Chapter

Analysis of Methods Used to Diagnostics of Railway Lines

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Abstract

Complex diagnostics of railway lines involves techniques based on discrete and continual data acquisition. While discrete measurements belong to conventional methods, the modern continual ones use automated robotized instruments with continuous recording. Observations have become more time-efficient, but the processing epoch has become longer to evaluate a large number of data. Railway line diagnostics is realized by relative methods lead to determine relative track parameters as the track gauge, elevation, and track gradients and absolute, geodetic techniques determine directional and height ratios of the track, defined in a global coordinate and height system.

Keywords: railway diagnostics, ballastless construction, spatial polar method, terrestrial laser scanning, digital leveling

1. Introduction

Railway technical condition has a significant impact on the safety and traffic flow. One of the most important tasks of a railway responsible is to ensure regular maintenance that includes the diagnostics of the actual condition. The diagnostics prolongs the railway service life and contributes to preserve or improve the quality of geometrical and construction parameters of railway lines mainly dependent on materials used in its construction or reconstruction.

There are many ways to diagnose railway lines, starting from visual fault detection through video inspection and ending with the use of various automated diagnostics systems differed by their physical principles. The paper deals with diagnostics methods of railway track that the railway responsible required from civil engineers.

The diagnostics of the railway track done by civil engineers have to enable to determine the main railway parameters: operational safety, changes in the designed geometric directional and height parameters of the railway construction, the impact of quality degradation, material wear of constructional elements [1].

The diagnostics method are divided concerning the range of diagnostics needs and the possibilities of used methods. Generally, we distinguish diagnostics of absolute geometric position, diagnostics of relative geometric position, and diagnostics of constructional track parameters.

The geometric track position represents the projected directional and height parameters of railway lines. From the point of view of the assessment of traffic influences, we divide the geometric position into absolute and relative one. The absolute geometric track position refers to the projected one and relative track position refers to the mathematical functions of analytical geometry like curve, line, cubic parabola, etc. In practice, the absolute directional position of the track is given by the horizontal distance between the track axis and a railway benchmark, and the absolute height position of the track is given by the vertical distance between the top of the non-elevated rail and the benchmark. The relative directional position of the rails represents the positional differences of rails from the projected values. The relative height position of the rails contains a longitudinal change of height of both rails, the mutual height position of rails called rail cant, and the change of the mutual height position of the opposite heads called rail collapse [2, 3].

The track arrangement includes track gauge, gauge change as widening or shrinking, transverse inclination of the rails, size of connection gaps, parallelism of connections, division of sleepers, fastening of rail tracks.

2. Influence of railway traffic and climate changes on railway condition

Traffic effects appear as vertical and horizontal forces acting on the railway track with the character of static and dynamic loading. Long-term traffic effects cause changes in the geometric position and arrangement of the track, changes of the constructional elements, which will be reflected in track deformations, material wear, and material fatigue, and changes in the subsoil, which cause deformations and degradation of physical railway characteristics.

Climate conditions especially temperature, water, and snow influences cause changes in rail length. Low temperature causes the creating of cracks of wooden sleepers and changing the elasticity of some materials. High temperature worse quality properties of non-metallic materials as plastic and rubber elements. Waterfalls cause corrosion of metal parts of the construction, mold, and rot of wooden sleepers, and overall deterioration of subsoil. Long-term precipitation causes increasing the level of groundwater. Snowfall reduces traffic cross-section and makes it inoperable. The effects of traffic and climate changes on the railway line depend on:

- traffic loading and speed,
- type and intensity of railway traffic,
- the quality of the material of the constructional elements of the railway line,
- the quality of the railway construction,
- condition of railway vehicles,
- the scope and quality of maintenance and repairs.

Traffic harms the absolute and relative directional track position. Concerning the absolute directional position, the horizontal forces cause moving the rail in their direction, which caused the change of axial distances of multi-track lines or the change of the distance to objects located around the track. The absolute directional track position can be found out by using measuring devices or geodetic methods.

Concerning the relative directional position, the horizontal forces cause a change in the curvature expressed as ratio 1/r, which appears as changes in the size and direction of the acting forces. Directional deformations are determined by measuring the uplift above the curve chord. The difference between the projected and the actual measured value shall not exceed the value predetermined in national technical standards. The most common directional deformations include:

- disorders in the subsoil,
- improperly designed geometric position of the track,
- climatic conditions,
- influence of railway vehicles,
- insufficient maintenance or repairs.

Defects in directional position are expressed in discomposed driving, deterioration of comfort, increasing the stress of constructional elements, greater wear of the material, and finally the deterioration of quality traffic route. Corrections of errors in the directional track position are performed mechanically by automatic or mechanical tamper [4, 5].

