Investigation of the Geometrical Deterioration Process of Tramway Superstructure Systems – A Case Study

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Abstract: Tramway tracks deteriorate over time due to operational loads, environmental conditions, and structural factors. This study analyzes the geometric degradation of Budapest's tramway tracks using long-term measurements. Track gauge and longitudinal level were assessed with the TrackScan 4.01 instrument to evaluate deterioration across different superstructure types. Findings indicate that concrete slab tracks experience gauge widening, while embedded rail systems tend to narrow under similar conditions, with structural design playing a greater role than traffic intensity. Measurement limitations highlight the need for improved monitoring tools. These insights support more effective maintenance strategies, ensuring greater durability and sustainability.

Keywords: tramway; deterioration; geometric parameters; track gauge; longitudinal level; TrackScan

1 Introduction

Fixed-rail transportation systems, like railways, tramways, and subways, play a vital role in urban planning, especially in bustling cities with high commuting demands. They tackle issues such as traffic congestion and pollution while supporting urban sustainability, economic growth, and social equity [1-10]. For instance, tramways have made a comeback in cities like Casablanca and Nantes, driving urban renewal and symbolizing sustainable policies [11, 12]. Subways, on the other hand, offer rapid transit in crowded areas, reducing reliance on cars and cutting emissions, which helps combat the urban heat island effect [13-15].

Combining green spaces with these systems enhances urban living by improving air quality and public health. Easy access to parks and green areas via tramways and subways encourages healthier lifestyles [15,16]. Cities like Paris and Berlin have successfully managed urban mobility through extensive tram and subway networks, reducing carbon footprints and adapting to the needs of growing populations [17, 18]. Smart technologies further enhance these systems, making them more efficient and user-friendly [17].

Economically, fixed-rail systems boost property values, attract businesses, and create jobs while also saving money in the long run by reducing road maintenance and healthcare costs [17-19]. Socially, they promote fairness by offering affordable transportation for low-income communities, fostering inclusivity [17]. Environmentally, they cut congestion and emissions, aligning with global climate goals. Electric trams and energy-efficient subways further boost sustainability efforts [15, 20].

However, tramway systems are not without challenges. Over time, they face wear and tear due to environmental, operational, and material factors. Research by Jóvér and Fischer [21] shows how weather conditions can weaken tracks, while studies in Budapest by Jóvér et al. [22, 23] reveal issues like track gauge widening, highlighting the need for regular monitoring. Corrosion, especially in reinforced concrete structures, is another concern. Zaghian et al. [24] explain how it can lead to cracks and spalling, compromising safety. Thankfully, innovative solutions like concrete jacketing can help extend the life of these structures [25].

Modern technology also plays a significant role in maintaining tramway systems. Tools like structural health monitoring (SHM) and machine learning, as discussed by Kim et al. [26] and Jha [27], help detect problems early and predict maintenance needs. Effective maintenance strategies, emphasized by Lin et al. [28] and Chu and Durango-Cohen [29], are key to keeping these systems running smoothly. On the economic side, performance rating models by Zayed et al. [30] help balance efficiency and budgets, while public policy and investment, as explored by Althaqafi and Chou [31] and Park [32], ensure long-term sustainability.

Sustainability is another critical focus. Moroń [33] highlights the importance of integrating eco-friendly practices into tramway planning. Advanced modeling techniques, like the fuzzy Markov process [34] and probabilistic models [35], help predict deterioration and plan maintenance more effectively. Climate change adds another layer of complexity, with Duvillard et al. [36] stressing the need for adaptive strategies to handle challenges like temperature swings and increased rainfall, which can speed up wear and tear.

Tramway systems are vital for sustainable urban transport [1-20], but their long-term performance is affected by geometric deterioration due to operational loads, environmental factors, and material degradation [21-24]. Prior research has explored track aging, weather impacts, and maintenance strategies, highlighting the need for continuous monitoring and predictive maintenance [25-30]. However, understanding how different tramway superstructures degrade under similar conditions remains a gap. Studies by Jóvér et al. [21-23] on Budapest's tram network identified track gauge widening, but the link between geometry deterioration and superstructure type, mainly longitudinal level variations, is underexplored. Modern tools like machine learning and structural health monitoring, though applied to railways [26, 27], are underutilized for tramway track assessment. This study addresses these gaps by analyzing geometric deterioration across superstructure types using long-term TrackScan 4.01 data. It statistically evaluates track gauge and longitudinal level under varying traffic loads, comparing superstructure types in real-world conditions. A novel aspect is the direct comparison of two structurally different but similarly aged and loaded systems, revealing distinct degradation patterns. Section 2 details materials and methods, Section 3 presents findings on track geometry trends, and Section 3 compares concrete slab and ESCRB III. systems (elasticly supported continuous rail bedding system; III. type is defined in Section 2), showing significant deterioration differences. The conclusion offers design, maintenance recommendations, and future research directions.

