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STATISTICAL ANALYSIS OF TRACK GEOMETRY PARAMETERS ON TRAMWAY LINE NO. 1 IN BUDAPEST

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Abstract. The article examines the superstructures of the tramway tracks of tramway line No. 1 in Budapest (the capital of Hungary). Since the first appearance of tramways, several technological advancements have been made to serve passenger needs as efficiently as possible. Several types of tramway track superstructure systems can be differentiated, which are implemented differently in each project. Furthermore, these superstructure types have different degradation times (both geometrical and structural), which depend on several factors. Nowadays, visual inspections are no longer considered sufficient in monitoring the tracks' condition and deterioration, thus it is necessary to consider examinations carried out using the sensors mounted on the vehicles. Adopting appropriate methods, the measured data can be modeled and the life cycle of superstructures and structural elements can be determined as a result of sufficiently long-term studies (i.e., life cycle costs, the whole lifetime, etc.). First, the authors present a review of the relevant international literature, after that they conduct analysis of track geometry parameters of the superstructures related to five sections on the investigated tramway line based on the results of the measurements performed for three consecutive years between 2019 and 2021. The analyses consist primarily in statistical examination of the measured and calculated parameters.

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Introduction

Nowadays, determination of deterioration of tramway track superstructure is a task of national economic significance, although only a few countries deal with these solutions. Constructing the public transport network for cities and towns is very costly, as is track maintenance and operation (Bensalah et al., 2017). It is also essential to know the triggers and factors of deterioration from the construction and maintenance point of view. The long-term goal is to reduce maintenance costs, increase passenger safety and comfort, and maintain competitiveness of public transport. Although the dynamic and geometrical tramway measurement methodology in Hungary is not yet fully 'mature', many relevant examples of well-functioning systems can be found in the surrounding countries.

Light rail transit systems are not equivalent to (common) railways due to decreased speeds and axle loads of the vehicles. Thus, their life cycle has to be investigated from different perspectives. While the maximum speed of tram cars according to Hungarian regulations and standards is 50 km/h (BKV Zrt, 2019), in the case of railways, it can be as much as five to seven times the value (on traditional ballasted track, including scheduled speeds, in case of a magnetic levitation train this speed could be higher, of course). Deterioration of tramway tracks can be observed and evaluated considering the structural elements (rails, fastenings, sleepers, etc.) or geometrical parameters (track gauge, alignment, longitudinal level, etc.) (Ahac & Lakušić, 2015). The first is called structural deterioration, and the second is geometrical deterioration. In the case of ballasted tracks, the geometrical deterioration usually appears first, followed by structural deterioration (of course, with higher geometrical deterioration). The speed of the geometrical deterioration is usually significantly lower in the case of direct fixation tracks (or non-ballasted tracks), mainly the structural deterioration can be detected, yet at a materially lower rate and extent compared to the ballasted railway tracks (Ahac & Lakušić, 2015).

In the present research, the authors selected the 'standard sections' that are regularly observed and subjected to geometrical and dynamic measurements. Measurement results are analyzed statistically, and the life cycle of structural elements and the complete superstructure structures will be forecasted on their basis if there is enough data about the selected sections.

Analyzing tramway tracks and their deterioration, it is worth mentioning also other aspects, i.e., (i) rail wear (mainly in curves) and rail deformations (Kurhan et al., 2020; Kurhan & Fischer, 2022; Zboinski & Woznica, 2021); (ii) ballast deformation and support problems (Przybyłowicz et al., 2022; Sysyn et al., 2021a; Sysyn et al., 2021b); (iii) ballast particle degradation (Benmebarek & Movahedi, 2021; Czinder & Török, 2021; Orosz et al., 2021); (iv) deterioration of rail joints (Németh & Fischer, 2021); (v) turnout monitoring (Kampczyk & Dybel, 2021); (vi) modern elasto-plastic mechanical models (Movahedi et al., 2021); (vii) taking into account extraordinary effects, e.g., earthquake (Haladin et al., 2021; Lakusic et al., 2020), (viii) higher-speed railway use experience (Rashidi et al., 2019); (ix) etc.

The authors have not dealt with all aspects mentioned above, only the geometrical deterioration of the tramway tracks; however, they plan to expand their research field to include more topics in the future.

1. Literature review

In order to accurately predict the deterioration of the railway track, it is necessary to set up models that can serve as the basis for the management systems needed to maintain the railway infrastructure (Falamarzi et al, 2019a).

The challenges and opportunities of track degradation and maintenance modeling can be divided into four areas (Soleimanmeigouni et al., 2016):

i) Finding the appropriate track geometry parameters;
ii) Accurate prediction of track geometrical behavior;
iii) Modeling track geometry recovery after maintenance and modeling maintenance strategies;
iv) Proper maintenance schedule.

Finding the adequate track geometry parameters is one of the critical steps in addressing the issue of track degradation. Therefore, during the measurements and analyses, the examined characteristics should be carefully selected and taken into account. It allows for accurate prediction of the behavior of the track geometry by considering the axle loads.

It is also considered expedient to observe and model the railway track after the maintenance works, because it allows determining tracks' service life and its deterioration after interventions and select the appropriate track maintenance strategies. Therefore, the schedule of maintenance works on each line can be planned months and years ahead.

The early detection of track deterioration and subsequent planning of repair works and maintenance interventions are essential even in the initial stage of the appearance of geometrical defects. Moreover, it is a precondition for achieving a longer life of the structure, determining the necessary repair and maintenance costs, and operating the line safely (Ižvolt et al., 2017).

Deterioration is usually measured based on several geometrical parameters:

- Longitudinal level defects/faults;
- Alignment defects/faults;
- Excessive gauge deviations;
- Cross-level and track twist (Falamarzi et al., 2019b).

In Hungary, TrackScan 4.01 instrument developed by Metalelektro Méréstechnika Kft is currently used to measure the geometrical characteristics of tramway tracks (see Figure 1). The description of the instrument and its characteristics are described in Chapter 2.3.

In Croatia, a similar instrument is applied to measure the geometrical characteristics of the railway tracks, which allows investigating two parameters: track gauge and longitudinal level. Track gauge is measured and documented at the time of construction of the track, and it is recorded in the same cross-section for a minimum of three

Figure 1. TrackScan 4.01 instrument (authors' photo)

additional years. Based on the results, it was concluded that the change of parameters is mainly due to the dynamic load of the moving vehicles. It is caused by irregularities in the wheel-rail contact surface and the horizontal geometry of the track. The more heavily the track is exploited, the faster its geometrical and structural deterioration occurs. Three phases of change of track gauge can be identified: first, a slight increase in values, then a long-lasting and faster deterioration, and finally, a significant decrease in the rate of deterioration (Ahac & Lakušić, 2015).