The vertical forces acting on the railway cause elastic or flexible permanent deformation of the height position of railway tracks, which is reflected in the reduction of level one or both of the tops of the rails. The height deformations can appear as continual or short changes of a track. The continual changes of track height are generally evaluated as absolute errors of height position, with uneven drops of the rails causing a change of cross-section and the change of the mutual relative position of the track and the traction line. The absolute height position of the track is measured either manually (by a simple measuring device) or by geodetic height measurements. Changes in relative height may affect all or some of the monitored parameters of geometric position (track depression, elevation, or collapse). The longitudinal height changes of the rails arise in places of increased vertical forces (joints) or failures in the subsoil sediments. The deformations can be single-sided on a rail or double-sided-symmetrical on both rails in the same place and double-sided-cross on both rails with a shifted start. Cracks and drops of joints affect driving comfort and cause an increase of vertical forces (shocks). The longitudinal height of the rails is determined by geodetic methods or by measuring wagons. The mutual height changes of both rails negatively affect the loading on the rails. Demolition is the most monitored parameter in terms of operational safety.

Track collapse is calculated from the height difference measured at the length of the respective base and calculate as the slope (in form 1: n). The not permitted inclination is assessed as an error only if the length of the slope is minimal 2.0 m. The most common causes of changes in the height position of the rails are the following:

- uneven compaction of the trackbed,
- disorders in the subsoil,
- changes in the properties of the subsoil,
- loose fasteners,
- contact gaps,
- uneven distribution of sleepers,

- incorrect cant
- acting the railway vehicles (unevenness loading),
- poor maintenance and repairs

Troubleshooting at the height of the rails is done manually by small range devices or mechanically by automatic machine jacks. The negative effect of the traffic on the track arrangement appears as an extension or reduction of the track gauge. These changes affect the movement of railway vehicles on the running track, which causes changes in the loading of constructional elements. Track gauge is controlled in discrete points using gauges, or continuously by measuring devices. Besides the value of the track gauge also the course of the change of the gauge between two different values at a distance of 1,0 m is assessed. The reasons for the widening of the gauge include poor installation of the rail grate, lateral wear of the rails, wear and loosening of fasteners, uneven pushing of the bases, construction of railway vehicles, bending of sleepers, and insufficient maintenance and repairs. The reduction in gauge causes rolling of railheads, deformation of sleepers, uneven wandering of the rails. Repair of the incorrect gauge is performed according to the type of fastening and sleepers by flipping the clamps, folding the clamps, or by turning flat rib bases.

3. Diagnostics of relative constructional and geometric track position

The main aim of diagnostics of the relative track geometric position is to find negative influences of force and dynamic effects of railway vehicles. Two types of relative diagnostics are used: partial diagnostics. Partial diagnostics is detecting changes in one or more parameters from the geometric arrangement rails. Complex diagnostics allows simultaneous measurement of all crucial parameters by one device on which the measuring means are located. According to the used measuring equipment and technologies, we divide diagnostics into analog devices based on manual manipulation, which detects permanent changes, and electronic devices, which allow registering the elastic deformations that occurred under traffic loading.

3.1 Partial diagnostics

Partial diagnostics of the track was the most used method in the past for control the geometric position of the rail. Nowadays, it is often applied as a complementary method to visual diagnostics because of its unquestionable advantages such as speed of use in operational conditions, simple manual manipulation, and immediate output of results. Partial diagnostics is used to measure track gauge, relative mutual directional, and height position of rails. The most suitable equipment for these purposes seems to be a gauge measuring device, which measures permanent deformations of the track without any influences of the other parameters. Depending on the technology, the gauge measuring device can be used for discrete data recording or continual measurement with graphical and numerical output [6, 7].

The constructional principle of the analog gauge measuring device used for discrete diagnostics is based on direct or indirect measurement of a specific parameter while other track parameters are possible to estimate by using numerical calculations. The continual measurement of track geometrical parameters has a wider base of measuring devices based on the electronic principle of data recording. These devices usually measure the track gauge and the relative height position at the same time. In addition to the measured parameters, the constructional track parameters are evaluated in post-processing.

3.2 Complex diagnostics

Complex diagnostics of relative geometric track parameters control the mutual position of the left and right rail, track gauge, relative gauge changes, the longitudinal relative height position of both rails, rail cant, and track collapse evaluated above the relevant base. In addition to these static values, also dynamic influences and other parameters belong to microgeometry and material diagnostics of rails are evaluated. Devices for complex diagnostics work continually, although the measurement is performed pointwise with measurement steps of 250 mm, measured values are included in the outputs of the evaluation of individual parameters and the condition of the line. Physical principles of complex diagnostics devices enable contact or contactless measurement, the result of which is in the form of graphical record, numerical record, local evaluation, sectional and overall evaluation of railway conditions, which output is in the digital or video form. Besides, the proposal of maintenance measures is a part of the output of complex diagnostics. The most complex diagnostics of the railway line is realized by Measuring wagon and is involved in regular maintenance programs, which prepare belong to the competence of railways management [5].

3.3 Diagnostics of constructional elements

Diagnostics of constructional elements of railway belong to the necessary part of the process of railway diagnostics. Great attention is paid to rail condition, its time changes, and deformation, while the other rail parameters are diagnosed only visually, due to their less impact on the safety and fluentness of traffic. More detailed diagnostics is applied only in case of abnormal occurrence of destructive phenomena [8, 9]. Diagnostics of constructional elements of the track is divided into:

- geometrical diagnostics of rail profiles,
- material diagnostics of rail profiles,
- diagnostics of microgeometry of rail profiles,
- diagnostics of sleepers, small rails, and fasteners.

