Transport project [22]. This EU-funded research project aimed to develop, test, and validate innovative solutions for public-transport urban railway tracks such as tram and metro. The project goals also included the development of innovative and harmonized preventive and predictive track maintenance methods based on EN 13848-5. The project resulted in the draft of a standard that attempts to find typical safety limits for European urban transit networks following the development of high-speed and conventional standard-gauge railways and broad-gauge railways.

EN 13848-5 defines three primary limit levels where: (1) Alert Limit (AL) refers to the values which, if exceeded, require that the track geometry condition is analyzed and considered in the regularly planned maintenance operations; (2) Intervention Limit (IL) denotes the value whose exceedance calls for the corrective maintenance so that the immediate action limit shall not be reached before the next inspection; and (3) Immediate Action Limit (IAL) denotes the value whose exceedance calls for action to reduce the risk of derailment to some acceptable level. Limits are prescribed as a speed function for the nominal track gauges 1435 mm, 1524 mm, and 1668 mm [34]. Furthermore, the limit values are given for a loaded track as defined in EN 13848-1 [33]. Table 2 presents the prescribed AL, IL, and IAL for line speeds up to 80 kph.

Table 2. Alert Limits (AL), Intervention Limits (IL), and Immediate Action Limits (IAL) for line speeds of up to 80 kph according to EN 13848-5 [34].

Parameter/Defectiveness	AL	IL	IAL
Gauge (mm)	−7.0/+25.0	−9.0/+30.0	−11.0/+35.0
Cross level (mm)	−20.0/+ 20.0	−20.0/+ 20.0	−20.0/+ 20.0
Twist (mm/m)	−4.0/+4.0	−5.0/+ 5.0	−7.0/+7.0
Horizontal alignment (mm)	−12.0/+12.0	−15.0/+15.0	−22.0/+22.0
Longitudinal level (mm)	−12.0/+12.0	−17.0/+17.0	−28.0/+28.0

Limit values for geometry parameters measured in loaded track conditions given in Deliverable 2.4 of the Urban Rail Transport project [22] are presented in Table 3. They are defined for three primary limit levels where AL refers to ride-comfort issues, IL refers to maintenance cost-effectiveness issues, and IAL refers to safety issues.

Table 3. Alert Limits (AL), Intervention Limits (IL), and Immediate Action Limits (IAL) according to the Urban Track project [22].

Parameter/Defectiveness	AL	IL	IAL
Gauge (mm)	−3.0/+22.0	−5.0/+30.0	−5.0/+30.0
Cross level (mm)	−13.0/+ 13.0	−14.0/+ 14.0	−16.0/+ 16.0
Twist (mm/m)	to be defined following stiffness and constructional characteristics of the running gear		
Horizontal alignment (mm)	−14.0/+14.0	−16.0/+16.0	−22.0/+22.0
Longitudinal level (mm)	−18.0/+18.0	−20.0/+20.0	−29.0/+29.0

As measurements of the track geometry parameters in the City of Osijek were performed in unloaded track conditions, it was impossible to determine the synthesized W by directly applying the limits prescribed by the European Standard or Urban Track project.

According to the limit levels given in these documents, it was concluded that internal regulations for narrow-gauge tram tracks directly defined only Construction Limit (CL) and Immediate Action Limit (IAL) values for gauge and Construction Limit (CL) for cross-level [23]. Because of that, the limit values (CL and IAL) for other geometry parameters were defined indirectly by considering the prescribed design and exploitation restrictions given in both internal and national regulations on narrow-gauge tracks [23,35,36], as follows. Cross-level IAL was defined as a maximum permissible deflection on tram tracks in operation. Twist CL and IAL were defined by the prescribed slope of the cant transition, which for a maximum permissible cant of 80 mm and a minimum transition length of 8000 mm, may not exceed 1:100. Horizontal alignment CL and IAL were defined by an allowable deviation of the track in the direction of a chord length of 10 m. The longitudinal level CL and IAL values were defined by the allowable vertical irregularity at the location of rail welds. AL values for all five parameters were then established in coordination with the tram track manager considering the experience gained with track geometry quality analysis of tram networks with similar characteristics by combining CL and IAL values (Table 4).