In addition, to study the geometrical characteristics of tramway tracks, it is also essential to observe the dynamic characteristics, as the assessment and deterioration of the track condition are directly related to the speed of vehicles running on the line (Madejski, 2005). The railway track condition can be monitored almost continuously with sensors mounted on vehicles in Germany. Furthermore, separating the resonance signals from the measurements, it is possible to deduce the deterioration of the track (Baasch et al., 2019). In Hungary, the measurement of dynamic characteristics is currently performed with the so-called instrumented in-service vehicle, developed and manufactured by BKV Zrt and Metalelektro Méréstechnika Kft (see Figure 2). The dynamic measurement system was installed on an articulated GANZ type tram with eight axles, its ID number is 7476. To

Figure 2. Instrumented in-service vehicle by BKV Zrt. and Metalelektro Méréstechnika Kft. (authors' photo) measure the parameters, digital 3-axis accelerometers are mounted on the wheel, the frame of the boogie, as well as the car body, allowing the system to detect multi-level dynamic effects. Compared to TrackScan 4.01 instrument, the advantage of the instrumented in-service vehicle is that it provides the dynamic characteristics of the track to be measured with a loaded vehicle (Metalelektro Méréstechnika Kft, 2016). It is important to mention that the measurement results of dynamic characteristics cannot be related to geometrical characteristics yet. They allow detecting disadvantageous track condition and structural problems only (Bocz et al., 2018).

In Central Europe, one of the most complex investigations of superstructure conditions is carried out in Poland. Within the MONIT research program, a system for monitoring the technical condition of tracks has been developed, based on a sensor network of multi-location sensors which are installed on the vehicle. It includes a data acquisition unit and a data server. The vehicle examines the track both dynamically and geometrically. The sensor network collects data and performs data processing while filtering out unnecessary data according to a specified aspect. Measurements have shown that different sensors and parameters work better for detection of different defects. The applied acceleration and angle sensors are located on the frame of the boogie, the front wheel axle, and all axles of the front boogie. To monitor the condition of the track, two cases are distinguished: the ‘parent loop’ and the ‘conditional loop’. Parent loop is continuous monitoring mainly used to monitor the condition of the track. The conditional loop is used in monitoring when the selected criterion(s) are met (e.g., monitoring at a given speed or section), so it is more suitable for monitoring and checking the vehicle’s condition. An exciting feature of the developed monitoring system is that it can track the vehicle(s) online during the measurements (Firlik et al., 2012).

It is also important to mention the track measurements performed in Slovakia related to Rheda 2000 type superstructures. In this case, models are made for selected experimental sections, the characteristics of the track quality are represented by so-called quality indicators (indexes). These indicators are the most essential elements of the diagnostic data; these affect the maintenance and possibly repair activities for the superstructure. The nature and structure of the indicators depend on the initial geometrical and material properties of the structural elements and the unique properties of the structure, such as how it ‘reacts’ to traffic loads. First of all, to determine the quality indicators, the ‘weak points’ of the selected sections were identified: these are the points where the quality of superstructure systems deteriorates the most. For this, the track was continuously measured geometrically, it was also scanned. After that, the quality indicators were evaluated and used to predict the quality of the track as a model. The models were created using mathematical, statistical, and probabilistic methods. The operational quality of the track shows that the structure can transmit the traffic loads (both static and dynamic loads) and resist the non-traffic load effects (such as climate effects) without deterioration of the structure or deformation exceeding the permissible values specified by the vehicle. Therefore, the quality of track geometry is the key factor in the decision-making process of the infrastructure manager regarding the conditions for operating and maintaining the track. The results of data analysis confirm that for each model, the maximum variation values of the determining quantities (alignment and high of track) and the quality indexes (standard deviation values, value of the quality number) are linearly related to (elapsed) time (Šestaková et al., 2019).

Measurement of the track parameters with the vehicles and sensors is very expensive and due to the daily traffic is difficult to implement. It is important to find innovative solutions to reduce costs and increase opportunities to conduct inspection. There are some mobile track inspection systems, like RILA in Netherlands, which can measure the condition of the tracks using a train-mounted survey system (Wang et al., 2021).

The tramway network in Melbourne, similar to the one in Budapest, is extensive. Another similarity is that the repair and maintenance works are planned and performed by experience. Researchers dealing with track deterioration are currently working on the methods for forecasting maintenance operations to make the city’s tramway network intelligently sustainable (Yousefikia et al., 2014). In most countries worldwide, the track gauge and its variation are the primary focus of analysis, the results of which can help provide a forecast as well as serve as one of the primary conditions for establishing preventive maintenance operations. In the case of the Melbourne tramway network, track deterioration is predicted by considering track gauge variation, traffic data, and structural parameters (Falamarzi et al., 2019b).

It is recommended to examine deterioration of railway tracks in sections, considering the structural, environmental, and operational characteristics. The measured data should be analyzed both mechanistically and statistically (Soleimanmeigouni & Ahmadi, 2015).

2. Methods/Experimental

2.1. Presentation of the examined tramway line

Selecting the line to be examined, the primary consideration was to find the line with a variety of superstructure systems and equal allowable load on the same tramway. For this reason, the authors chose tramway line No. 1 in Budapest, which was constructed over a number of years in several phases.

The tramway line is 18.2 km long, it is the longest line in Budapest. In Hungary, seven different superstructure systems of tramway tracks can be differentiated (BKV Zrt, 2019). Six different types of superstructure systems are used on tramway line No. 1, the authors were able to investigate four of them:

i) Concrete slab track;
ii) ESCRB I track system (ESCRB means elastically supported continuous rail bedding system);
iii) ESCRB III track system;
iv) Ballasted track superstructure.

The concrete slab track superstructure system (see Figure 3) includes a reinforced concrete slab or beam. Rails are stabilized by anchor bolts or by bonding direct fastening or spring rail fastening. The superstructure system is usually open(ed), and the types of rail profile include grooved rails or flat-bottom rails (BKV Zrt, 2019).

ESCRB I superstructure system (see Figure 4) is an elastically supported continuous rail bedding system, rubber plates are used in this

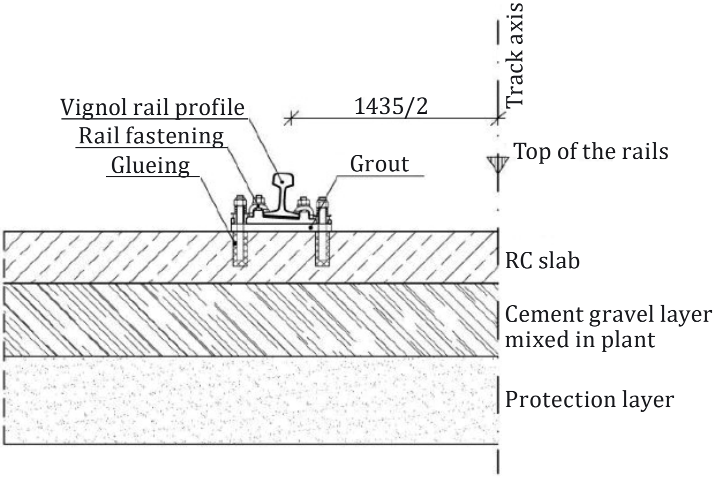

Figure 3. Cross-section of the concrete slab track (BKV Zrt, 2019)

case. The coupling rod can help fix the track gauge, but it can be also built without them. The rails are stabilized by elastic rail clips on a reinforced concrete slab. This superstructure system is covered, and the rail can be of any type (BKV Zrt, 2019).