The size of wear of railhead (**Figure 1**) caused by railway traffic, horizontal deformation at the rail leading edge, and vertical deformation at the head of a rail are determined during geometrical diagnostics of rail profiles. The wear of the railhead is caused by wheel friction as the railway vehicle moves along the rail. The geometric shape of the railhead is gradually changed by the influence of traffic loading.

Material diagnostics of rail profiles aim to detect inner faults that occurred during railway traffic. Material defects can appear at the surface of the rail part, close below the surface, and inside the rail. Material diagnostics prefers non-destructive methods without any restriction in railway traffic as visual, capillary, or ultrasonic detections. The ultrasonic method is the regular diagnostics method and is performed by manual devices, measuring vehicles, or wagon detectors.

The diagnostics of sleepers focuses on concrete sleepers to search for cracks, which worsen its qualitative properties, damages of the surface of the basement,

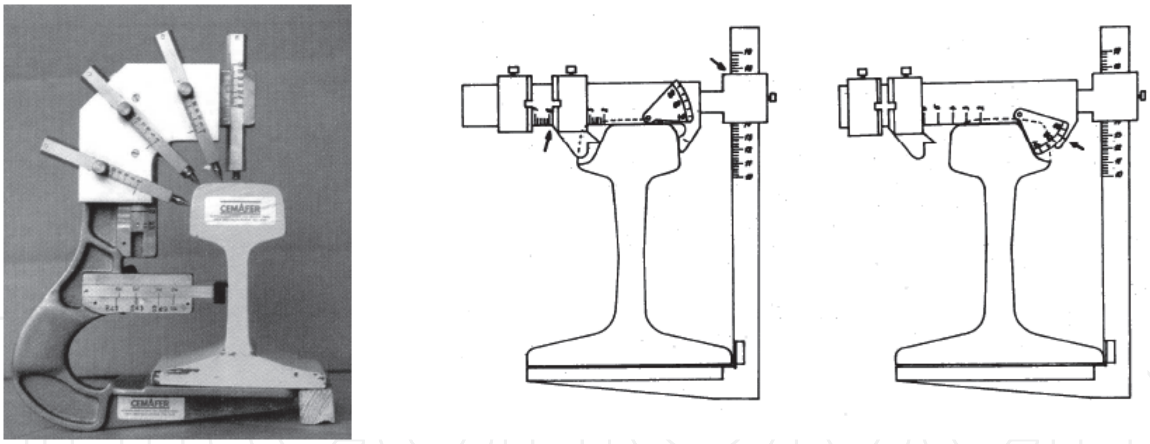

Figure 1.
The manual device for measuring the rail wear on-site (source [10]).

developed by incorrect repair technology and faults of holes need for sleeper screws. The visual inspection of sleepers focuses on the cracks laying on the surface of the basement, mechanical damage of the surface of the basement caused by railway traffic at the points of contact with other constructional elements, deformations of the shape of sleepers, rot, and mold, etc. Steel sleepers are controlled from the point of view of developing the cracks, shape deformations, changes of the shape and size of holes, and material corrosion.

4. Diagnostics of the track absolute geometric position

The diagnostics of the absolute geometric position of the track is practically based on the control of the change of the track spatial position concerning the designed parameters included in the project documentation. The absolute track diagnostics is usually realized by geodetic methods that enable the determination of the spatial position of the track axis concerning the railway benchmarks defined in global European or national coordinate and height systems. Depending on the used geodetic method, the control of the spatial track position can reveal either directly a spatial change or only a change in directional or height position of the track. Generally, the spatial change of a point is defined by the spatial vector defined by three main components: size, direction, and time. Defined by the three main components, which are the magnitude of the direction and the time of action [11–13]. The detection of these parameters can capture geodetic methods, based on the contact and contactless principle, such as terrestrial laser scanning, digital photogrammetry, spatial polar method, kinematic GNSS method, etc. Altitude changes are monitored by the method of precise leveling, and the polar method provided by robotic total stations is currently suitable for detecting displacements of the railway structure in 2D space. The use of the geodetic method for monitoring a railway line depends on the accessibility of the track, length of the railway closure, accuracy requirements, the expected size of the spatial change, which depends on the construction of the railway superstructure, etc.

5. Application of diagnostics method on a ballastless railway line

Ballastless railway line (BRL) is a modern railway construction that ensures safety and traffic comfort while increasing demands for traffic speeds above

160 km/h, which is accompanied by an increase in traffic loading. The BRL refers to the construction of a railway superstructure in which the spreading function of the trackbed is replaced by reinforced materials and which is placed on a concrete or asphalt base plate. The ballastless construction has proven to be a practical and advantageous construction system of the railway superstructure in many countries. An essential reason to build such a railway superstructure is the high track stability associated with fluent vehicles movement and traffic comfort, especially for passengers. The railway responsible appreciates significantly lower requirements for track maintenance, which is accompanied by smaller financial demands. This high driving comfort can only be obtained, in the case of the classic superstructure design, in conjunction with very high operating costs. According to [1] the ballastless railway construction can reduce the following cost items:

- demands on revision and inspection of geometric track position,
- climate influence on railway superstructure and subsoil,
- vegetation care,
- demands on track reconstruction,
- minimization of cleaning track bed,
- increasing time interval of track renewal.

