The maintenance of the railway superstructure and its influence on the track geometry of regional line

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Abstract: The results of the railway track quality assessment, obtained as part of the diagnostics during its operational phase, are used by the construction manager to plan repair activities. The aim of the railway infrastructure manager is to maintain the longest possible good condition of the structure, most often represented by a stable track geometry quality. In the case of low economic efficiency of quality assurance of the structure through the improvement of diagnosed parameters, according to the monitored factors in the diagnostics results it is possible to decide on the operability of the structure or its individual structural elements. The interval between repairs of determining geometrical parameters or representative quality indicators, shortened to technically, technologically, and economically inefficient time, indicates the end of life of the component or structural unit and it is necessary to plan and perform its replacement. In many cases, the structure continues to operate at the final phase of its life, for example, due to financial constraints. The infrastructure manager continues to carry out regular diagnostics and then plans and carries out routine maintenance activities to ensure a safe and reliable track. The article deals with the issue of interval diagnostics and related effects of corrections of the track geometry quality of the selected section of the regional railway line with a continuously repaired railway superstructure. Attention is paid to determining the degradation rate of track geometry quality in relation to achieving the limit values of quality indicators and the efficiency of corrective maintenance.

Keywords: diagnostics; life cycle; quality index; railway track geometry interval diagnostics; correction of the track geometry quality

I. INTRODUCTION

Individual structural units, parts or elements of the railway track are described by sets of defined evaluated parameters, characteristic for structural groups of the railway track. In the operational phase of the service life of the structure, the following parameters characterizing the quality of the railway superstructure are verified as a matter of priority: track geometry and geometric and material properties of the components of the track skeleton and the ballast bed. (**Fig. 1**).

The railway track for railway vehicles consists of two parallel rails fastened at the prescribed distances to the rail supports. If the track is not in the designed geometric position, irregularities cause dynamic effects in the dynamic system track - vehicle, i.e. *vibrations both track and vehicle, which causes a decrease in running comfort and a gradual deterioration of the quality of the track structure.*
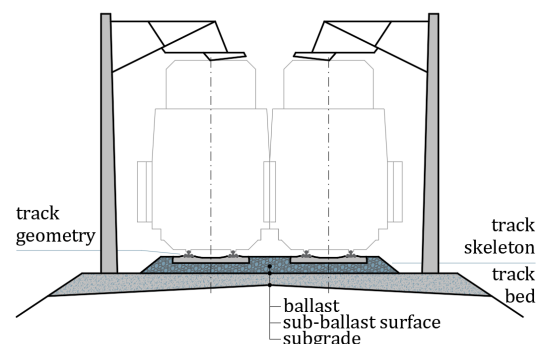

***Figure 1.** Structure of railway track*

1. Traffic and non-traffic loading of the track

In addition to the traffic load of static and dynamic forces, *the structure of the railway track is also*

stressed by the load related to railway operation and repair work and the load imposed by climatic influences.

The traffic load resulting from the interaction of the rolling stock and the track (wheels of the rolling stock and the rail) cause the highest stress of the rails, or switches in railway turnouts, the load-bearing capacity of which determines the load-bearing capacity of the entire structure of the railway superstructure or turnouts. The rail is directly (centrically or eccentrically) loaded by vertical wheel forces (Q, in the z-axis direction), horizontal (guiding) forces transverse to the rail axis (Y, in the y-axis direction) and wheel forces parallel to the rail axis (T, in the x-axis direction). The rail is also loaded by the normal force N caused mainly by changes in the rail temperature. (**Fig. 2**).
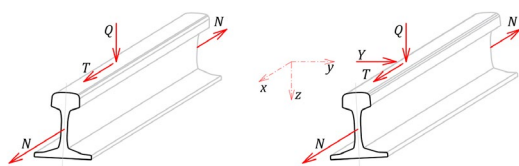

***Figure 2.** Forces loading the rails*

The vertical load, represented by the vertical wheel force Q, is composed of quasi-static components and a dynamic component. The loading of the outer (elevated) rail in the horizontal transverse direction by the total transverse wheel force Y is also composed of quasi-static components and a dynamic component [1]. The vertical wheel force causes the bending stress of the foot and the rail head, while the stress of the rail foot is not fundamentally affected by the eccentricity of the force Q and the magnitude of the force Y [2]. The combination of the loading of the rail with the forces Q and Y causes normal stresses in the rail. Residual stresses from production, rail handling, contact stresses on the rail head and stresses from the dynamic shocks of the rail vehicles also contribute to the rail stress. The position of the wheelset of a moving rail vehicle causes an uneven distribution of the load of variable values on the rails.