ESCRB III superstructure system (see Figure 5) is also an elastically supported continuous rail bedding system on a reinforced concrete slab or reinforced concrete beam. However, in the case of a covered superstructure system, a homogenous continual elastic support along the entire length of the rail profile is used (BKV Zrt, 2019).

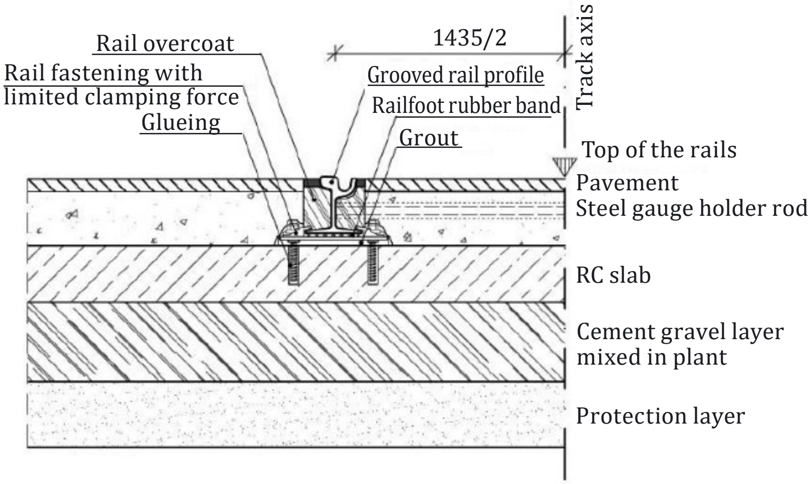

Figure 4. Cross-section of ESCRB I (BKV Zrt., 2019)

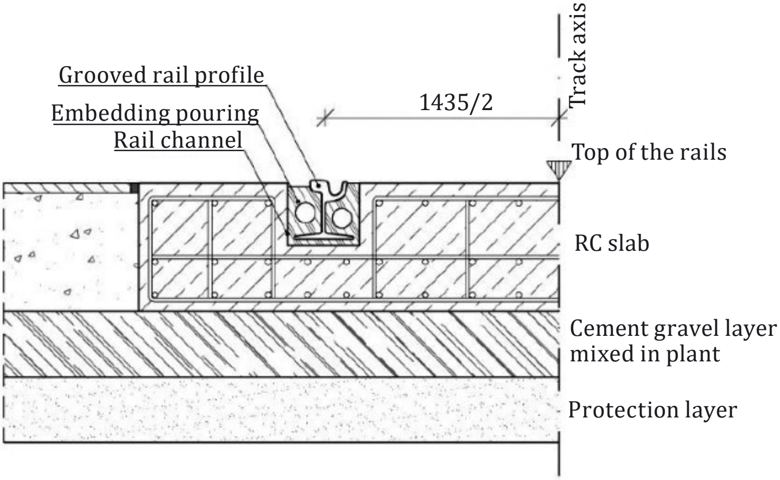

Figure 5. Cross-section of ESCRB III (BKV Zrt., 2019)

The most commonly applied ballasted track superstructure system (see Figure 6) can be implemented in many ways. The sleepers can be made of reinforced concrete, wooden or synthetic material. The fastening can be regular fastening or spring rail. The rail systems are usually groove rails or flat-bottom rails (BKV Zrt., 2019).

After the second prolongation rate of the railway line, mainly CAF URBOS 3/9 and T5C5 vehicles are run, Siemens Combino NF12B vehicles can also be found, although rarely. The newer types of low-floor vehicles have significantly higher axle loads and weights than T5C5 vehicles (see Table 1).

2.2. Examination of deterioration of superstructure systems

The characteristics of the selected standard sections on tramway No. 1 are given in Table 2, they are also shown in Figure 7.

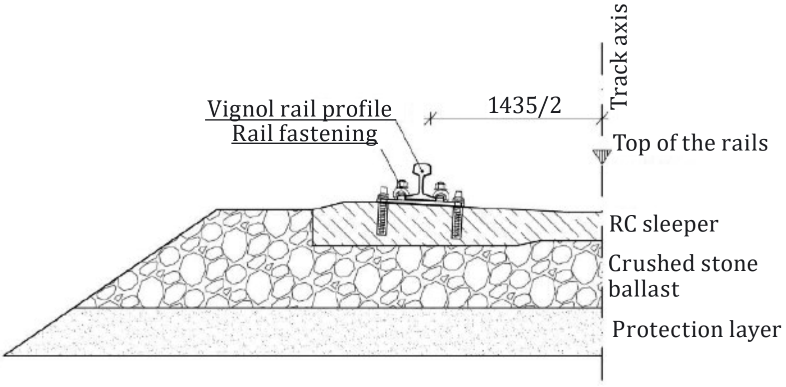

Figure 6. Cross-section of the ballasted track (BKV Zrt., 2019)

Table 1. Characteristics of vehicles (BKV Zrt, 2019)

Type of vehicle	Car body			Axle load, kN	Maximum axle load, kN	Mass of the vehicle	
	Length, mm	Height, mm	Width, mm			Dead weight, kg	Charge weight, kg
T5C5	14 700	3140	2480	41.25	70	16 500	28 000
Siemens Combino NF12B	53 900	3300	2400	58.0	98	69 700	99 500
CAF URBOS 3/9	55 861	3453	2400	66.8	105	66 800	94 465

Table 2. Characteristics of the selected standard section

Name of the standard section	Type of the superstructure system	Start of chainage (the format is hectometer based on the Hungarian practice)	End of chainage (the format is hectometer based on the Hungarian practice)	Length, m	Year of construction
Section 1	concrete slab track	94 + 11.59	97 + 89.21	377.62	2001
Section 2	ESCRB I track system	34 + 69.70	45 + 37.60	1067.90	2014
Section 3	ESCRB III track system	49 + 77.30	53 + 76.40	399.10	2001
Section 4	ESCRB III track system	17 + 12.71	26 + 54.63	941.92	2014
Section 5	ballasted track superstructure	112 + 99.03	120 + 70.13	509.92	2018