In Slovakia, the ballastless railway construction is built on modernized railway sections especially in tunnels, which have the required subsoil properties, with minimal settlement and bridges without subsidence. In summary, the construction of BRL is suitable due to the reduction of the excavation area, durability and stability of the track position, and minimal demands on maintenance.

The diagnostics of geometrical track position was realized railway section with ballastless construction RHEDA 2000®. The total length of the ballastless construction is 4480 m and passes through various types of track subsoil as tunnel (**Figure 2**), open-air (**Figure 3**), and bridges (**Figure 4**). Due to the difference in subsoil stiffness in the particular line sections, the system of the ballastless railway line was modified to reflect the thickness and reinforcement of the concrete structure.

The critical part of ballastless construction is the transition section laying between ballastless and standard railway construction because of the change of

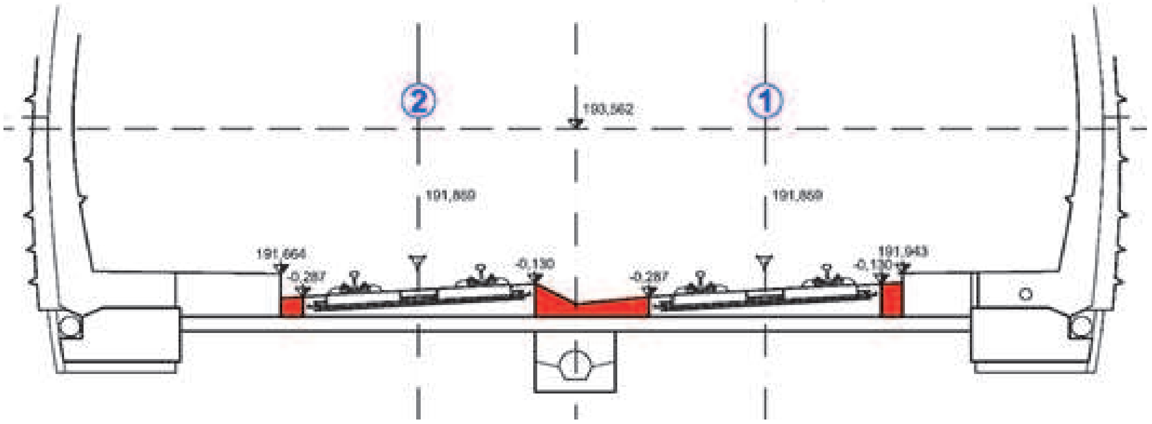

Figure 2.
Ballastles railway line in a tunnel.

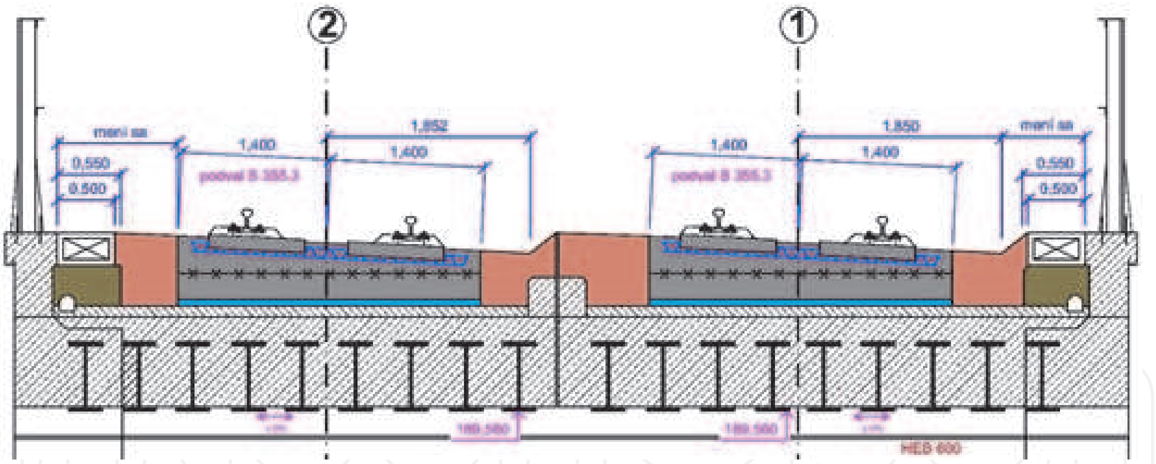

Figure 3.
Ballastles railway line on bridges.