2 Materials and Methods

2.1 Materials

In Hungary, BKV Ltd. maintains more than 300 km of railway tracks and uses seven types of superstructure systems for tramway tracks; there are two larger classifications: open or paved track. These systems are used in varying proportions across the entire tramway network: (i) open ballasted track: 42%; (ii) open concrete slab track: 3%; (iii) paved concreted ballasted track: 5%, (iv) paved ESCRB I.: 20%; (v) paved ESCRB II.: 6%; (vi) paved ESCRB III.: 8%; (vii) paved large slab (paved big panel): 16%.

In addition to the above grouping, classification by the annual through-rolled tonnages is also used, which is the mass of all crossing vehicles on a specific line traveling in one direction in a given year. The traffic load classes are the following [22, 37]: (i) extremely heavy loaded line; (ii) heavily loaded line; (iii) medium loaded line; and (iv) low loaded line.

From the beginning of the research, the concreted ballasted track superstructure system was not investigated ever since the constructed length of this type is very short, and it is usually installed in a turnout area. As is known, vehicles can only travel at a specified speed in turnout areas, so the geometric (and dynamic) investigation of this superstructure system would not have been practical. During the research, 21 sections were regularly examined, the age and annual load of which are known. 3-4 sections per type of superstructure system of varying ages were examined in order to obtain a complex picture of the life cycle of each type.

Table 1 contains the examined sections and characteristics, where MGT means million gross tons (million through-rolled axle load). In order to prevent the sections from being identifiable, they were marked with a code. In Section 3, findings were not made for individual sections but for the types of superstructure systems.

Table 1

Examined sections and their characteristics

Consignation	Type of superstructure system	Age	MGT/year/direction (2019-2023)	Traffic load class
BT-1	ballasted track	39	1.97	low loaded line (HLL)
BT-2	ballasted track	37	1.18	low loaded line (LLL)
BT-3	ballasted track	22	3.91	medium loaded line (MLL)
BT-4	ballasted track	6	6.45	heavily loaded line (HLL)
CS-1	concrete slab track	38	3.69	medium loaded line (MLL)
CS-2	concrete slab track	23	6.94	heavily loaded line (HLL)
CS-3	concrete slab track	14	4.75	medium loaded line (MLL)
ES.I-1	ESCRB I.	16	4.13	medium loaded line (MLL)
ES.I-2	ESCRB I.	21	3.80	medium loaded line (MLL)
ES.I-3	ESCRB I.	10	7.04	heavily loaded line (HLL)
ES.II-1	ESCRB II.	13	4.74	medium loaded line (MLL)
ES.II-2	ESCRB II.	10	5.74	heavily loaded line (HLL)
ES.II-3	ESCRB II.	8	9.24	extr. heavily loaded line (EHLL)
ES.II-4	ESCRB II.	10	4.29	medium loaded line (MLL)
ES.III-1	ESCRB III.	23	6.96	heavily loaded line (HLL)
ES.III-2	ESCRB III.	15	4.13	medium loaded line (MLL)
ES.III-3	ESCRB III.	10	7.03	heavily loaded line (HLL)

ES.III-4	ESCRB III.	6	12.98	extr. heavily loaded line (EHLL)
LS-1	large slab	7	1.47	low loaded line (LLL)
LS-2	large slab	17	4.37	medium loaded line (MLL)
LS-3	large slab	7	1.97	low loaded line (LLL)

2.2 Methods

Based on the prescription [38], it is obligatory to check the geometric condition of tramway tracks regularly by measuring in Budapest. Mechanical track measurement must be carried out at least once a year, for which the company uses the TrackScan 4.01 instrument.

Because of these, during the research, the TrackScan 4.01 instrument was used for geometric measurements, as seen in [21-23, 39]. The instrument is a complex track-measuring device, and its attributions were described in the authors' earlier articles [23, 39]. The instrument is measured with the following parameters – which are taken into consideration in the current paper –: track gauge and longitudinal level. The details of the data processing method are the same as published in [23].

3 Results, Discussion and Proposals

3.1 Usability of TrackScan 4.01 Instrument

The first measurements were taken in June 2021. During the measurements at that time and later, the authors made numerous observations regarding the operation of the TrackScan 4.01 instrument, which led to the abandonment of the examination of certain previously designated sections. Findings regarding the usability of the instrument are presented in the following sections.