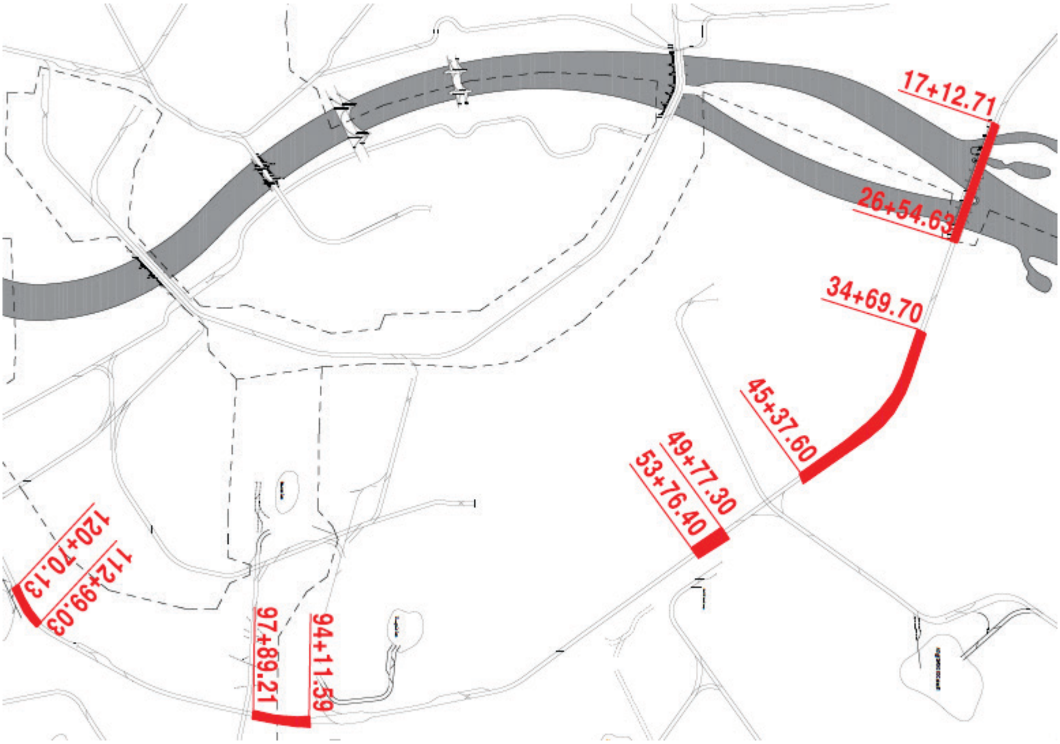

Figure 7. The selected standard sections on tramway No. 1 according to chainage

Section 1 is a concrete slab track where MAV48 rail profiles (Figure 8) are stabilized by GEO (so-called K-type) and embedded fastening on a reinforced concrete slab. The nearly 380 m long section was built in 2001, and the main straight section is an underbridge. The track has a 33.5‰ gradient (i.e., per thousand; 1‰ = 0.1%) along the measurement direction, and after the lowest point, it rises to 39.3‰ (see Figure 9). The curvature of Section 1 is presented in Table 3.

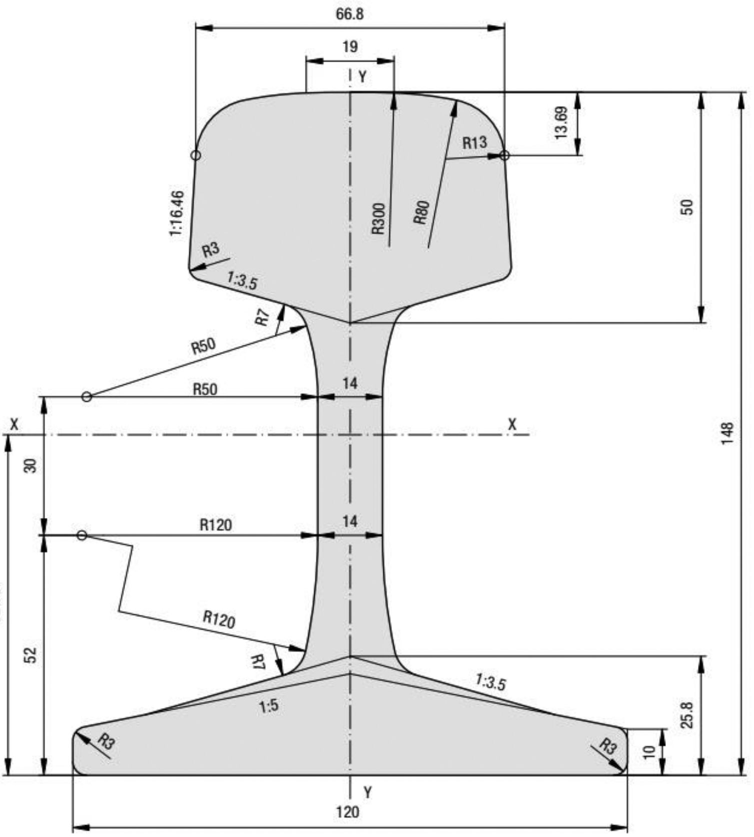

Figure 8. Cross-section of MAV48 rail profile (VoestAlpine Schienen GmbH, Profile Programme)

Table 3. The curvature of Section 1 according to the chainage

Direction of the horizontal curve	Horizontal curve radius, m	Transition curve	Start of chainage	End of chainage
Right	240	Yes	94 + 11.59	95 + 85.99
Right	1125	No	96 + 72.92	97 + 89.21

Figure 9. Section 1, 2021 (authors' photo)

Section 2 is ESCRB I superstructure system: 59R2 rail profile (see Figure 10) with rubber plates and Gantry type fastening on a reinforced concrete slab. The first half of the section rises by an average of 2.8‰, the gradient of the second half of the section is 5.4‰. The track was built in 2014, and there are no turnouts but rather several level crossings. Because of extensive traffic lights control, vehicles are not able to move at a constant speed. The traffic passing through the level crossings can affect the geometrical characteristics of the track, but this fact is neglected by the authors of the present article (see Figure 11). The curvature of Section 2 is presented in Table 4.