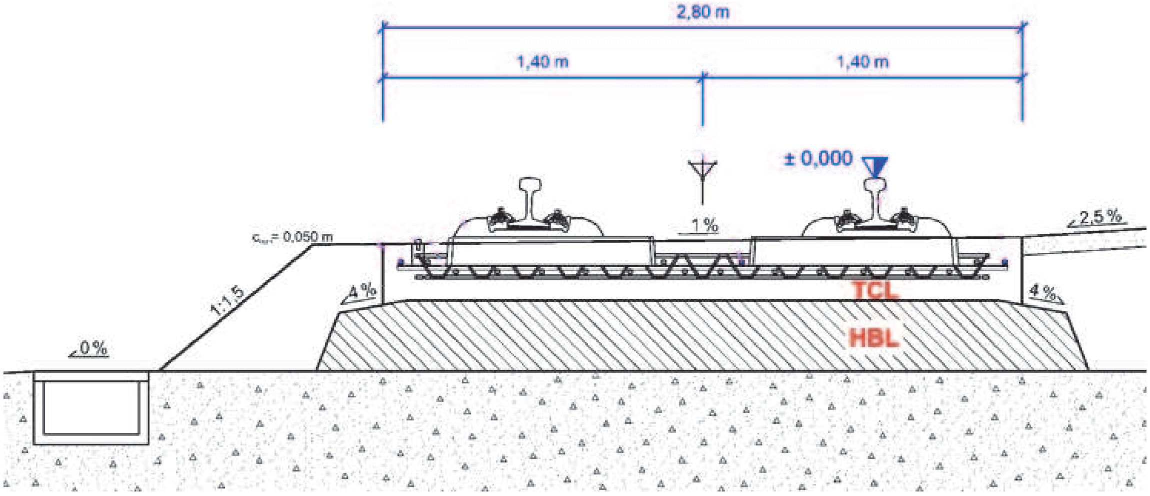

Figure 4.
Ballastles railway line in open-air.

construction stiffness. During the diagnostics process, great attention was paid to this part of railway construction to determine deformations.

5.1 Evaluation of partial and complex diagnostics of BRL

Partial diagnostics of geometrical track position was performed by manual gauge devices ROBEL and GEISMAR to find out gauge changes and track elevation at each mounting node. Complex diagnostics of the structural and geometrical track position was realized by the electronic measuring system KRAB™-Light. The track geometric parameters are measured by contact sensors and recorded in each 250 mm step. The result of diagnostics is obtained in postprocessing:

- track gauge is measured by a potentiometric sensor on the left separate wheel (**Figure 5**),
- the directional position is given by horizontal uplift of the right rail,
- height position is given by vertical uplift of the right rail,
- track elevation measured by inclinometer (**Figure 6**),

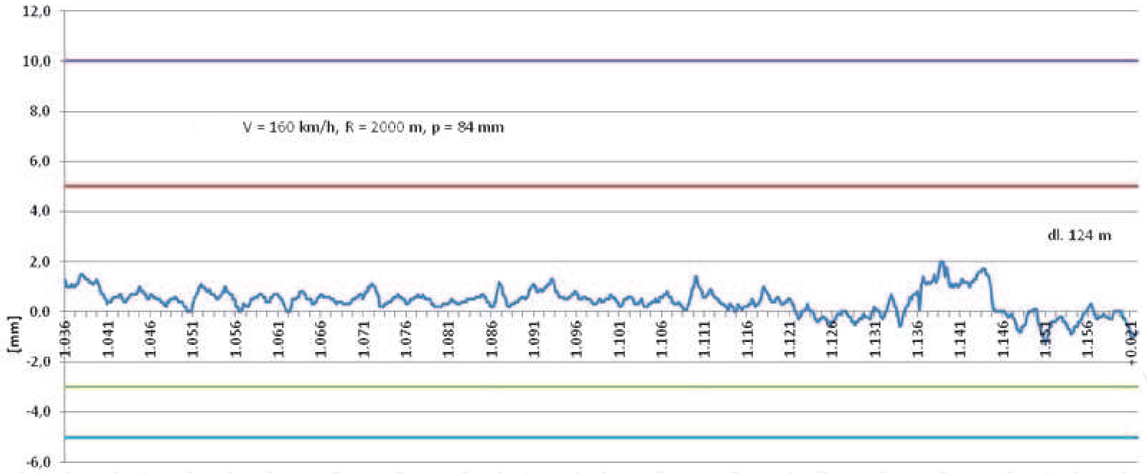

Figure 5.
Changes in track gauge defined in mm.