Table 4. Allowable tram-track geometry parameters defectiveness tolerances and established Alert Limits (AL) used in W calculation.

Parameter/Defectiveness	**CL**	**AL**	**IAL**
Gauge (mm)	−2.0/+3.0	−2.0/+9.0	−2.0/+25.0
Cross level (mm)	−4.0/+4.0	−4.0/+4.0	−8.0/+8.0
Twist (mm/m)	−10.0/+10.0	−10.0/+10.0	−10.0/+10.0
Horizontal alignment (mm)	−2.0/+2.0	−3.0/+3.0	−3.0/+3.0
Longitudinal level (mm)	−0.2/+0.2	−0.2/+0.2	−1.0/+1.0

2.5. Defining the Analytical Segments

Following the most straightforward procedure of track segmentation, i.e., division of the linear infrastructure into segments with homogeneous characteristics of exploitation periods and the type of track construction, the tram tracks in Osijek could be divided into 34 segments with varying lengths from 136 to 4932 m. However, additional track-geometry degradation influential factors (regarding track alignment, tram speed, and track loads) were identified within such defined segments.

The tram track alignment was markedly inhomogeneous as it consisted of horizontal straight sections and curves of large and small curvatures (with or without transition curves), different vertical grades, and track sections with superelevation (track sections that are part of the road surface). In addition, parts of the tram track passed through road intersections and tram stops, on which the track was exposed to different loads due to road traffic and inconsistent tram speeds. All the listed phenomena that affected the degradation process required additional segmentation of the tracks. If these were considered standard in the segmentation process, the tram network would be divided into more segments of varying lengths.

To justify this more detailed approach to the tram track segmentation, but at the same time to secure the desired simplicity of the segmentation procedure, the tracks were divided into consecutive segments of equal lengths (200-, 100-, 50- and 25m-long), regardless of the position in respect to the road traffic or tram stops, track alignment or type of construction. On the thus-defined segments, the W and J synthesized indices were calculated for the same set of measured geometry data. The calculation of the synthetic W was performed by applying AL given in Table 4, and the J index values were calculated based on the weighted mean of standard deviation values of track geometry parameters on each track segment. Both indices were calculated on 140 200m long segments, 277 100m long segments, 552 50m long segments and 1103 25m long segments.

3. Results

The five-number descriptive statistics for the calculated values of W and J indices by lengths of the analytical segment are given in Table 5. The values of the W index on the analytical segments range between 0 and 1, where the value of the median, depending on the length of the analytical segment, is between 0.33 and 0.42. The values of the J index calculated on the same analytical segments range between 0.00 mm and 5.52 mm, where the value of the median, depending on the length of the analytical segment, is between 0.73 mm and 1.40 mm.

Table 5. Five-number summary for the calculated values of W and J indices.

Percentile	W (-)				J (mm)			
	200 m	100 m	50 m	25 m	200 m	100 m	50 m	25 m
Minimum	0.02	0.01	0.00	0.00	0.37	0.25	0.20	0.00
First Quarter	0.14	0.12	0.12	0.08	0.72	0.61	0.54	0.46
Median	0.42	0.37	0.35	0.33	1.40	1.04	0.91	0.73
Mean	0.46	0.45	0.44	0.44	1.66	1.45	1.24	1.02
Third Quarter	0.81	0.79	0.81	0.82	2.42	2.14	1.76	1.38
Maximum	1.00	1.00	1.00	1.00	4.87	4.96	5.52	4.83

The distributions of the calculated W and J indices according to the track sections and analytical segment lengths are presented in Figure 7. Each row presents the distribution of the synthesized index on L1, L2A, and L2B track sections calculated on consecutive segments, from top to bottom: 200-, 100-, 50-, and 25m long segments.

Figure 7. Distribution of the synthesized tram-track quality index W and J.