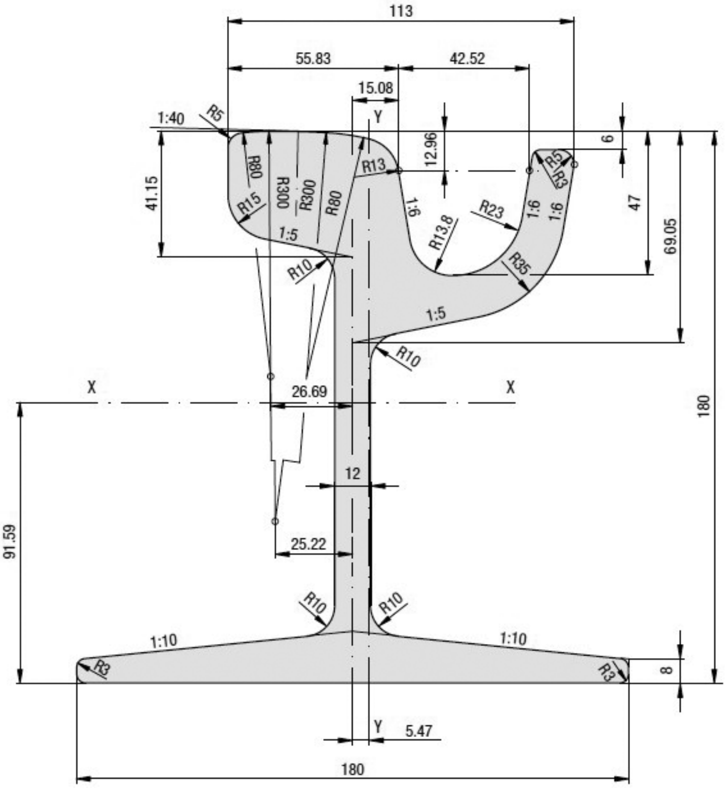

Figure 10. Cross-section of 59R2 rail profile (VoestAlpine Schienen GmbH, Profile Programme)

Table 4. The curvature of Section 2 according to the chainage

Direction of the curve	Curve radius, m	Transition curve	Start of chainage	End of chainage
Left	500	Yes	34 + 69.70	35 + 32.79
Right	925	Yes	35 + 32.79	35 + 97.19
Left	2000	No	37 + 47.06	38 + 21.40
Right	2000	No	38 + 21.40	38 + 75.12
Left	450	Yes	39 + 22.43	39 + 83.11
Right	550	Yes	39 + 83.11	40 + 57.51
Right	1000	Yes	42 + 77.28	43 + 28.02
Left	1200	Yes	43 + 28.02	43 + 82.67

Figure 11. Section 2, 2021 (authors' photo)

Section 3 is one of the oldest built ESCRB III in Budapest. 51R1 rail profile was installed in a reinforced concrete overbridge in 2001, and it was embedded by homogenous continual elastic support along the entire length of the rails. The track is straight, which according to the direction of measurement, rises to 48.6‰. After that, it falls to 31.8‰. There is no turnout or level crossing, only rail expansion devices, they were marked during the measurements with the TrackScan 4.01 instrument. However, this article does not cover their examination data (see Figure 12). The curvature of Section 3 is presented in Table 5.

Table 5. The curvature of Section 3 according to the chainage

Direction of the curve	Curve radius, m	Transition curve	Start of chainage	End of chainage
Left	800	Yes	49 + 77.30	49 + 91.75

Figure 12. Section 3, 2021 (authors' photo)

Section 4 covers the entire tramway track on Árpád Bridge, which is also ESCRB III track system, 51R1 rail profile is embedded in a reinforced concrete overbridge by homogenous continual elastic support along the entire length of the rails. The straight track rises and falls by several breaking points. It was built in 2014, and there are no turnout, grade crossing, or road traffic. A nearly 950 m long section has many rail expansion devices. However, similarly to Section 4, these were not examined separately (see Figure 13). The curvature of Section 4 is presented in Table 6.

Table 6. The curvature of Section 4 according to the chainage

Direction of the curve	Curve radius, m	Transition curve	Start of chainage	End of chainage
Right	200	Yes	17 + 12.71	17 + 18.70

Figure 13. Section 4, 2021 (authors' photo)

Section 5 was rebuilt in 2018 to MAV48 rail provided with the reinforced concrete slab, SKL type rail fastening, and ballast bed. There is no level crossing or turnout on the nearly 510 m long section, so the vehicle travel speed is constant. The downgrade of the track is 3.9‰. The line layout is mainly straight, and there is also a curve (R = 302 m) without superelevation, but with transition curves (see Figure 14). It is assumed that the influence of directional curves has no effect on the measured geometrical parameters. The curvature of Section 5 is presented in Table 7.

Table 7. The curvature of Section 5 according to the chainage

Direction of the curve	Curve radius, m	Transition curve	Start of chainage	End of chainage
Right	302	Yes	115 + 60.48	116 + 83.50
Right	1050	No	118 + 71.06	119 + 29.34
Left	1150	No	119 + 39.65	120 + 02.71

Figure 14. Section 5, 2021 (authors' photo)

2.3. Examined geometrical parameters

As said before, in Hungary, TrackScan 4.01 instrument is currently used to measure the geometrical characteristics of the tramway tracks. This complex track measuring device is suitable for the continuous inspection of railway tracks and turnouts. It can measure and record the following characteristics at the same time:

i) Track gauge, mm, with an accuracy of at least 1 mm;
ii) Flange gauge, mm, with an accuracy of at least 1 mm;
iii) Superelevation, mm, with an accuracy of at least 1 mm;
iv) Alignment, mm, with an accuracy of at least 0.025 mm;
v) Longitudinal level, mm, with an accuracy of at least 0.01 mm;
vi) Length of the railway section [in meters to the nearest mm];
vii) Twist, mm (Jóvér et al., 2020).

The disadvantage of the instrument is that its weight is low, thus the measurements will be in a way unloaded. For this reason, the values of some geometrical characteristics of the track (alignment defect, longitudinal level, etc.) may be higher under the effect of a loaded vehicle (loaded axles).

The authors performed the geometrical measurements of the selected standard sections in the fall of 2019, 2020, and in the spring of 2021 on the right track (according to chainage) at night (see Figure 15).

Figure 15. Geometrical measurement in Budapest (authors' photo)

The measurements were performed with TrackScan 4.01 instrument. The data were evaluated using TrackScan Desktop software. The instrument recorded the parameters of track geometry every 25 cm.

The authors examined the following parameters in detail:

i) Track gauge;
ii) Superelevation;
iii) Alignment;
iv) Longitudinal level.

Track gauge is the distance between the two rails of the track, measured at a given height of the head of the rails between the inner guiding surface perpendicularly in the axis of the track, in the radial direction in case of a curved track.

Measured in cross-section, the track gauge (G) is the smallest distance between the lines perpendicular to the planar of the sunning surface of the rails, these intersect the head of the rails at point P. It is located in the range between the running plane and P point. The value of Z_{p} is generally 14 mm, but in the case of grooved rails, it is 9 mm (MSZ EN 13848-1, 2019) (see Figure 16).

In case the head of the rails is worn, the height of point P of the left rail may differ from that of the right rail (see Figure 17).