It is evident, however, it should be mentioned, or it is worth mentioning, that if the groove is full of dust, the instrument measures inaccurate values for all of the parameters.

3.1.1 Errors Arising from Construction or Maintenance

During the measurements of different superstructure systems, a typical error occurred: the moving arms of the instrument, which measure the track gauge, have 'slipped out' of the groove. This incidence occurred in two cases; first of all, the cases caused by maintenance errors are presented.

There are several level crossings in Budapest where the rail is Vignol; next to it, there is a groove in which the tram wheel runs and the middle part is asphalted. In these level crossings, due to the passing car traffic, the asphalt is constantly sinking and is not replaced. In such cases, the tram wheels find their way, but the TrackScan 4.01 instrument is unable to move and measure. The moving arms of the instrument that measures the track gauge get stuck on the sunken asphalt; the instrument cannot move further and is unable to measure the geometric characteristics of the given road crossing. This incidence is visible in Fig. 1, left.

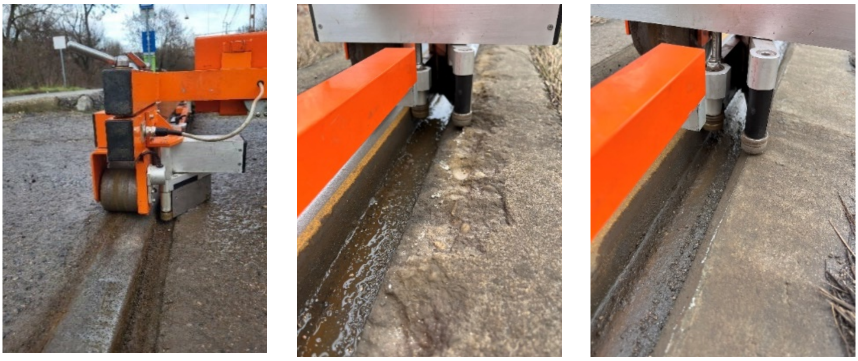

Figure 1
TrackScan 4.01 instrument, left: stuck instrument because of the sunken asphalt; middle and right: errors arising from maintenance or construction on ESCRB III. superstructure system

The same event can be detected in the case of ESCRB III. (details: 49E1 rails, embedded by homogenous continual elastic support in a reinforced concrete slab), when the surface of the concrete is broken. However, during the measurements, it was proven that the instrument cannot be used not only in the case of broken concrete but also in the case of the newly built ESCRB III. with 49E1 rails. The height of the concrete next to the groove is not appropriate, so the moving arms will definitely slide out onto the surface of the concrete. Both cases are shown in Fig. 1, middle and right, which shows that the instrument cannot be used to perform measurements in these cases.

3.1.2 Examination of Large Slab Tracks

During the measurements of large slab tracks, the on-site experience was that the TrackScan 4.01 instrument did not glide 'smoothly' on the track; it got stuck countless times. Another experience was that if the gripping rubber next to the rail came out of its original place, i.e., it was higher than the rail (which was often worn), then the gripping rubber lifted the instrument wheel. This means that the instrument does not measure the geometric characteristics of the rail, and the measurement results are not valid. The error is visible at the top of Fig. 2, while the evaluation of the geometric measurement is visible at the bottom.

The diagrams in Fig. 2 show a clear jump in the parameters of the track gauge, alignment and longitudinal level. In reality, the error does not occur in the rail or the slab and the measurement results can mislead specialists and track maintenance.

Defects resulting from inadequate track maintenance are also evident in the ESCRB I. superstructure system, where the separation of the gripping rubber and excessive wear of the rail cause measurement errors.