Loading the track structure with the wheels of rolling stock is an iterative process. Cyclic stress causes fatigue failure of loaded components. The total dynamic track stress can be determined as the product of the static force and the dynamic coefficient, depending on the line speed and track quality [3]. In addition to the wheel forces, the forces acting on the fastening and rail support elements arising from the movement of the rolling stock, in which a vertical 'wave' is generated in front of and behind the wheel in approximately two-meter sections, also contribute to the vertical loading of the track. In addition to temperature changes (especially in continuous welded rails), changes in normal

forces in the rails also cause changes in the shape of the rail grate, such as slipping of the track or creeping of rails as a result of deficiencies in fastening nodes and ballasting of the track. The acceleration and braking of the rolling stock cause horizontal longitudinal force T. The limit values for the load on the railway are set by [4].

2. The reaction of the structure to loading

The structure of the railway track withstands the stress of traffic and non-traffic loads *due to its material properties and the interaction of structural elements (resistances) against force actions*. The condition of the structure is influenced by the current structural and geometric arrangement of the track (track geometry), the system of the railway superstructure, the structure of the railway substructure, the type and intensity of railway traffic, the condition, maintenance [5] and speed of railway vehicles, or the quality of railway superstructure and substructure repairs. After exceeding the limit value of the relevant parameter, the railway track responds to the load by deteriorating quality and the occurrence of the defect. From the point of view of actually performed activities of finding and evaluating operational quality, defects and imperfection of the spatial position of the track, track geometry and material and geometric quality of structural elements of the track grate and track bed are registered in the structure of the railway superstructure.

Horizontal transverse forces affect the occurrence of track alignment faults. In the spatial position, these forces cause the track to move in the direction of their action, while the mutual distance of the track axes on multi-track lines and the distance from fixed barriers changes. In the geometry of the track, there is a change in curvature and sudden changes in the smoothness of the track represented by the deviation of the actual versine from the design versine value. *The vertical forces cause elastic or permanent deformations of the track level*, manifested by a lowering of the vertical track alignment of one or both levels of the rails. Deformations can form in continuous or short isolated sections. In the spatial position, the changes manifest themselves as a continuous (most often uneven) decrease, while the position of the cross-section and the mutual position of the track and the traction line change. In the geometry of the track, there are decreases of rail joints and low point of the track, changes in the superelevation – cannot of the track, or also twist of the track.

Dynamic loading of the track skeleton and *fitting defects, or maintenance* of the track skeleton *are the cause of changes in the track gauge*. The most frequent reason for the reduction of the track gauge is the rolling of the rail heads, deflection of the sleepers, and uneven slipping of the rails. Increasing

the track gauge causes wear and loosening of the fasteners, lateral wear of the rails, uneven pushing of the baseplates into the rail supports, deflection of the sleepers, incorrectly designed track cannot, poor quality of the track skeleton assembly and the condition of the railway vehicles wheels.

II. RELATED WORKS

The quality of a railway track is represented by all its prescribed technical and ecological characteristics during the entire lifetime: in the construction phase and the operation phase. In operation, the quality of the railway track is described by the state of the parameters of the track geometry, possibly also by the state of the geometry and material of structural elements or the whole structure. The behavior of the structure, which is assessed based on its quality, is represented by a value of the quality index for the assessed section. The determination of the quality index of the track section is affected by the structure of the data that enters the evaluation process. The structure and content of the data affect the accuracy of the prediction of the future development of the construction condition. The basic group of data is information about the geometry of the track, the geometry of the rail profiles, the mechanical characteristics of the substructure and the characteristics of the rolling stock and their response to the condition of the railway track. The quality of the track geometry is defined by the values of deviations from the reference geometric characteristics of the prescribed parameters in the alignment and level of the track, and thus it is determined from the diagnostics data of railway track spatial position (it is clearly defined in the plan by co-ordinates) and track geometry (geometrical position arrangement: track gauge, the relative level of rails: cant, cant gradient, the relative gradient of rails, level of the track and alignment and profile of line). The quality of the track geometry is significantly influenced by the condition of the rails with their material and geometric parameters. The rail head profile has a direct impact on the track geometry if unevenness and shape changes are formed in the running surface and top surface of the railhead. These rail defects are caused by traffic load and have the character of a deviation from the reference shape with various depths and lengths.

The quality of a railway track changes in the individual phases of its life cycle. The initial phase of the life cycle is represented by the parameters achieved by construction activities. In the operational phase of the railway, its condition is affected by the effects of traffic and non-traffic loads, which are manifested by permanent changes in the geometric parameters and material characteristics of the structure and structural elements.