One can see in Figure 7 that there is a certain regularity in the distribution of both TQI calculated values, i.e., that the calculated TQI values for the analytical segments are proportional. Furthermore, reducing the analytical segment length in the case of the W index leads to a redistribution of the W index on shorter analytical segments while retaining the value level in relative terms. In the case of the J index, reducing the analytical segment length reduces the value of the J index on shorter analytical segments.

The distribution of the W and J indices calculated for different analytical segment lengths is presented in Figure 8. Their values are displayed as stacked bar lines. The bar line closest to the center line presents track geometry quality calculated for the 200m long analytical segment. Calculated W index values are categorized using different colors, where the green color indicates good quality ($W < 0.2$), the yellow color indicates satisfactory quality ($W < 0.6$), and the red color indicates insufficient quality ($W \geq 0.6$) of the track geometry in operation. The distribution of the J index values is presented in a similar way, where the J index values are classified according to colors with a step of 2 mm.

Figure 8. Track quality W and J index distribution along the tracks.

Table 6 presents the share of W and J index limit values calculated for different segment lengths regarding the length of the entire network. Reducing the analytical segment length increases slightly the share of tracks with a good track quality $W < 0.2$ while the share of tracks with unsatisfactory track quality $W > 0.6$ decreases. On the other hand, reducing the analytical segment length significantly increases the share of segments with $J < 2$ mm and reduces the share of tracks with $J > 4$ mm.

Table 6. Shares of W and J indices values calculated for different analytical segment lengths.

TQI	Quality/Value	Analytical Segment Length			
		200 m	**100 m**	**50 m**	**25 m**
W	Good	35.2%	38.1%	39.3%	41.1%
	Sufficient	25.4%	21.4%	22.1%	21.0%
	Insufficient	39.4%	40.5%	38.7%	37.9%
J	<2 mm	43.2%	49.4%	53.7%	61.9%
	2–4 mm	21.9%	19.3%	26.0%	25.2%
	>4 mm	34.9%	31.3%	20.2%	12.9%

4. Discussion

The distribution of calculated values of the W and J indices along the Osijek tram network confirmed that the tram-track geometry quality depends on exploitation intensity and is significantly influenced by the type of rail fastening, curvature of the alignment, and position of the tracks in the urban network. Most of the analytical track segments not constructed with the discrete double-elastic rail fastenings showed insufficient track geometry quality. Furthermore, on sections with the same tram-track construction type and exploitation intensity, the tram-track geometry quality was poorer on the analytical segments in the curves of small radii than the ones located in the straight line. Finally, the analytical segments along intersections or stops showed faster track-quality degradation than those not affected by road traffic.

By comparing distributions of W and J values over track sections for the same analytical segment length, similarities in the behavior of both indices were observed (Figure 9).

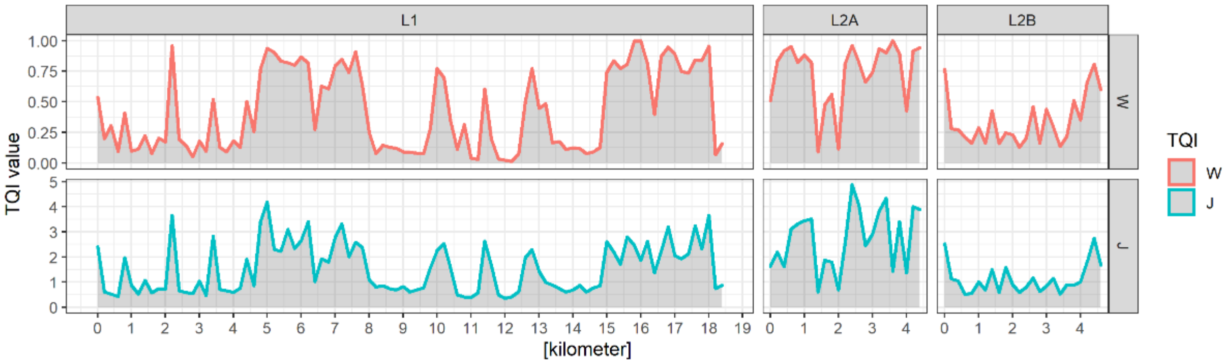

Figure 9. Distribution of the W and J indices for 200 m-long analytical segments.