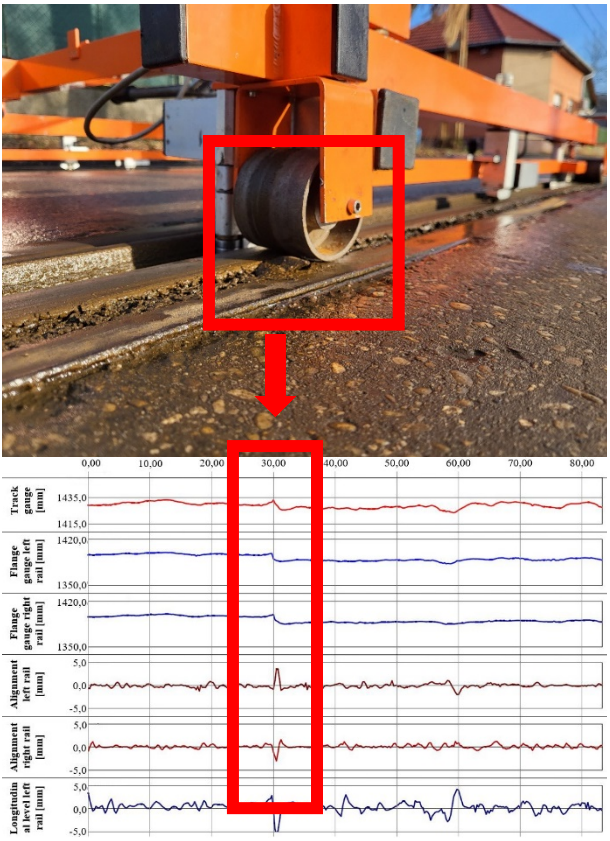

Figure 2

Error caused by gripping rubber and the evaluation of its

Based on the measurement experiences and results presented in the previous chapters, it can be stated that the TrackScan 4.01 instrument cannot be used reliably and adequately in the case of large slab tracks or improperly maintained ESCRB I. tracks. If it were to be used in the case of these types, the instrument would need to be modified, probably by changing the wheel width, but this should be discussed with the manufacturer.

In the case of errors resulting from construction and maintenance, the conversion of the instrument is not recommended for the time being; it should be done in accordance with the construction and track maintenance, according to the regulations.

3.2 Statistically Examined Geometric Parameters

The examined sections – presented in Table 1 – also included curves and straights, as well as level crossings, turnouts and stops. In order to eliminate geometric deviations resulting from these conditions, only straight sections of each selected section were examined in the following, where the speed of the traveling vehicle is also constant.

The measurements were taken between June 2021 and October 2023, a total of eight times for open tracks and six times for paved tracks. The conclusions presented below are all derived from these measurements made by the authors.

3.2.1 Track Gauge Parameter

One of the most significant geometric characteristics of tracks is the track gauge; every maintenance company assigns a size limit to it; the nominal value of the standard gauge – which is used in Hungary – is 1435 mm.

During the research, the parameters were measured and then evaluated for each examined section, which allowed conclusions to be drawn regarding the individual superstructure system types and traffic loads.

In the case of the examination of tracks with concrete slab superstructure systems, the trendline of the average values of the track gauge parameter showed an increase from measurement to measurement, and the direction of the trendline did not change between measurements. It means that the deterioration of the track gauge parameter in the case of concrete slab tracks is clearly described as the broadening of the track gauge (Fig. 3) [23]. One likely reason for this is that in the case of the concrete slab superstructure system, the distance between the fastenings is too large, and the track's frame stiffness of the track is not adequate. This could be eliminated by thickening the fastenings or using a steel gauge holder rod during the construction, but this would increase the installation cost by an unknown amount.

Contrary to the above statement, in the case of the other "open" type superstructure system (ballasted track), the change of the track gauge is not unclear. In the heavily loaded track, the track gauge is narrowing, while the low and medium loaded tracks have a broadening (widening) track gauge. Unfortunately, the extent of broadening is not similar, so that no clear conclusions can be drawn regarding the case of ballasted tracks.

Another important finding regarding the change in the track gauge of the concrete slab superstructure system is that the magnitude of the average value depends on the age of the section, not on the load. Based on experience, it would be expected that the average value of the track gauge parameter would be the highest for the most heavily loaded section, but this is not true.

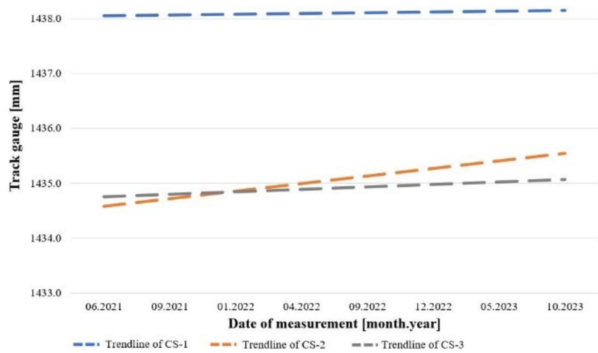

Figure 3

Trendlines of average values of the track gauge parameter in the case of concrete slab tracks

Based on the authors' measurements, it was proven that in the case of younger but more heavily loaded sections (CS-2 and CS-3), the average values of the track gauge parameter resulting from all measurement results are 0.21-0.22% lower than in the oldest but least loaded section (CS-1) (Table 2).