Throughout the lifetime of the railway track, parameters representing the state of the structure are recorded, evaluated, and analysed (diagnostics). In relation to the standardized values of the prescribed parameters, the quality of the railway track repeatedly goes through phases of degradation and rehabilitation. Evaluation and analysis of data representing the degradation of railway track quality influence decisions on optimal intervals for determining the current state of the structure [6], estimates of residual life, determination of life cycle costs of the whole structure [7], [8], or its components [9], [10], [11] and to predict the appropriate time and format of quality rehabilitation. While defects occur in the initial phase of the life cycle (consequences of structural creep, insufficient load resistance, non-compliance with production or construction technology) with a decreasing risk, the risk of defects is approximately constant in the middle of the life. At the end of its service life, the risk of defects increases and is affected by the operational condition of the structure and its parts: age of the structure, wear due to load, and insufficient or incorrect rehabilitation activities [12]. When the interval between two quality rehabilitations is reduced to technically and economically inefficient time, the service life of the structure ends, and the structure must be replaced [13] (**Fig. 3**).
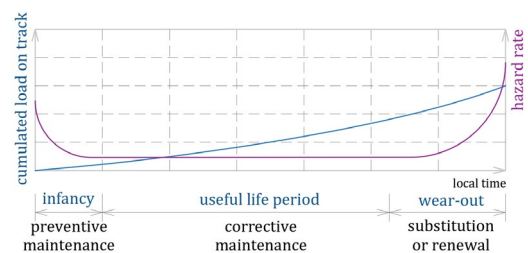

Figure 3. *Cumulated load and hazard rate during the life cycle of the railway track* [12], [13]

The life cycle of structures or maintenance and repair activities on a typical intensively operated main railway line loaded with average intensity operations are shown in **Table 1**. According to [14], the standard operating life cycle of the highest category railway line (line speed, load carried) is up to 8 years. The cleaning of the track bed is performed only in connection with other major repairs (in the track with wooden sleepers approximately every 20 years, with concrete sleepers approximately every 30 years). The service life of the rails (about 10 years) is usually half of the service life of the rail skeleton: the limiting factor is usually not the complete wear of the rail head, but the occurrence of material defects on the running surface. The replacement of the track bed is usually carried out in connection with a complete replacement of the track grate (at intervals of 20 to 30 years). The service life of turnouts is about 20 years when using wooden

sleepers and about 30 years when using concrete sleepers. In cases of extremely heavy load, it may be necessary to replace the frogs of the turnouts up to three times a year, but under average conditions, the normal life of the frog is five years.

Table 1. Typical service lives on a typical intensively operated main line [14]

Typical life cycles	Operational load	Years
tamping	40 – 70	4 – 5
grinding	20 – 30	1 – 3
ballast cleaning	150 – 300	12 – 15
rail renewal	300 – 1 000	10 – 15
timber sleeper renewal	250 – 600	20 – 30
concrete sleeper renewal	350 – 700	30 – 40
fastenings	100 – 500	10 – 30
ballast renewal	200 – 500	20 – 30
formation renewal	> 500	> 40

Railway tracks in the Slovak Republic are classified into 6 categories by the annual operating load: tracks with a load of more than 47,450 million tons per year are classified as category No. 1 and tracks with a load of fewer than 1,825 million tons per year are classified to the category No. 6 [15].

Given the limited resources of maintenance financing and the effort to reduce the time spent on diagnostics and track maintenance, it is necessary to use an efficient and effective system of maintenance linked to diagnostics [16], [17]. Targeting maintenance to meet safety limits and achieve cost-effectiveness directs maintenance strategies from corrective to preventive maintenance, which places extremely high demands on the quality of diagnostic outputs, especially in the field of evaluation, analysis, and prediction [18], [19], [20], [21].

The railway infrastructure manager can increase the cost and time efficiency of maintenance by using maintenance planning scenarios that are based on analyses of structural failure risk, i.e., occurrence of a critical error [22]. A suitable model of the degradation of the parameters of a structure or structural elements makes it possible to determine the limit value of the operating time or accumulated traffic load in the event of a structural failure. It is possible to use analytical tools of safety limits and optimal time of maintenance in the management and maintenance of railway structures. To prevent the risks of failure, modern concepts of reliability, availability, maintainability, and safety (*RAMS*) analysis are used for railway tracks. Analyses help to minimize the risks of failure to an acceptable level [23].

One of the ways to ensure the safety of the railway track and the comfort of running railway vehicles is to maintain the high quality of its geometry. The low quality of the track geometry can directly or indirectly result in safety problems, speed reduction, traffic reduction or interruption, higher maintenance costs and a higher degree of quality degradation of affected structures (rails, turnouts, crossings, etc.) and railway vehicles. If the correct track geometry maintenance strategy is not selected, the quality of the structure may deteriorate above a defined level (e. g. intervention limit – *IL*), leading to a higher frequency of track geometry repair (tamping) and consequently higher maintenance costs [24], [25].