The relations between the W and J index values calculated for the same analytical segment are presented in Figure 10. The decrease in the analytical segment length causes the grouping of segments with extreme values of the W (0.0 and 1.0), while at the same time, the J value uniformly decreases.

By analyzing the change in the track geometry quality depending on the analytical segment length, it was noticed that the change in the segment length has a different effect on the value of the calculated W index than on the value of the calculated J index (Figures 7 and 8). Track geometry quality defined by the W index changes as the length of the analytical segment decreases. For example, individual shorter analytical sub-segments, which belong to the same 200m analytical segment, progressed to poorer track quality (larger W value). In contrast, the remaining sub-segments progressed to better track geometry quality (smaller W value) than the corresponding 200m analytical segment. However, by reducing the analytical segment length relative to the 200m length of the segment, the value of the J index on individual shorter sub-segments was less than or equal to the value of the J index of the corresponding 200m analytical segment. To obtain more information on what happens to the W and the J indices values with the change in the analytical segment length, the average, maximum, and minimum values of the calculated indices, depending on the length of the analytical segment, were compared to the value of the corresponding calculated index values for the 200m-long analytical segment. The results are shown in Figure 11.

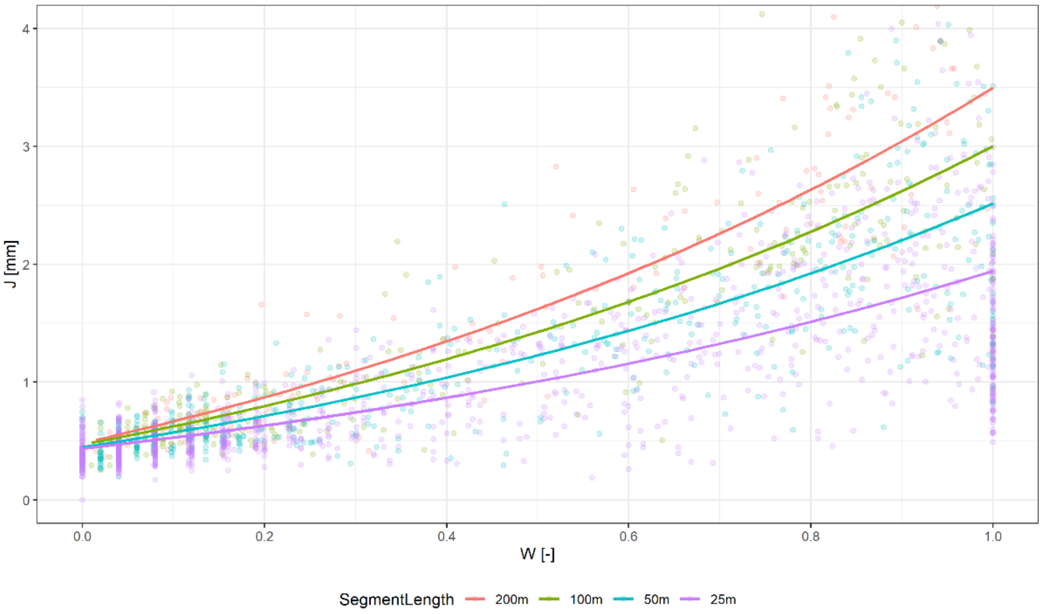

Figure 10. Relationship between the W and J indices values.