Table 2

Difference in values of age, load and average track gauge compared to the oldest section (CS-1)

Consignation	Age [year]	Age deviation in %	MGT/year/direction	Load deviation in %	The average track gauge of all measurements [mm]	Average track gauge deviation in %
CS-1	38	-	3.69	-	1438.10	-
CS-2	23	⬇ –39%	6.94	⬆ +87%	1435.06	⬇ –0.21%
CS-3	14	⬇ –63%	4.75	⬆ +28%	1434.91	⬇ –0.22%

Examining the changes in the gauge parameter, another important finding – which is based on the results by the authors' measurements – is in the case of elasticly supported continuous rail bedding superstructure systems (ESCRB), regardless of the exact type and age of the superstructure system, the deterioration of the track gauge parameter in the case of medium loaded lines can be clearly described as a broadening of the track gauge (Fig. 4) [22].

Since the steepness of the trendlines is very similar, taking the average of the trendline equations obtained from the measurements, the deterioration of the track gauge in the case of medium loaded ESCRB superstructure systems can be described by Eq.(1), where *x* means elapsed time from the first measurement (x=1 equals to 4-5 months, it should be cumulated).

$$0.3289 \cdot x + 1432 \text{ [mm]} \quad (1)$$

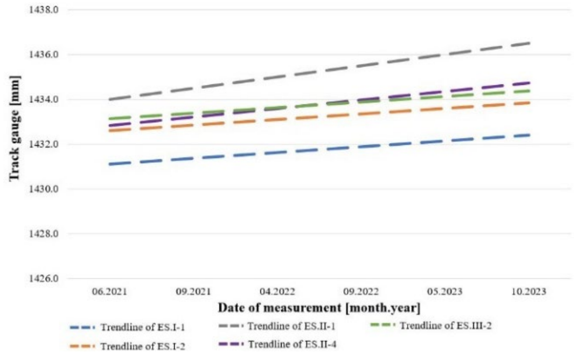

Figure 4
Trendlines of average values of the track gauge parameter in the case of medium loaded ESCRB lines

The reasons for these are presumably the following, depending on the type:

- ESCRB I.: the distance between the fastenings is too large, so the distance between the two rails increases, the concreted steel gauge holder rod deforms,
- ESCRB II.: this superstructure system has no fastenings, steel gauge holder rod, only rail overcoat; as a result, the rail inclines outwards,
- ESCRB III.: this superstructure system has no fastenings, steel gauge holder rod, only rail overcoat, as a result, the rail inclines outwards.

Fig. 5 gives trendlines of track gauge parameter for ESCRB and HLL.

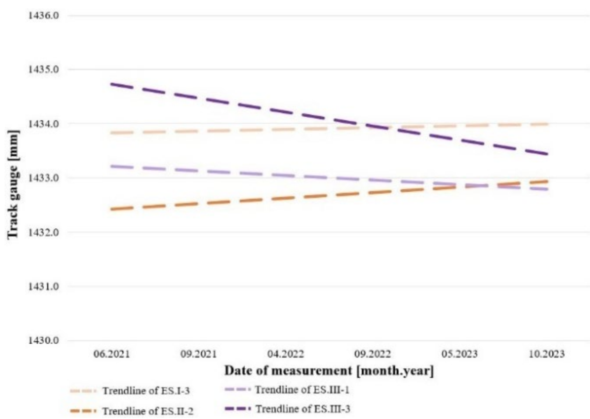

Figure 5
Trendlines of average values of the track gauge parameter in case of heavily loaded ESCRB lines

Determining the exact causes requires further investigation and, in some cases, even taking apart the affected track.

During the research, heavily loaded ESCRB lines were also examined; however, while ESCRB I. and II. (ES.I-3 and ES.II-2 section) are also characterized by a broadening of the track gauge, ESCRB III. type is characterized by a narrowing of the track gauge (ES.III-1 and ES.III-3) (Fig. 5). Based on the measurements, it was proven that the ESRB III. superstructure system reacts differently to different load levels.

3.2.2 Longitudinal Level Parameter

In addition to examining the track gauge parameter, the measured values of the longitudinal level parameter were also evaluated. There is no specific size limit defined for this parameter in Hungary, yet it is one of the most important geometric characteristics with which the condition of the tracks can be described.

The evaluation of the measurement results in this case was also done statistically. These values can have negative or positive signs, so the parameter values were examined in absolute terms to avoid errors.

Table 3 contains a comparison of the individual characteristics of the ballasted track sections.

Based on the evaluation of the measurement results (Fig. 6), it can be seen that the oldest section has the highest absolute value of the average values of the longitudinal level parameter during the measurements, but it was followed by the section with 327% higher load and 85% younger. The section with the lowest value was of similar age, like the BT-1 section, but had 60% less traffic load.

Based on these results, it was proven that in the case of the ballasted track superstructure system, the absolute value of the average values of the longitudinal level parameter depends also, on the magnitude of the load and its age. Further measurements are needed to determine the correlations more precisely, but the conclusions are clear.