In order to make an effective decision on how to repair the railway line, it is necessary to have representative data from the entire evaluated section. Signals of track geometry parameters are at the first level (diagnosed quality indicators) of diagnostics data. Their structure is shown, for example, in Chapter III, Part 1 of this article. The quality of the geometric parameters of the track affects the quality of each evaluated section, which is expressed by the diagnostics data at the second level (calculation, valuation): track quality index (*TQI*) [26]. TQI is a combination of diagnosed quality indicators, and several approaches can be used to calculate it, which were developed for different railway infrastructure administrations [27] and use numerical calculation methods. The authors have been dealing with the issue of verifying the quality of railway track geometry since 2012. The main goal of monitoring the parameters of track geometry is to verify the rate of degradation of its quality and to model future quality development. The experiments are focused on the transition areas between the track bed structure and the slab track on the main lines of the Railways of the Slovak Republic (*ŽSR*) [28], [29] and on monitoring the quality development of selected sections of railway lines of regional importance. In this article, the authors focus on the evaluated diagnostics of the track geometry, the structure of which is in relation to the technical quality and technological efficiency of maintenance and repairs in the final phase of the life cycle.

III. METHODS

Configuration of the tested section of railway line no. 162 in the *ŽSR* Lučenec – Utekáč network is shown in **Fig. 4**. For software evaluation, the beginning of the tested section is simply identified: km 0.000 000 = rkm 24.550 000.
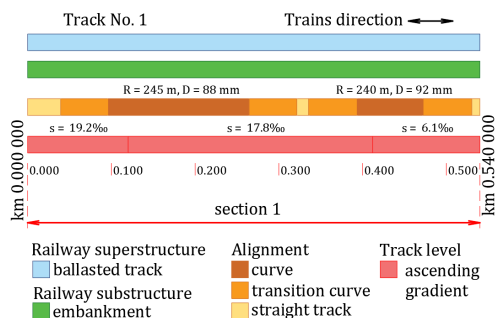
Figure 4. *Segmentation of the tested section*

The alignment of the section consists of two curves with transition curves and adjacent straight sections. The grade of track level of the whole section rises in the direction of the stationing. The values of the radii of the curves (*R*), their cants (*D*) and gradients of the track level (*s*) are in **Fig. 4**.

The tested section was put into operation in 1958. It is currently included in the *SR*1 speed range and trains run on it at a maximum speed (*V*) of 60 km.h^{-1} with some sections with permanently reduced speed due to lower quality of track geometry and level crossings with road communications without safety and signalling. The line is used mainly for passenger train transport, namely light diesel class series 813 and 913. That investigated section is a part of the railway line, which is included in category No. 6 with an annual operating load of fewer than 1.825 million tons.

The structural composition and condition of the track skeleton in the track bed corresponds to the age of the structure: jointed track with A/75 rails 20 m long, concrete sleepers (PAB or SB2 with division 'c') in a combination of single or short sections with wooden sleepers, The fastening of the rails is stiff with clip baseplates. The structural elements of the railway superstructure show defects and imperfections (**Fig. 5** to **Fig. 8**) typical for the structure on which corrective maintenance is applied [30].

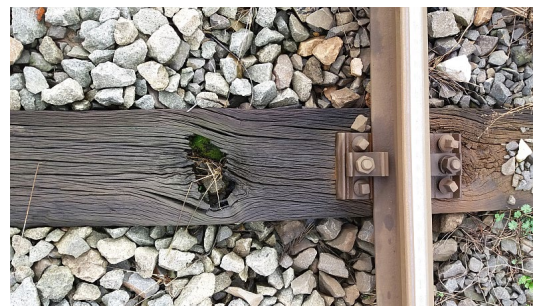**Figure 5.** *Railway superstructure of the tested section*

Figure 6. *Defect of a wooden sleeper*

Figure 7. *Pushed baseplate*

Figure 8. *Lip on the rail head*

1. Data collection

The diagnostic of the monitored section focuses on the collection of track geometry data, the calculation of prescribed quality indicators and the evaluation of the quality of track geometry parameters. As part of the experimental verification, five measurements (*M*1 to *M*5) have been carried out at approximately half-yearly intervals since 2019.

Measurements are performed with an electronic hand measuring trolley KRAB$^{\text{TM}}$–Light, which captures the track condition without load. Data collection is performed by a continuous method – reading and recording of measured quantities every 0.25 m, while the track structure is not under traffic load during the measurement. The measurement method is in the conditions of the *ŽSR* the main method allowed for tracks operated at a maximum speed of 120 km.h^{-1}. During the measurement, all required values of the track geometry are read and recorded at the same time, which defines the method

as a complex method. The sensors of the measuring device are in contact with the structural elements (rails) of the measured structure during the duration of sensing the quantities.