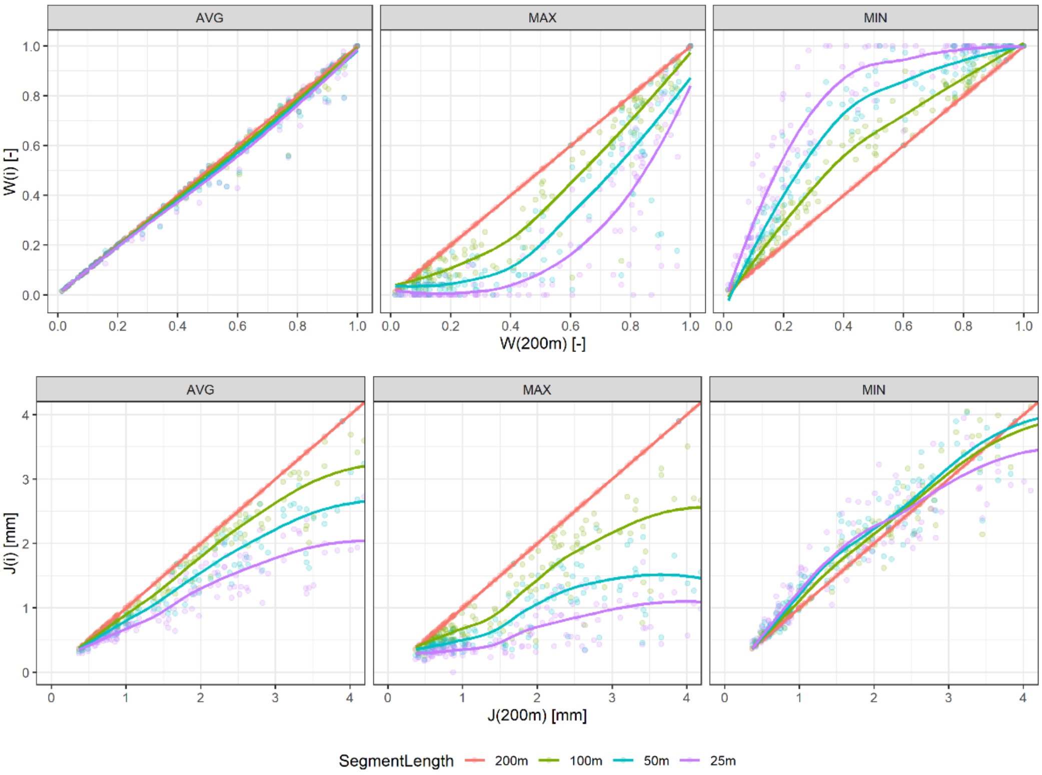

Figure 11. An influence of analytical segment length on the W and J index values.

Compared to the W value of the corresponding 200m long segment, the average value of the W index on shorter sub-segments remains unchanged. On the other hand, reducing the analytical segment length increases the maximum W value while the minimum W value decreases. In other words, a decrease in the length of the analytical segment along 200 m of tracks will increase the value of the W index on a few sub-segments, while on the remaining sub-segments, there will be a decrease in the value of the W. The average value of the W on the short sub-segments will be relatively equal to the W value on the corresponding 200m-long segment. The same analysis shows that decreasing the analytical segment length causes the average and minimum J index values to decrease while the maximum value of the J index stays the same relative to the value of J for the corresponding, more significant 200m segment.

Calculated J index values for all analyzed analytical segments did not exceed 5 mm. By comparing the calculated to the prescribed allowable J value of 12 mm for a speed of 30 km/h, it could be concluded that the tram tracks in the City of Osijek are in good condition. However, considering that the tram track was measured in unloaded conditions and that the tram tracks constructed on the concrete slab showed very small deviations of horizontal alignment and longitudinal level, the correctness of applying the synthetic J index (or its allowable values) in assessing the tram track geometry quality is questionable. Future research should explore the possibility of modifying the J index calculation, as well as re-defining the allowable values of horizontal alignment and longitudinal level for tram track geometry measured in unloaded track conditions.

5. Conclusions

The track geometry quality assessment can be performed in two ways, by comparing the individual measured values of the track geometry parameters concerning the allowable tolerances or by calculating the TQI along the track segment of a specific length. The established TQIs are mainly intended to assess the track geometry quality for high-speed and conventional standard-gauge railways and broad-gauge railways, where track geometry data are collected by track recording vehicles in loaded track conditions. They are commonly calculated as standard deviations or average or weighted values over a 200m long track segment. A comparison of the five narrow-gauge tram-track geometry parameters recorded on the Osijek tram network with a manually operated trolley in unloaded track conditions with the prescribed permissible tolerances defined for measured values collected in loaded track conditions showed that the measured values of individual tram-track geometry parameters are significantly lower. This is especially true for horizontal alignment and longitudinal levels, where the application of prescribed tolerances in track quality assessments could lead to the conclusion that the track quality is good or that these parameters do not affect the calculated value of TQI. Additionally, the heterogeneity of tram-track geometry degradation influential factors cannot be adequately considered by analyzing the fixed 200m long track segments. From the above, several questions arose: (1) how to assess the tram-track geometry quality by using measurements collected in unloaded track conditions; and (2) whether and how a change of the analytical segment length affects the track geometry assessment.