In accordance with the above, a statistical analysis of the longitudinal level parameter of concrete slab superstructure systems was also carried out; Table 4 contains a comparison of the individual characteristics of these sections.

Based on the evaluation of the measurement results (Fig. 7), it can be seen that the most loaded section has the highest absolute value of the average values of the longitudinal level parameter during the measurements; it is 41% more than the section with the lowest traffic load. Another interesting thing is that it was followed by the second most loaded section, which is 21% more (almost half of the previous section) than the section with the lowest traffic load. The section with the lowest value has the lowest traffic load.

Table 3
The difference in values of age, load and the absolute value of the average of longitudinal level compared to the oldest section (BT-1)

Consignation	Age [year]	Age deviation in %	MGT/year/direction	Load deviation in %	The average longitudinal level of all measurements [mm]	Average longitudinal level deviation in %
BT-1	39	-	1.97	-	1.0325	-
BT-2	37	↓ –5%	1.18	↓ –40%	0.8830	↓ –15%
BT-3	22	↓ –44%	3.91	↑ +98%	0.9460	↓ –8%
BT-4	6	↓ –85%	6.45	↑ +127%	0.9722	↓ –6%

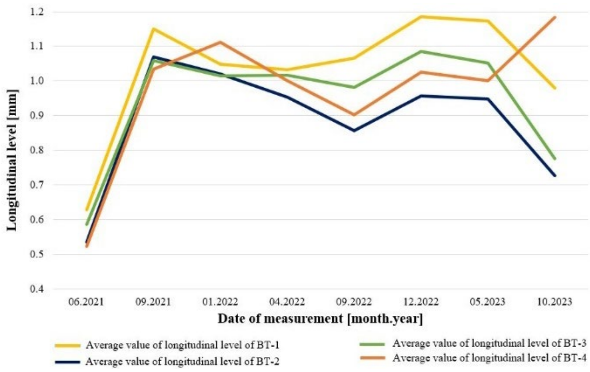

Figure 6
Changes in longitudinal level parameter values in the case of ballasted track sections

Based on these results, it was proven that in the case of concrete slab track superstructure systems, the absolute value of the average values of the longitudinal level parameter depends on the magnitude of the load. Further measurements are needed to determine the correlations more precisely, but the conclusions are clear.

In the case of paved superstructure systems, measuring the large slab tracks was not possible due to the reasons described in Section 3.1.2; however, ESCRB types have been measured, and the statistical evaluation of the measurements has been carried out over the years.

Table 5 contains a comparison of the individual characteristics of the ESCRB I., II. and III. track sections. This is a summary table that always compares other sections of the same type to the oldest section of the given type.

Figure 8 shows the change in the absolute value of the average values of the longitudinal level parameter during the measurements in the case of ESCRB I. tracks.

Table 4
The difference in values of age, load and the absolute value of the average of longitudinal level compared to the oldest section (CS-1)

Consignation	Age [year]	Age deviation in %	MGT/year/direction	Load deviation in %	The average longitudinal level of all measurements [mm]	Average longitudinal level deviation in %
CS-1	38	-	3.69	-	0.7519	-
CS-2	23	–39%	6.94	+87%	1.0565	+41%
CS-3	14	–63%	4.75	+28%	0.9073	+21%

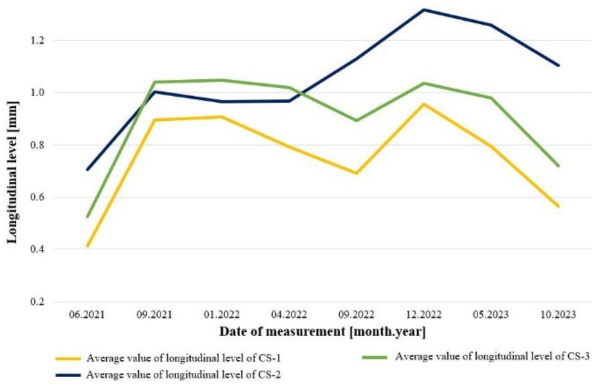

Figure 7
Changes in longitudinal level parameter values in the case of concrete slab track sections

Based on the measurement results, it can be seen that the most loaded section had the highest absolute value of the average values of the longitudinal level parameter during the measurements, and this was followed almost similarly by the other two examined sections. Fig. 8 shows that for the section that is five years younger but has a similar load, the average of the measured values increased significantly after April 2022. Based on these results, it was proven that in the case of ESCRB I. track superstructure system, the absolute value of the average values of the longitudinal level parameter depends on the magnitude of the load, but after nearly 15 years, the deterioration is likely to speed up. Further measurements are needed to determine the correlations more precisely.