The track geometry in terms of [26] is represented by:
- quantities of the geometric arrangement of the track:
  - deviations from the designed position of the track alignment (*Al*) (unit: mm),
  - deviations from the designed level of the rail position (*Tp*) (mm),
- track design values:
  - track gauge (*Ga*) (mm),
  - track cant (*Ct*) (mm)

The quantities *Al* and *Tp* characterize the running track of rolling stock, which is represented by spatial curves, which are also in the whole range of wavelengths. It is only possible to measure them indirectly - by determining the smoothness of the curves that the alignment and vertical profile of the track create. The evaluation of the fluidity of the curves is performed on the principle of measuring the versines on the chords. The quantities *Ga* and *Ct* are direct measures in the respective cross section of the track, they are directly (absolutely) measurable as the so-called real geometry, in the whole range of wavelengths $\lambda \in \langle 1m, \infty \rangle$. From the track gauge, the track gauge change is calculated per 1 m of the track (*Ga/m*; mm/m). From the cant values, it is possible to derive the twist of the track (*Tw*) on the bases of the prescribed lengths (for *ŽSR* 3.00, 6.00 or 12.00 m (mm/m)) [31].

2. Evaluation of track geometry quality

In the conditions of the *ŽSR*, the operating condition of the railway track is primarily evaluated and presented by the condition (quality) of the track geometry, the condition of individual structural elements of the track skeleton, or the ballast bed.

In [31], limit levels of permissible deviations from nominal or projected values of geometric quantities or limit values of quantities (highest values of local defects parameters) are defined for track geometry quality evaluations.

The Alert Limit (*AL*), Intervention Limit (*IL*) and Immediate Action Limit (*IAL*) are intended for the evaluation of the operational quality of the railway track, while the achievement or exceeding of *IL* levels or *IAL* is being monitored. The values depend on the speed range in which the diagnosed structure is categorised. The maintenance time also depends on the inspection interval and the speed of the evolution of the defect:
- operating deviations from the designed or prescribed value of a geometric quantity during the operation of a railway line:

- Alert Limit: if the set value is exceeded, the state of the track geometry variables must be assessed and taken into account in the planning of repair and maintenance activities,
- Intervention Limit: if the set value is exceeded, maintenance work must be carried out so that the operating deviation is not exceeded before future inspections,
- limit operating deviations from the designed or prescribed value of the track geometry quantity during track operation, which should not be exceeded and are defined as the Immediate Action Limit; if this deviation is exceeded, structure and transport measures must be taken to reduce the risk to an acceptable level.

Limits for *SR*1 ($V \leq 60$ km.h^{-1}) during operation are in **Table 2**.

Table 2. *Limit deviations and values of track geometry parameters during operation for SR1* [32]

Parameter	Value					
	AL		**IL**		**IAL**	
Ga (mm)	-5	30	-7	32	-9	35
Ga/m (mm/m)	not evaluated		5		6	
Ct (mm)	-13	13	-15	15	-20	20
Tp (mm)	-15	15	-20	20	-28	28
Al (mm)	-15	15	-18	18	-20	20
Tw₁ (mm/3.0 m)	12		15		18	
Tw₂ (mm/6.0 m)	16		20		24	
Tw₃ (mm/12.0 m)	31		34		36	

By [33], the track geometry quality is described by the standard deviation (*SD*) of the parameter over a defined length (minimum 200 m, usually 1,000 m), the quality mark of the geometric quantity (*QM*) and the quality number of the evaluated section (*QN*) (equations (1) to (3) [32]).

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

$$QN = \sqrt{\begin{array}{c}1.6 \cdot SD_{Al}^2 + 0.6 \cdot SD_{Ga}^2 + \\ + 1.6 \cdot SD_{Ct}^2 + 1.6 \cdot SD_{Tp}^2\end{array}} \qquad (2)$$

$$QM = \frac{ln\frac{SD}{b}}{m} \qquad (3)$$

where *n* is the number of points measured each 0.25 m,
i is the designation of the measuring point,
x_i is the dynamic component of the relevant quantity (deviation from the median in the range *D*1),
b and *m* are numeric constants determined based on *SD* statistics of the relevant

parameter and speed range.

The Railways of the Slovak Republic quality indices for $SR1$ during operation are in **Table 3**.

SD of decisive quantities	
SD_{Al}	3.10
SD_{Ga}	2.70
SD_{Ct}	2.90
SD_{Tp}	3.40
QN of the evaluated section	
QN	7.20
evaluation of the track geometry condition by QM	
$0 < QM \leq 2$	satisfactory
$2 < QM \leq 3$	it is recommended to design a track geometry correction to the maintenance plan
$3 < QM < 4$	it is recommended to correct the track geometry by the next inspection
$4 \leq QM \leq 6$	it is recommended to take immediate measures to arrange the safety of operation

IV. RESULTS AND DISCUSSION

Monitoring of the quality of the track geometry is put at the end of the service life of the tested section – in the near future, reconstruction is planned with a comprehensive replacement of the railway superstructure.