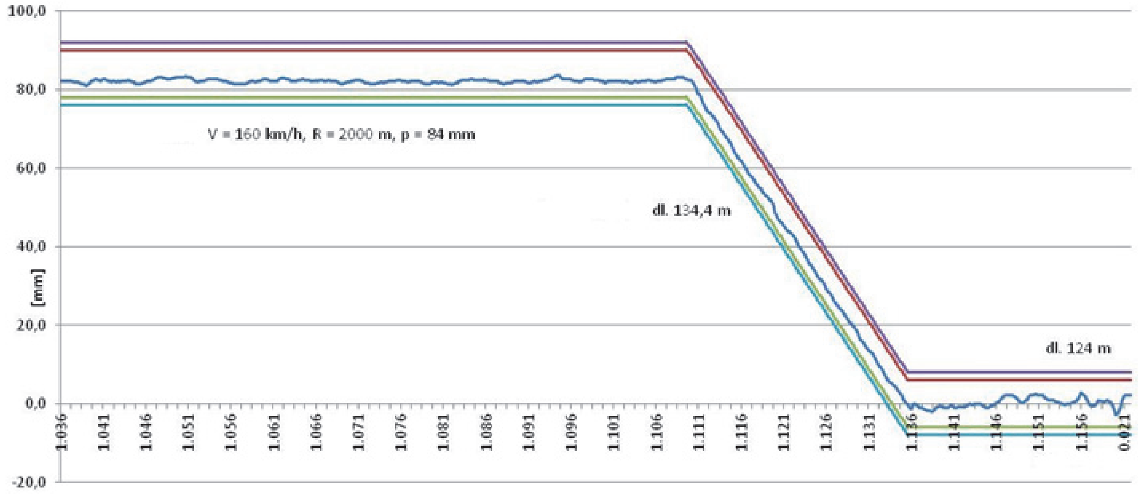

Figure 6.
Track elevation defined in mm.

- quasi-collapse on a short base,
- the longitudinal inclination of the track obtained only by special inclinometer configuration,
- distance traveled obtain by an incremental rotary sensor.

5.2 Evaluation of geodetic diagnostics of BRL

The project of diagnostics of ballastless railway line suggested using geodetic methods to define the spatial, height, and positional track changes.

5.2.1 Analysis of spatial observations

The positional observations of BRL were realized by a video-assisted robotic total station utilizing Trimble VISION technology, which means that it sees everything without a trip back to the instrument and selects targets with just a tap of the controller screen. So, measurements are drawn to the video image and the surveyor can be certain to never miss a shot he needs. The total station involves also FineLock technology to detect targets without interference from the surrounding prism and SurePoint accuracy assurance to correct instrument pointing. The primary precision of the total station is defined by angle accuracy of 0.3 miligons, distance accuracy in standard prism mode is 1 mm + 2 ppm and in tracking mode, it is 4 mm + 2 ppm. So, the technology is destined to be used for both discrete and continuous measurements of the ballastless railway.

Geodetic observations of ballast-less track were realized in standard prism mode to find out spatial track change of ballastless construction in particular points and in tracking mode to evaluate spatial changes from continual observations. The measurements were realized in observational epochs with a period of half a year and spatial changes were evaluated from the differences of the actual and first epoch of spatial vectors.

The organization of the observational epoch consisted of a particular measurement of both rails under traffic closure. The particular points were signalized on each eighth sleeper (5 m) by the marks drawn on the concrete sleeper. Diagnostics of geometrical track position assumes also to determine the longitudinal and transversal changes of the track axes, which are monitored in particular measurement epochs. For this reason, the geodetic observations were pointed to the right rail of the railway line the axes position was defined in post-processing by offset regime. For the purpose to eliminate a pointing error, coordinates of the particular points were converted into a projected system by using track-projected parameters. The analysis of track positional changes belongs to the statistical hypothesis testing based on the postulate of null hypothesis [14]:

$$H_0 : \Delta Z = 0, \Delta z = -\varepsilon_{\Delta z} \tag{1}$$

where ΔZ is the real positional displacement of a point and Δz is measured displacement. If the null hypothesis is confirmed the real displacement is not proven and it is only a function of real observational error $\varepsilon_{\Delta z}$

$$\Delta Z = \Delta z + \varepsilon_{\Delta z} \tag{2}$$

and the measured displacement in the i-th and first epoch of measurement Δz:

$$\Delta z = z_i - z_1 \tag{3}$$

Suppose, the measured values are normally distributed $N\left(\Delta Z,\ \sigma_{\Delta z}^2\right)$ and also the measuring errors will be normally distributed, the confidential interval for measured displacement can be defined as follows:

$$P(|\varepsilon_{\Delta z}| > t_\alpha \sigma_{\Delta z}) = P(|\Delta z| > t_\alpha \sigma_{\Delta z}) = \alpha, \tag{4}$$

where $\sigma_{\Delta z}$ is random standard deviation depended on random variances of both observation epochs:

$$\sigma_{z1i} = \sqrt{\sigma_{zi}^2 + \sigma_{z1}^2} \tag{5}$$

In practice, the real value of displacement is unknown and hypothesis testing of the positional displacement can be established by the following inequalities:

If $|\Delta z| < \sigma_{\Delta z1i}$ the null hypothesis is confirmed and positional displacement is not evident.

If $\sigma_{\Delta z1i} \leq |\Delta z| < 2\sigma_{\Delta z1i}$the null hypothesis is not confirmed and positional displacement is considered as possible.

If $|\Delta z| > 2\sigma_{\Delta z1i}$ the null hypothesis is not confirmed and positional displacement is evident.