Figure 9 (left) shows the change in the absolute value of the average values of the longitudinal level parameter during the measurements in the case of ESCRB II. tracks. Figure 9 (right) shows the change in the absolute value of the average values of the longitudinal level parameter during the measurements in the case of ESCRB III. tracks.

Table 5
The difference in values of age, load and the absolute value of the average of longitudinal level compared to the oldest section (ES.I-2, ES.II-1 and ES.III-1)

Consignation	Age [year]	Age deviation in %	MGT/year/direction	Load deviation in %	The average longitudinal level of all measurements [mm]	Average longitudinal level deviation in %
ES.I-2	21	-	3.80	-	0.9026	-
ES.I-1	16	⬇ –24%	4.13	⬆ +8%	0.8986	⬇ –0.5%
ES.I-3	10	⬇ –38%	7.04	⬆ +70%	1.0185	⬆ +13%
ES.II-1	13	-	4.74	-	1.1053	-
ES.II-2	10	⬇ –23%	5.74	⬆ +21%	0.9989	⬇ –9%
ES.II-3	8	⬇ –38%	9.24	⬆ +95%	0.8670	⬇ –22%
ES.II-4	10	⬇ –23%	4.29	⬇ –9%	0.9401	⬇ –15%
ES.III-1	23	-	6.96	-	0.9439	-
ES.III-2	15	⬇ –35%	4.13	⬇ –40%	0.8422	⬇ –10%
ES.III-3	10	⬇ –57%	7.03	⬆ +1%	0.9200	⬇ –3%
ES.III-4	6	⬇ –74%	12.98	⬆ +86%	0.9881	⬆ +5%

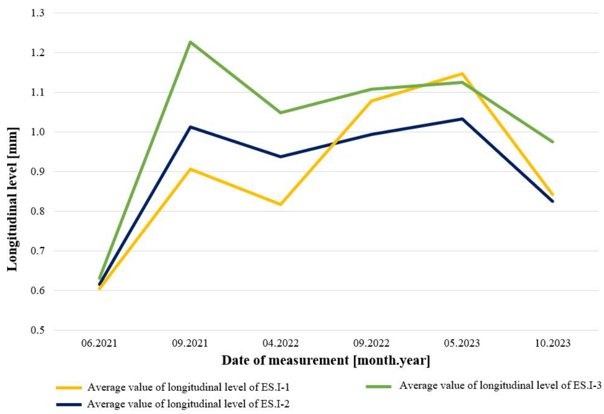

Figure 8
Changes in longitudinal level parameter values in the case of ESCRB I. track sections

Based on the measurement results in Fig. 9, it can be seen and concluded that the section with ES.II consignations resulted in relatively higher longitudinal level parameters considering the calculation and determination procedure and algorithm compared to ES.III sections. This means that the average steepness (tangents) of the linear regression trendlines is 0.1077 [mm/(4-5 months)] for ES.II, hence 0.064 [mm/(4-5 months)] for ES.III; the deterioration is approx. 1.683 times quicker in time in the case of ES.II than ES.III.

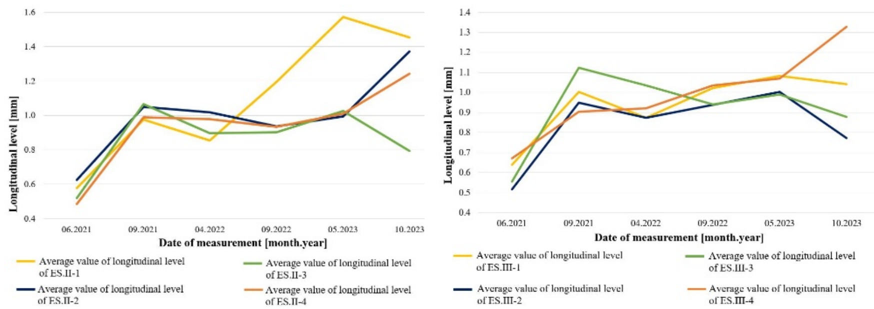

Figure 9

Changes in longitudinal level parameter values in the case of ESCRB II. (left) and ESCRB III. (right) track sections

3.2.3 Comparison of Heavily Loaded Concrete Slab and ESCRB III. Superstructure Systems

Table 6 summarizes the examined sections with the same characteristics.

Table 6

Examined sections with the same characteristics (MGT related to years 2019-2023)

Consignation	Type of superstr. sys.	Age [year]	MGT/year/direction	Traf.
CS-2	concrete slab track	23	6.94	HLL
ES.III-1	ESCRB III.	23	6.96	HLL

In the case of the examined sections, there are two sections whose load are very similar; their age are exactly the same, while the running vehicles on them are also the same, but their superstructure systems are different: concrete slab and ESCRB III (Table 6).