The evaluation of the track geometry quality takes into account in the quality indicators (SD, QM, QN) the influence of the four determinants, which are listed in Chapter II, Part 1 (Al, Tp, Ga, Ct). Since [26] sets the alignment (Al) and vertical level of rail (Tp) values of the track (rails) as determining variables for maintaining the reliability and safety of railway operation, some evaluation outputs are processed in this article only for these variables (**Table 4**, **Fig. 9** to **Fig. 12**).

The period of monitoring carried out so far is limited by the events of No. 1 to No. 7 (**Table 4**) and contains 2 activities related to the rehabilitation of the quality of the track geometry:

- activity No. 1: maintenance focused on manual elimination of track geometry defects detected by the recording car of the *ŽSR*, which captures the track condition under load (section quality assessment day 0, rehabilitation phase No. 1),
- activity No. 6: tamping of the track with an automatic lifting and levelling tamping machine, backfilling of material of the track bed and its adjustment to the prescribed profile and a unique replacement of the track structure components (day 774 of the section quality assessment, rehabilitation phase No. 2).

The determination of the current state of the track by diagnostics of its geometry in the cases of measurements $M1$ and $M5$ took place shortly after the previous maintenance by the measurement trolley, which captures the track condition without load: 66 or 14 days and the interval between individual measurements is 160 to 197 days.

Table 4. *Improvement or deterioration of track quality indexes between measurements*

	Activity	Days from action No. 1	Improvement (-) deterioration (+)		
			SD_{Al}	SD_{Tp}	QN
No. 1	Manual maintenance	0			
No. 2	$M1$	66			
No. 3	$M2$	254	-0.13	-0.20	-0.38
No. 4	$M3$	414	+0.28	+0.14	+0.35
No. 5	$M4$	611	-0.12	+0.03	-0.11
No. 6	Machine maintenance	774			
No. 7	$M5$	788	-1.14	-1.31	-2.12

-2.50 improvement   0   deterioration +2.50

It follows from the above that the $M1$ measurement is placed almost at the beginning of the 1st degradation phase of the track geometry quality, which ends with activity No. 6. The $M5$ measurement is placed at the beginning of the 2nd degradation phase, which currently lasts. Development of improvement or deterioration of the quality indicator between individual measurements in **Table 4** presents a constant level of quality, represented by indicators SD_{Al} and SD_{Tp}.
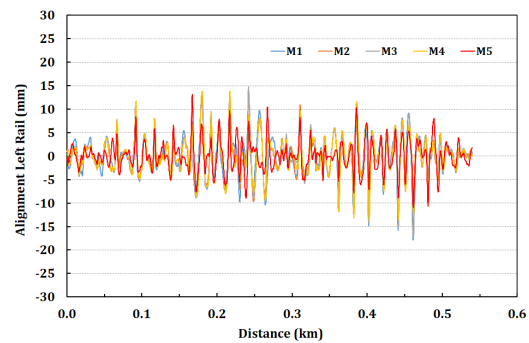

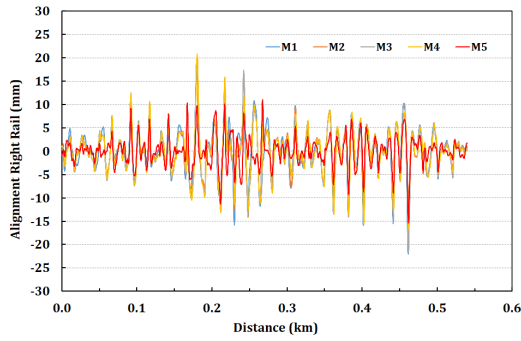***Figure 9.*** *Deviation of alignment of left rail*

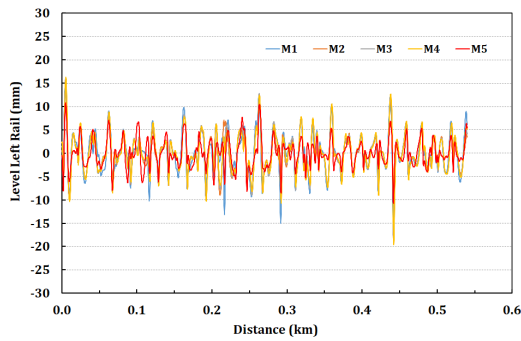***Figure 10.** Deviation of alignment of right rail*

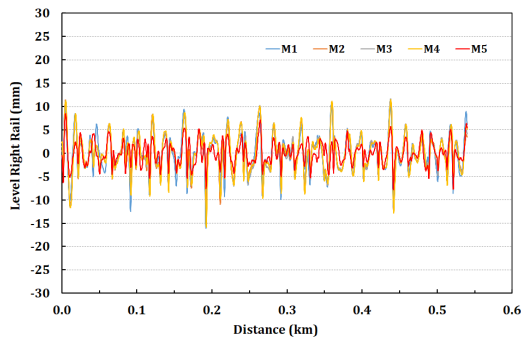***Figure 11.** Deviation of level of left rail*

***Figure 12.** Deviation of level of right rail*

The values of their improvement / - / or deterioration / + / between measurements are from -0.20 to +0.58 mm) and *QN* (-0.38 to +0.35). After the corrective activity at the level of the machine tamping and the related improvements of the track bed, a significant improvement in the quality of the track geometry is detected. The track rehabilitation phase is therefore quantified by a reduction (improvement) in SD_{Al} of 1.14 mm, SD_{Tp} of 1.31 mm and a *QN* was improved by 2.12.