5.2.2 Analysis of height observations

The height measurements were performed by precise leveling method with the level instrument, of which the unit standard deviation does not exceed value 0.40 mm in every observational epoch. The height differences were related to the reference network, which consists of permanently stabilized leveling marks, stabilized either on the base of the masts or in the concrete curb. The critical value for determining the height stability of the reference network was determined from the measured height change test and is determined as twice the mean value of the standard deviations found in the particular observation epochs. The process of control the stability of the height reference network consists of estimating the parameters of the regression line, constructed from the difference between the elevation in the first epoch and the i-th epoch, testing of outliers, and estimating the a posteriori accuracy of the network [15].

The analysis of height changes consists of assessing the elevation differences of the i-th and the first leveling. If the standard deviation of the leveling network of the length L in the i-th measurement is given by the relation:

$$\sigma_{hi} = \sigma_{0i}\sqrt{L} \tag{6}$$

the accuracy of the heights differences is defined by the standard deviation:

$$\sigma_{\Delta h} = \sqrt{\sigma_{hi}^2 + \sigma_{h1}^2} \tag{7}$$

out of which we define the probability α and the coefficient of the Student distribution t = 2:

$$\Delta h \geq 2\sigma_{\Delta h} \tag{8}$$

However, the critical limits which represents the reliability interval for the proof of the height changes of the particular points were defined according to the relation:

$$\Delta\bar{h} - 2\sigma_{\Delta h} \leq \Delta h \leq \Delta\bar{h} + 2\sigma_{\Delta h} \tag{9}$$

5.2.3 Analysis of laser scanning

Terrestrial laser scanning has become a very useful method for acquiring an accurate three-dimensional detail of a complex observed object or facility, but its application in engineering surveying has some limitations resulting from the uniqueness of a measured structure. Railway track belongs to the long line ground objects and so the technology of its laser scanning has to be conformed to this fact.

For the scanning procedure of rail track, we used pulsed dual-axis compensated laser scanner Leica ScanStation C10 with the prescribed accuracy of a single measurement in position ±6 mm and distance ±4 mm and angular accuracy is ±12″. These specifications designate standard deviation for target acquisition ±2 mm. The scanning system is based on a 3R green laser of wavelength 532 nm with a scanning range of 300 m [16].

ScanStation was situated on both sides of railway lines and its 3D position was determined by resection method related to the railway benchmarks. The scan

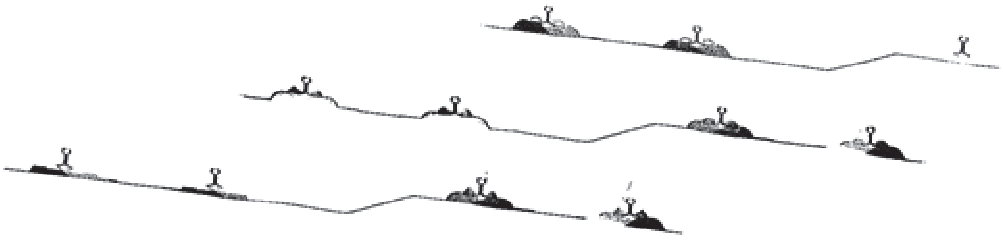

Figure 7.
Illustration of transversal profiles of both railway lines obtained by numerical analysis of clouds of data.

resolution was 3 cm at a range of 30 m while keeping the prescribed accuracy in position ±6 mm. The scan area was limited by the horizontal field of view from 0° to 180° and vertical field of view from −45° to +90°.

The point cloud processing belongs to the most time-consuming and very important part of data utilization. Each point in the point cloud is measured concerning the scanner position, and so the parameter transformation from local to the global national system is necessary to fit the point cloud to coordinate system. For this fact, the connection between laser scanning and terrestrial measurement is necessary, which is based on the 3D position of identical points of both systems. The combination both of measurement methods also helps to verify the positional data, which are utilized in the post-processing procedures. The positional control of the observed point cloud is also realized by the photogrammetric method, which enables the overlapping digital photos, made by a video camera, with corresponding scans.

The point cloud processing continues with the feature codes extraction directly from the point cloud and their export to feature code processing software. While scanning a site, the scanner captures everything in the selected field of view. Objects, which are not relevant to the surveyor have to be removed from the scan. This removal process is an interactive process and a skilled operator needs only a few minutes for extracting and deleting the useless objects. The process of determination of track changes consists mostly of applying mathematical procedures especially regression analysis and mathematical modeling to receive the faithful model of reality [17, 18]. The received mathematical model was finally used to reconstruct the railway track geometry and to evaluate the transversal and longitudinal profiles of a track section (**Figure** 7).

6. Conclusion

Evaluation of partial and complex track diagnostics consists of determining "Local errors" specified in railway sections, which differ by the subsoil construction. The Local errors are defined by values of deviation of the measured parameter from design one. Complex track diagnostics is evaluated by "Quality number", which is determined as the ratio between both observed standard deviation and theoretical one. Based on the value of the quality number, the level of maintenance of the railway line is recommended or repair work is specified.