Thanks to this, during the research, it was possible to observe how their geometric characteristics change and how they differ from each other.

Based on several years of measurements, it has been proven that the track gauge parameter in the case of these two superstructure systems changes in different ways: the concrete slab system's track gauge is broadening, while the ESCRB III. system's track gauge is narrowing (Fig. 10, left).

The change in the values of the track gauge and the longitudinal level parameter per measurement for the two sections is shown in Fig. 10, right.

Based on the evaluation of the measurement results, it can be seen that, despite the same age and load, the track gauge values of the concrete slab superstructure system (CS-2) are, on average, 0.13% higher than the ESCRB III. superstructure system's (ES.III-1) track gauge values. The analysis of the longitudinal level parameter shows a similar result; in this case, the values of the concrete slab superstructure system are 8% higher.

Based on the evaluation of the measurement results, it can be clearly stated that, in the case of the same load and age, the ESCRB III. superstructure system is more resistant, and the deterioration process begins later than in the case of the concrete slab superstructure system. The reason for this may be the typical characteristics of superstructure systems described earlier:

- concrete slab superstructure system: the distance between the fastenings is too large, and the track's frame stiffness of the track is not adequate; track deterioration starts earlier and is more significant,
- ESCRB III.: this superstructure system has no fastenings, steel gauge holder rod, only rail overcoat which provides the track with adequate track's frame stiffness.

As further measurements are performed, the difference between the average values of the parameters of the two types of superstructure systems will probably become larger.

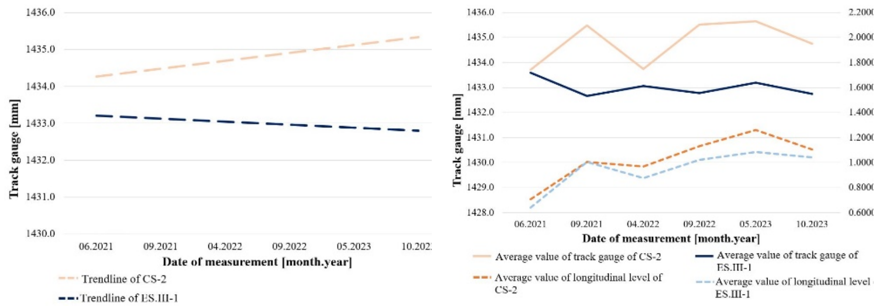

Figure 10

Trendlines of average values of the track gauge parameter in case of heavily loaded concrete slab and ESCRB III. sections (left); Changes in track gauge and longitudinal level parameter values in case of heavily loaded concrete slab and ESCRB III. sections (right)

Conclusions

The findings of this study confirm that tramway superstructure systems exhibit distinct geometric deterioration patterns, with track gauge and longitudinal level variations influenced by age, load, and structural design. The comparative analysis highlights that ESCRB III. demonstrates greater resistance to deterioration than concrete slab systems under identical operational conditions, emphasizing the need for revised material selection and fastening techniques in future infrastructure projects. The statistical evaluation of long-term TrackScan 4.01 data underscores the necessity of continuous monitoring and maintenance strategies tailored to specific superstructure types to ensure optimal track performance and longevity.

However, limitations in the TrackScan 4.01 instrument for specific track conditions suggest the need for modifications or alternative measurement methods to improve accuracy. Future research should further investigate tramway deterioration mechanisms by integrating predictive maintenance models and machine learning techniques to enhance the sustainability of urban rail infrastructure [40-43].

Detailed and further conclusions can be written as follows: on the basis of the authors' track geometry measurements with TrackScan ME 4.01 and their mathematical-statistical evaluation (time series analysis), it is certified that the absolute value of the average values of the settlement (longitudinal level) parameter is directly proportional to the load magnitude for the concrete slab superstructure systems; hence in the case of ESCRB superstructure systems, the deterioration pattern varies by type – ESCRB I. and II. exhibit track gauge widening, whereas ESCRB III. tends to experience track gauge narrowing under heavily loaded conditions. Furthermore, the longitudinal level parameter in ESCRB systems is significantly influenced by both load magnitude and superstructure design with ESCRB III. showing greater resilience against degradation compared to concrete slab systems. The statistical evaluation of deterioration trendlines indicates that ESCRB II. experiences a significantly higher rate of longitudinal level deterioration compared to ESCRB III., with a trendline tangent of 0.1077 [mm/(4-5 months)] and 0.064 [mm/(4-5 months)].

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