As can be seen from the graphs in **Fig. 9** to **Fig. 12**, the deviations of the determining quantities from the projected position *Al* and *Tp* exceed the values of the permitted deviations *AL*, *IL* or *IAL* only in short solitary sections:

- in the 1st degradation phase, a maximum of 5 sections (*Al*), 2 (*Tp*) in the level of *AL*, or 1 (*Al*) at the *IAL* level,

- in the 2nd degradation phase, 1 section (*Al*) in the *AL* level.

Clear display of the total length of sections with exceeded permissible deviations of all measured values of the track geometry at *AL* levels, *IL* and *IAL*, and the ratio of the length of the sections with defect to the total length of the test section is shown in **Fig. 13**. The figure visualizes the course of the track geometry quality in terms of the length of defects in the 1st degradation phase between the 0th and 1st rehabilitation phase (vertical dashed lines) and the initial track geometry quality in the 2nd degradation phase of the structure quality.
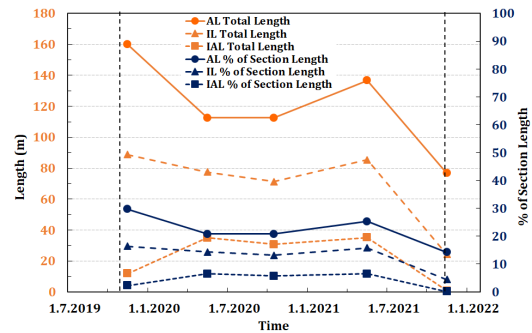

***Figure 13.** Total length of track geometry defects and percentage of examination section length*

The length proportion of the individual rail geometry values in the total length of the section with defects is shown separately for the level of *AL* (**Fig. 14**), *IL* (**Fig. 15**) and *IAL* (**Fig. 16**). In this view, the worst variable is *Ct*, which is the best variable in terms of the variance of the mean value (**Fig. 17**).

With the support of the outputs of the measuring device, we can assume that within the repeated cycles of track geometry correction, the cant was gradually built by tamping in the long section of the track, exceeding the projected cant above the value of permissible deviations. Defects of parameters *Al* and *Ct* were corrected by tamping after *M*4. The *Ga/m* defects were corrected by individual replacing of sleepers after *M*5.
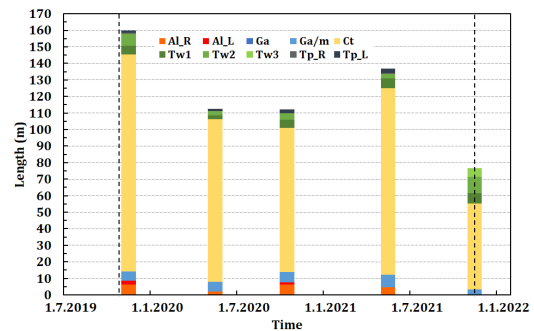

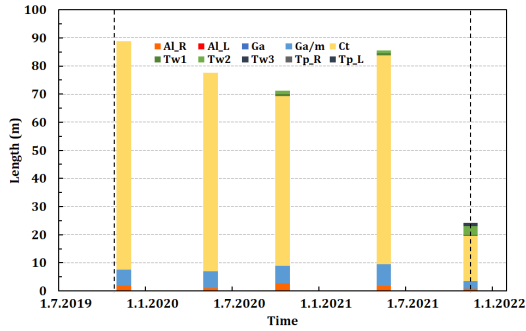***Figure 14.** Total length of track geometry defects (alert limit)*

Figure 15. *Total length of track geometry defects (intervention limit)*
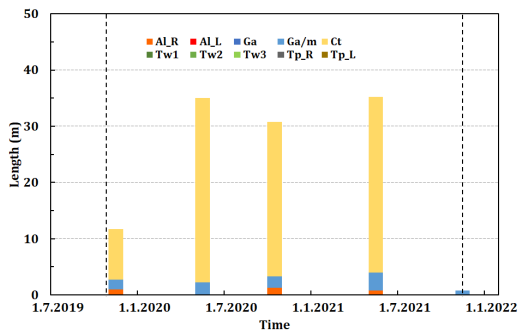