The standard deviation of determining track changes measured by geodetic methods gives the view on a-posteriori accuracy of the observed track parameter. It involves the error of multitrack target position regarding track axis (±2 mm) and precision of displacement estimation process (±2–3 mm). The longitudinal displacement of the ballastless track was not evaluated, because the precision of multitrack target positioning in the longitudinal direction of the track is out of the assumed value of longitudinal displacement. Concerning the discrete observations, the main problem seems to be in permanent signalization of the particular points on the ballast-less track construction to minimize the error of reflector target positioning.

Precision analysis of digital leveling realized on ballast-less track consists in both analyses of vertical reference network and precision analysis of the track measurements. The first one brought the view on the stability of reference system and the standard deviation, as the main characteristic of used leveling method. Precision analysis of track measurements consists of defining the standard deviation of height differences and the confidential interval, which qualifies the evident vertical displacements of track construction. The precision analysis of geodetic observations realized on ballast-less track construction was performed in conformity with the appropriate technical standards. Accuracy of used digital leveling satisfies the demands, which are defined for observation of such an unconventional track construction.

The application of laser scanning brings to surveyors a great possibility to display the real world in much more detail than it was in past, and it brings also new approaches to utilize the scanning outputs by a using variety of software. For civil engineering, the most common output from laser scanning is the digital terrain model, which can be applied in map-making, designing, deformations diagnostics, construction inspection, or historical objects reconstruction.

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References

[1] Hodas S. Koľajové zhlavie a absolútna priestorová poloha koľaje. Civil and Environmental Engineering (SEI). 2010; **6/6**(2/2010); 72-77

[2] Villim A, Mužík J. Railway line route Trstená-Nowy Targ, the possibilities of maintenance. In: 15. Science Conference of Doctoral Studies. VUT v Brno Czech Republic: Faculty of Civil Engineering; 2013

[3] Slovak Technical Standard. STN 73 0275 Control Measurements of Line Building Objects. Bratislava: Slovak Technical Standard; 1985

[4] Direction SR. 103-8 (S) General Demands on Designing, Building, Maintenance, and Work Acceptance on Ballast-less Structure of Railway Line. Bratislava: The Direction of Slovak Railways; 2012

[5] Direction SZDC. S9 Continuous Railroad. Czech Republic, Prague: Railroad Administration; 2012

[6] Ralph G. The Swiss Trolley – A Modular System for Track Surveying. Vol. 70. Schweizerischen Geodätischen Kommission, CH-8093 Zärich, Switzerland; 2006. p. 199. Available from: https://www.sgc.ethz.ch/sgc-volumes/sgk-70.pdf

[7] Strach M, Lenda G. Concept of measuring and calculation system, based on Electronic clinometers to determine the geometry of Railway track in the vertical plane. Archives of Photogrammetry, Cartography, and Remote Sensing. 2011;**22**:389-399. ISSN: 2083-2214

[8] Grassie SL. Rail irregularities, corrugation, and acoustic roughness: Characteristics, significance, and effects of reprofiling. Proceedings of the Institution of Mechanical Engineers Part F Journal of Rail and Rapid Transit. 2012;**226**(5):542-557

[9] Chiacchiari L, Loprencipe G. Measurement methods and analysis tools for rail irregularities: A case study for urban tram track. Journal of Modern Transportation. 2015;**23**:137-147

[10] Sonmez HY, Ozturk Z. Effects of traffic loads and track parameters on rail wear: A case study for Yenikapi–Ataturk airport light rail transit line. Urban Rail Transit. 2020;**6**:244-264

[11] Herusgeber WS. Ingenieurgeodäsie. In: Handbuch der Geodäsie herausgeben von Will Reiner Rummel. Spektrum Berlin: Springer; 2018. p. 622

[12] Gikas V. Railway Geodesy: The Benefit of Using a Multi-discipline Approach for the Assessment of Track Alignments During Construction. Cairo, Egypt: FIG Working Week 2005 and GSDI-8; 2005. Available from: https://www.fig.net/resources/proceedings/fig_proceedings/cairo/papers/ts_22/ts22_04_gikas.pdf

[13] Weston P, Roberts C, Yeo G, Stewart E. Perspectives on railway track geometry condition monitoring from in-service railway vehicles. Vehicle System Dynamics. 2015;**53**(7):1063-1091. DOI: 10.1080/00423114.2015.1034730

[14] Niemeier W. Ausgleichungsrechnung. Berlin: Walter de Gruyter GmbH & Co; 2001. s. 407

[15] Koch KR. Parameterschätzung und Hypothesentests in linearen Modellen. Vierte bearbeitete Auflage ed. Bonn: Dümmlers Verlag; 2004. str. 366

[16] Leica Geosystems High-Definition Surveying Training Manual. HDS LLC European Office. 84 Bratislava: Geotech; 2020

[17] Coiner C, Brun AP. 3D Laser Scanning for Common Surveying Applications. San Ramon, CA: Cyra Technologies, Inc. A Leica Geosystems Company; 2006

[18] Chen Q, Niu X, Zuo L, Zhang T, Xiao F, Liu Y, et al. Railway track geometry measuring trolley system based on aided INS. Sensors. 2018;**18**: 538. DOI: 10.3390/s18020538. Available from: www.mdpi.com/journal/sensors