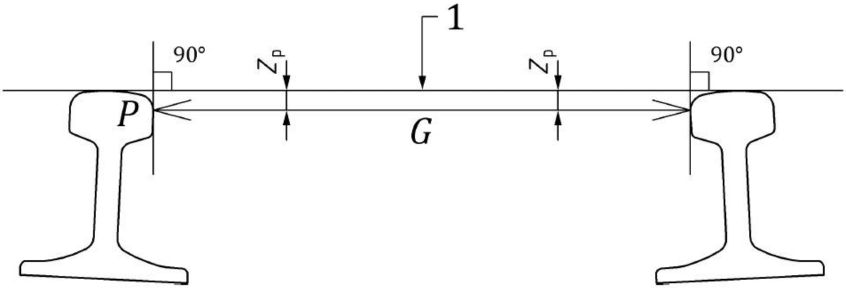

Figure 16. Track gauge in case of a newly built track (MSZ EN 13848-1, 2019)

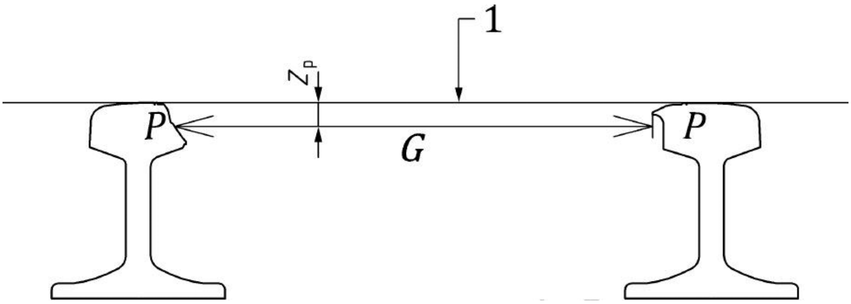

Figure 17. Track gauge in case of a used track (MSZ EN 13848-1, 2019)

Superelevation is raising the outside rail to the inside rail to reduce side acceleration in the curve. The change of superelevation is usually made along the entire length of the transition curve (BKV Zrt, 2019).

The alignment parameter shows the horizontal deviations of the rails, its base length is 1350 mm, and it is symmetrical. The longitudinal level shows the vertical deviations of the rails from the ideal, the base length of the measurement is 1510 mm, and it also uses a symmetrical basis.

The vehicles, which run in the selected section, were described in Table 1. The daily traffic load depends on the type and number of vehicles assigned per day. The selected sections are located on the same tramway line, so their loading is the same.

First of all, it is necessary to examine the measurement data statistically in order to observe the deterioration of the superstructure systems. The measurement data are characterized by the following metrics:

i) Average (A): *n* numbers are given, their sum is divided by *n*;
ii) Standard deviation (SD): the extent to which the values of a probability variable deviate from the expected value;
iii) Relative standard deviation (RSD): a measuring number of 'scattering', which compares the standard deviation of the template to the average of the template;
iv) Skewness: it refers to a distortion or asymmetry that deviates from the symmetrical bell curve, or normal distribution, in a set of data;
v) Kurtosis: like skewness, kurtosis is a statistical measure that is used to describe the distribution. Whereas skewness differentiates extreme values in one versus the other tail, kurtosis measures extreme values in either tail.

3. Results and discussion

The presented parameters of track geometry were examined separately on the selected sections mentioned above.

Standard deviation (SD) and relative standard deviation (RSD) values were compared for each examined parameter. In this case, the measurements results for year 2019 were used as the basis, and they were compared to the results from the measurements for years 2020 and 2021. The proportional difference obtained is shown in Figure 18. The change of the average values of the track gauge of the whole section is shown as the second axis 'y' in the diagram.

The average values of the track gauge in the case of all five selected sections significantly changed during the second measurement (see

Figure 18). It may be explained by the fact that the track gauge started to expand in several cross-sections. Based on the results of the third measurement, it was assumed that the track gauge started to narrow in similar values as the second year‘s expanding values in some cross-sections. These complement each other, producing similar average values to the results of the first year. However, it is essential to note that the changes between the measured data in all three years constitute a few millimeters, which fully correspond to the values of ‘C – size limit of arrangement’ defined in the Guidelines on Infrastructure Planning of Tramway Tracks (BKV Zrt, 2019).

In general, it can be stated that the standard deviation (SD) and relative standard deviation (RSD) values have increased over the years. However, in the case of Section 5, there was a decrease in the second year. For Section 1, the changes were twofold and then threefold – the results of Sections 2, 3, and 4 show only a few percent increase.

The values of skewness and kurtosis measurement of track gauge parameters are shown in Figure 19.

The values of skewness of Section 3 and 4 demonstrate a negative sign every year, so in these cases, the distribution is skewed to the left. It means that the average is less than the median. On the other hand, in these two sections, the values of kurtosis have a positive sign, so the distribution is more peaked than normal.

The negative kurtosis value was observed only in Sections 1 and 5, which means that the distribution is flatter than normal.

The superelevation values could be positive or negative, depending on whether the outside rail is higher or lower than the inside rail. Therefore, during the evaluation of the measurement results, the entire measured

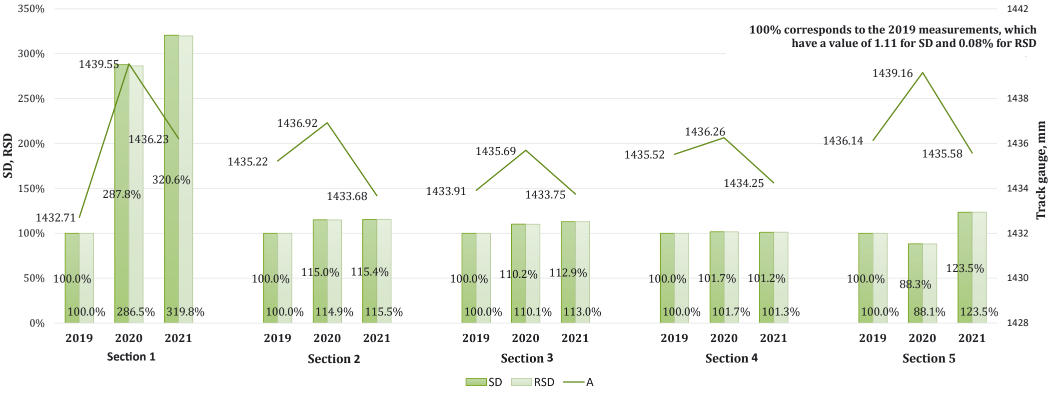

Figure 18. Statistical characteristics of the track gauge values of the selected sections

data were shifted by +40.0 mm to eliminate the errors caused by the different signs. This 'transformation' ensures that all the values are positive; in this way, the distribution of the measured values can be also examined without errors.

It is important to note that no selected section has superelevation.

Figure 20 shows the results obtained from the evaluation of the measurements. Similar to the track gauge parameter, the basis of the standard deviation (SD) values is made by the results of measurement in year 2019. The change of the average values of superelevation is shown as the second axis 'y' in the diagram. The relative standard deviation (RSD) values were not monitored in case of superelevation parameter, because shifting these values would make them unrealistically high.