Figure 16. *Total length of track geometry defects (immediate action limit)*

The frequency of occurrence of defects determining the quantities *Al* and *Tp* does not indicate a significant deterioration in the quality of the alignment and vertical profile of the track position of the tested section. The variance of the values of the deviations of these quantities from the average value by means of SD_{Al}, SD_{Tp} (**Fig. 17**) and QM_{Al} (**Fig. 18**) already places the section in a category with unsatisfactory quality. Such a combination of quality indicators indicates the multiple occurrences of deviations in the direction and elevation of the rails from the design position – for example at rail junctions – without exceeding the permissible deviation.
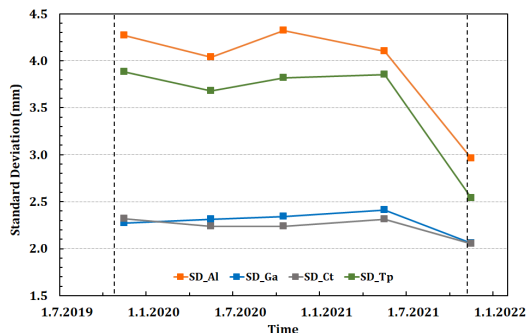

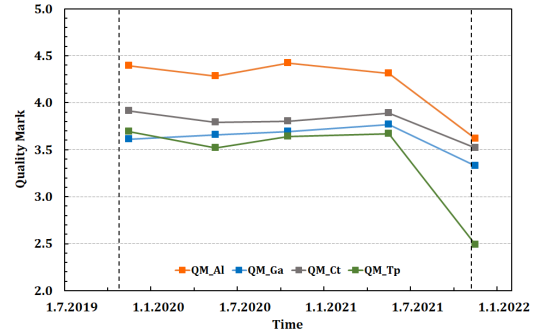**Figure 17.** *Standard deviations of track geometry parameters*

Figure 18. *Quality marks of track geometry parameters*

Based on the determined values of the quality number, it is possible to describe the development of the quality of the track geometry of the tested section (**Fig. 19**) as follows:

- the railway structure maintains the trend of not deteriorating the quality of the track geometry at the end of its service life under favourable operating conditions (intensity and mode of transport), but
- manual maintenance, implemented in selected short sub-sections, is not sufficient in the railway structure for the long-term elimination of track geometry defects and improvement of track geometry quality indicators above-defined limits, especially in determining parameters of track geometry *Al*, *Tp*,
- machine maintenance at the level of the rail tamping and supplementing of the rail bed material and the unique replacement of the track skeleton components rehabilitates the rail geometry to the prescribed quality level, but the results of the following monitoring activities in the 2nd degradation phase will provide information on the durability of such improvement.
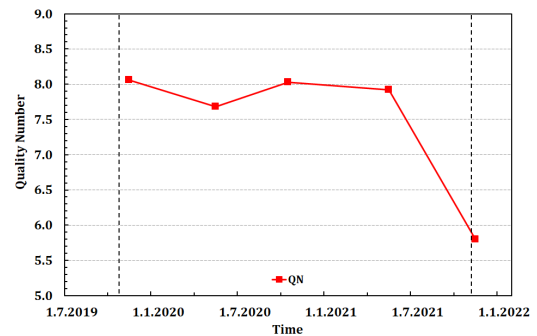

Figure 19. *Track quality indexes*

V. CONCLUSIONS

Monitoring of the track geometry, which forms the track structure at the end of the service life phase, focuses on verifying the effectiveness of maintenance that has the character of corrective

maintenance – i.e. is a response to defects detected by the measurement trolley. In the monitoring period (since September 2019), 5 measurements of track geometry values and 2 phases of quality rehabilitation – manual and machine maintenance (tamping) were performed, accompanied by a supplementary and unique replacement of track skeleton components. The results of the measurements show that the quality of the track geometry is maintained at approximately the same quality at the end of its service life under favourable operating conditions (intensity and type of transport) during the entire 1st phase of degradation. Parameters and efficiency of manual maintenance (0th rehabilitation phase), implemented in selected short sections, did not improve the quality of track geometry below the prescribed limit values of parameters and quality indices and this method of maintenance was not sufficient to eliminate track geometry defects and improve track geometry quality indicators, especially in directional and elevation parameters of the track and rails. Quality assessment of machine maintenance (1st rehabilitation phase) showed a significant improvement in the quality of the track geometry at the beginning of the 2nd degradation phase, up to the prescribed quality level.

Verification of the durability of the improvement in the track geometry quality will be the next research of the investigated section. It is assumed to create and evaluate a prediction model of quality degradation to determine the optimal interval of track geometry maintenance.

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AUTHOR CONTRIBUTIONS

J. Šestáková: Conceptualization, Experiments, Theoretical analysis, Writing, Review and editing.

A. Pultznerová: Conceptualization, Review and editing.

M. Mečár: Conceptualization, Experiments.

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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