The goal of the investigation presented here was to answer these questions by performing the track quality assessment on the Osijek tram network using two essentially different TQIs, W and J indices. The calculation of the W index was based on the ratio of geometric values that exceeded permissible tolerances. Permissible tolerances (explicitly defined for this investigation as Alert Limits) were established in coordination with the tram track manager and considering the experience gained with track geometry quality analysis of tram networks with similar characteristics. The calculation of the J index was based on weighted standard deviations of track geometry parameters. Both TQIs were calculated for the entire 27.5 km of operational narrow-gauge tram track on consecutive 200-, 100-, 50-, and 25m-long analytical track segments. The following conclusions were made:

1. Track segmentation has a significant role in assessing the tram track quality based on track geometry deviations or irregularities and planning track maintenance or reconstruction;
2. By reducing the length of the analytical segment, the resolution of the tram-track geometry quality analysis grows, which means that it is possible to determine the

sections of the tracks with insufficient quality more precisely by increasing the number of the analytical segments;

3. Both TQIs can be effectively used for tram-track geometry quality assessment. However, the W index, based on a weighted value of geometry deviations over an analytical segment, is less sensitive to a reduction in the segment length than the J index based on the standard deviation of geometric parameters–the decrease in the analytical segment length enlarges the number of segments with extreme values of W. At the same time, the J value uniformly decreases;
4. The segmentation process must be aligned with the tram track maintenance and reconstruction procedures. It should consider the following aspects affecting the choice of analytical segment length: which track repair/reconstruction technology will be applied; the allocated funds; and how the planned work will impact public and personal traffic along with the track segments.

Once the segments are defined throughout the entire tram network, it will be possible to develop models of track quality degradation (based on the results of geometry monitoring), which is essential for establishing more efficient, predictive tram track maintenance.

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Appendix A

Table A1. List of abbreviations, acronyms, and symbols.

Abbreviation	**Explanation**
AL	Alert Limit
CL	Construction Limit
GIS	Geographic Information System
IAL	Immediate Action Limit
IL	Intervention Limit
MGT	Millions of Gross Tons
TQI	Track Quality Index
Acronym	**Explanation**
GPP	Gradski Prijevoz Putnika–Osijek Municipal Transit System
ZET	Zagrebački Električni Tramvaj–Zagreb Municipal Transit System
Symbol	**Definition**
C	Cant (W calculation)
e	Gauge (J calculation)
G	Gauge (W calculation)
H	Horizontal irregularities (W calculation)

Table A1. *Cont.*

J	Synthetic Track Quality Index based on a standard deviation of the geometry parameters
N	Total number of measured geometry parameter values (W calculation)
n	Number of measured geometry parameter values (J calculation)
Np	Number of measured geometry parameter values exceeding a certain tolerance (W calculation)
Se	Standard deviation of track gauge e (J calculation)
Sw	Standard deviation of track twist W (J calculation)
Sy	Standard deviation of horizontal alignment Y (J calculation)
Sz	Standard deviation of longitudinal level Z (J calculation)
T	Twist (W calculation)
V	Vertical irregularities (W calculation)
W	Synthetic Track Quality Index based on a weighted value of geometry parameters
W	Twist (J calculation)
Wi	Indicator of the observed track geometry parameter along the analytical segment (W calculation)
x	The average value of the track geometry parameter along segment (J calculation)
xi	Measured values of the track geometry parameter at point i (J calculation)
Y	Horizontal alignment (J calculation)
Z	Longitudinal level (J calculation)

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