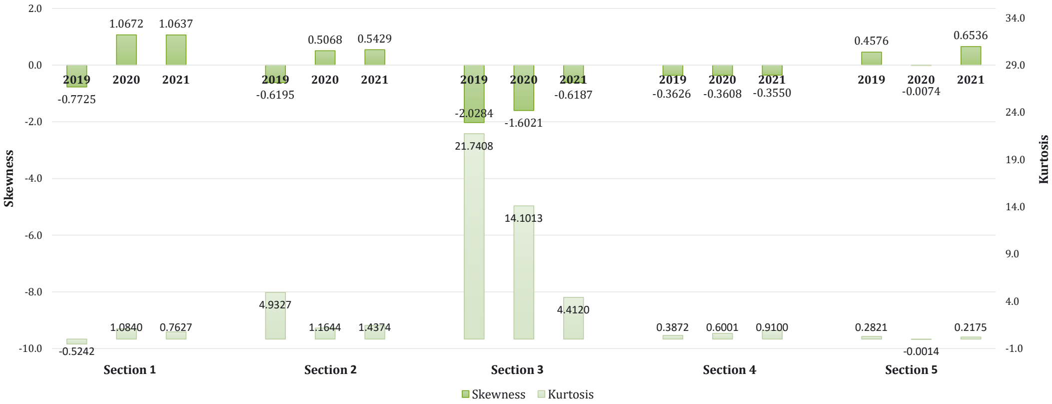

Figure 19. The change of the track gauge values of the selected sections over time, considering the skewness and kurtosis indicators

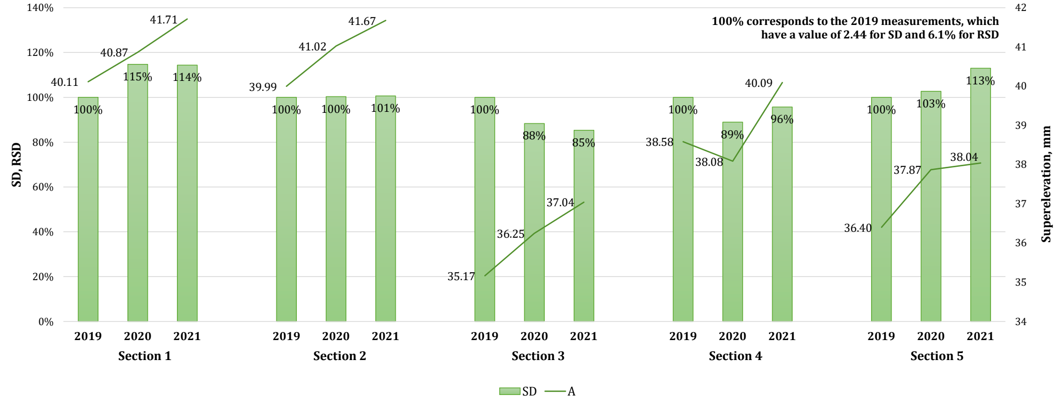

Figure 20. Statistical characteristics of the superelevation values of the selected sections

The superelevation values for the examined sections – except Section 4 – increase by approximately one millimeter per year, which means that the inside rail 'sinks' by one millimeter per year compared to the outside rail on average. The average of superelevation values of Section 4 decreased by only half a millimeter during the second measurement. However, the average value of the third-year measurement increased by two millimeters compared to the measurement of the first year. So, in this case, the annual increase of one-millimeter average elevation may be true.

The standard deviation (SD) values are very variable for all five sections.

The values of skewness and kurtosis measurement of superelevation parameter were examined (see Figure 21).

In the case of every selected section, the value of kurtosis has a positive sign, so the distribution is more peaked than normal.

The values of the skewness variable vary, but it is worth noting that in Section 2, the value was zero in 2020.

The alignment parameter measured by TrackScan 4.01 instrument points at the horizontal deviations of the rails. These values, like the superelevation parameter, can have negative or positive signs. In order to avoid the errors, the values of the alignment parameter were examined in absolute terms.

In Figure 22, the change of the average values of alignment parameters in absolute terms is shown as the second axis 'y' in the diagram. The alignment values for the examined sections varied by a few tenths of a millimeter from year to year. These changes are minimal. They largely comply with the prescribed geometric limits.

Similar to the previous parameters, the standard deviation (SD) and relative standard deviation (RSD) were compared.

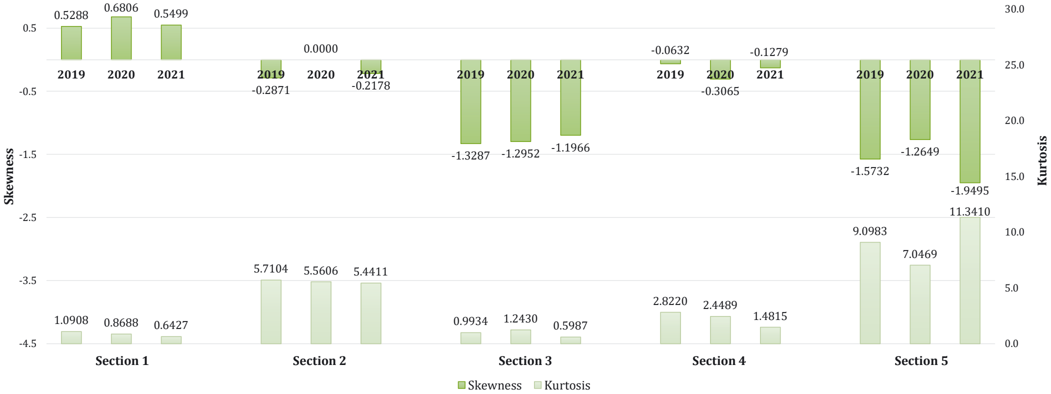

Figure 21. The change of the superelevation values of the selected sections over time, considering the skewness and kurtosis indicators

These values are very variable in the case of the examined sections. However, it is worth noting the change in the relative standard deviation (RSD) values for each section, which doubled on average between the second and the third measurements. In the case of Section 5, this value increased 4.6 times.

Analyzing the alignment parameter values, the skewness and kurtosis indicators were examined by the original measurement results (negative or positive signs). Every selected section value of kurtosis demonstrates a positive sign, so the distribution is more peaked than normal (see Figure 23). The values of skewness of Section 2 and 4 have a negative sign every year, so in these cases, the distribution is skewed to the left. It means that the average is less than the median. For the other sections, the values are positive, so the distribution is skewed to the right, the average is more than the median.

Figure 22. Statistical characteristics of the alignment values of the selected sections

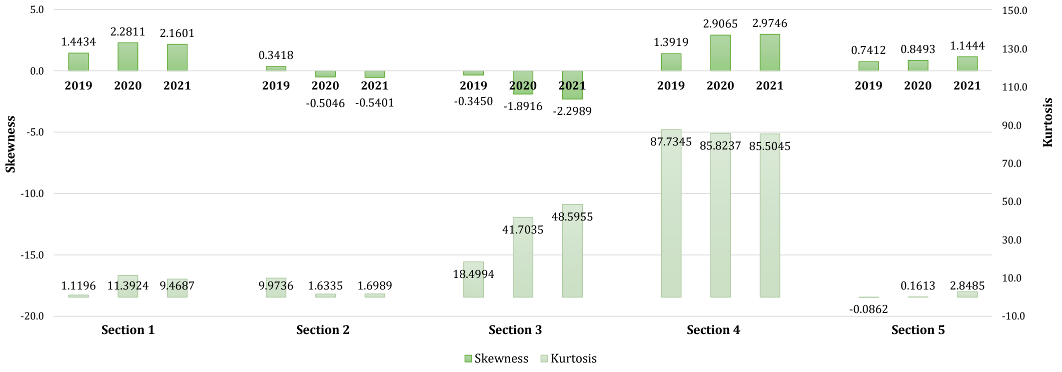

Figure 23. The change of the alignment parameter values of the selected sections over time, considering the skewness and kurtosis indicators

The longitudinal level parameter measured by the instrument shows the vertical deviations of the rails from the ideal. These values can also be negative or positive, so in order to avoid errors, the values of the longitudinal level parameter were examined in absolute values, similar to the alignment parameters.

The change of the average values of the longitudinal level parameter in absolute terms is shown as the second axis 'y' in the diagram (see Figure 24).

The average values of longitudinal level parameters for each section doubled on average between the measurement results of the first

Figure 24. Statistical characteristics of the longitudinal level values of the selected sections

Figure 25. The change of the longitudinal level parameter values of the selected sections over time, considering the skewness and kurtosis indicators

and the second year, and then in the third year, similar results were obtained as in the first year. It can be explained by the fact that the cross-longitudinal level characteristics of the second year were 'equalized' for the third year – like the average of track gauge values.

Similar to the other parameters, in the case of the values of settlement, the standard deviation (SD) and relative standard deviation (RSD) values were compared to each other, and the results of measurement in year 2019 were taken as the basis.

The relative standard deviation (RSD) values decreased on average by half between the first and the second year, while the second and the third-year results show a 1.5–3.0 times increase.

During the analysis of the values of the longitudinal level parameter, similarly to the alignment parameter, the skewness and kurtosis indicators were examined by the original measurement results (negative or positive signs). The kurtosis indicators are positive in each examined section every year (see Figure 25). The values of skewness of the selected sections (except Section 5) demonstrate a negative sign every year, so in these cases, the distribution is skewed to the left. It means that the average is less than the median.

Conclusions

Nowadays, determination of deterioration of the superstructure of tramway tracks is of national economic significance, although only a few countries develop solutions for this problem. For example, in Hungary, 7 different superstructure systems of tramway tracks can be differentiated. Anan instrumented in-service vehicle is used in examination, the vehicle was developed by BKV Zrt. and Metalelektro Méréstechnika Kft, however, complex (geometric and dynamic) measurements are made disregarding the condition of the tracks.

The research aimed to statistically examine the geometrical characteristics measured with TrackScan 4.01 instrument and the dynamic characteristics measured by the instrumented in-service vehicle. The results provide the first evaluation of various superstructure systems.

The authors could investigate four types of superstructure systems on tramway line No. 1 in Budapest since 2019:

i) Concrete slab track;
ii) ESCRB I track system (ESCRB means elastically supported continuous rail bedding system);
iii) ESCRB III track system;
iv) Ballasted track superstructure.

Among the geometrical characteristics of the track recorded by the measuring instrument, such parameters as track gauge, superelevation, alignment, and longitudinal level were examined and statistically analyzed. The measurement data are characterized by the following metrics:

i) Average (A);
ii) Standard deviation (SD);
iii) Relative standard deviation (RSD);
iv) Skewness;
v) Kurtosis.

The average values of the track gauge in all five selected sections increased during the second measurement and then decreased during the third measurement. It is important to note that the changes between the measured data in all three years are a few millimeters, which fully correspond to the values of 'C – size limit of arrangement' defined in the Guidelines on Infrastructure Planning of Tramway Tracks (BKV Zrt, 2019).

The superelevation values could be positive or negative depending on whether the outside rail is higher or lower than the inside rail. Therefore, during the evaluation of the measurement results, the entire measured data were shifted by +40.0 mm to eliminate the errors caused by different signs. The values of relative standard deviation were not monitored, because shifting of these values would make them unrealistically high.

The values of superelevation for the examined sections – except Section 4 – increased by approximately one millimeter per year, which means that the inside rail sinks by one millimeter per year compared to the outside rail on average.

The alignment parameter measured by TrackScan 4.01 instrument shows the horizontal deviations of the rails. Similar to the superelevation parameter, these values can have negative or positive signs. In order to avoid errors, the values of the alignment parameter were examined in absolute terms, but in case of the skewness and kurtosis indicators, the examination was based on the original measurement results (negative or positive signs) The alignment values for the examined sections varied by a few tenths of a millimeter from year to year. These changes are minimal and largely comply with the prescribed geometric limits.

The longitudinal level parameter measured by the instrument shows the vertical deviations of rails from the ideal. These values can also be negative or positive, so in order to avoid errors, the values of the longitudinal level parameter were examined in absolute values, similar to the alignment parameters. In case of the skewness and kurtosis indicators, the examination was based on the original measurement results (negative or positive signs). The average values of the longitudinal level parameters for each section doubled on average between the measurement results of the first and the second year, and then in the third year, similar results were obtained as in the first year. It can be explained by the fact that the second-year characteristics of the cross-longitudinal level were in a way ‘equalized’ with the third year – like the average of the track gauge values.

The skewness indicator varies for each section each year. When the value of skewness is positive, it is possible to speak about the skewed distribution on the right. In this case, the average of values is larger than the median. A negative value means a skewed distribution on the left when the average of values is less than the median.

In general, the kurtosis indicators are positive based on the results of most measurements, which means that the distribution is more peaked than normal.

The evaluation of the three measurement data shows evident changes in the individual track geometry parameters from year to year. However, these are minor changes in each case, and they largely comply with the prescribed geometric limits.

Obviously, no clear conclusions can be drawn from the measurement performed in three years. In order to clarify the deterioration and life cycle of various superstructure systems, additional measurements taken several times a year are required, considering the daily traffic load of the selected sections. The aim is to regularly evaluate the quarterly measurement data and draw the right conclusions about the behavior of different superstructure systems.

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