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Article

Investigation of "Open" Superstructure Tramway Tracks in Budapest

Vivien Jóvér [1], Zoltán Major [1,*], Attila Németh [1], Dmytro Kurhan [2], Mykola Sysyn [3] and Szabolcs Fischer [1,*]

[1] Central Campus Győr, Széchenyi István University, H-9026 Győr, Hungary
[2] Department of Transport Infrastructure, Ukrainian State University of Science and Technologies, UA-49010 Dnipro, Ukraine
[3] Department of Planning and Design of Railway Infrastructure, Institute of Railway Systems and Public Transport, Technical University of Dresden, 01069 Dresden, Germany
* Correspondence: majorz@sze.hu (Z.M.); fischersz@sze.hu (S.F.); Tel.: +36-(96)-613-544 (S.F.)

Abstract: The most important thing nowadays is to use available resources to develop infrastructure as efficiently as possible. In this regard, evaluating the deterioration of tramway tracks is critical from both a technical and an economic viewpoint. In Hungary, seven types of superstructure systems are currently differentiated in the case of tramway transport, but the geometrical deterioration, lifecycle, and lifecycle cost of the tramway tracks are not accurately known. The current study aimed to evaluate and compare the results of track geometry measurements of two different "open" tramway superstructure systems depending on their traffic load and age. The geometry measurements we re executed by TrackScan 4.01 instrument, developed and maintained by a Hungarian developer company called Metalelektro Méréstechnika Ltd. The evaluation of the measurements showed a clear relationship between the traffic load, age, and track deterioration. Based on the results, it can be generally stated, concerning "open" superstructure systems, that regardless of the "open" superstructure system or the level of traffic load, the average value of alignment is decreasing; however, the average value of the longitudinal level is increasing. Furthermore, the deterioration of an older ballasted track with lower traffic is similar to that of a younger ballasted track that has a higher traffic load. Another significant result was 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.

Keywords: tramway; deterioration; ballasted track; concrete slab track; geometrical analysis; traffic load

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1. Introduction

Transport can be divided into three main areas, following the classical grouping: (i) land transport, (ii) air transport—which includes space transport—and (iii) water transport, i.e., shipping.

Humans have been moving since time immemorial, with a greater or lesser need for mobility. Following the emergence of human societies, the demand for transport has increased significantly, generated and increased mainly by trade between settlements, cities, and countries.

The greatest steps (and innovations), quantitatively and qualitatively, can be linked to specific points in history. Examples include the invention of the wheel, the start of shipbuilding, the industrial revolution and the invention of the steam engine, the invention of the internal combustion engine, the invention of electricity and the electric drive, the harnessing of nuclear energy for transport, and space travel. In many cases, these were also the causes or consequences of major wars. For example, the invention of the atomic bomb and nuclear power was linked to the Second World War, so the peaceful use of nuclear power and its use in vehicles became important (see, for example, nuclear-powered submarines).

In each area, it is possible to distinguish between passenger and freight transport. In passenger transport, individual and collective transport are theoretically conceivable, but there are specific areas, such as rail transport or space travel, where individual transport is severely restricted—both from a technical and legal point of view. Although freight transport is solved and works in all areas, the only attractive area to discuss is perhaps space transport, where the concept of freight transport is not yet fully developed.

The following disciplines are considered to be closely related to transport sciences: (i) transport engineering with logistics-transport-packaging sub-disciplines [1–5], (ii) civil engineering [6–13], (iii) mining and metallurgical engineering [11,12,14], (iv) urban, municipal and architectural engineering [15,16], (v) mechanical engineering [17–21], (vi) electrical engineering [7,22–26], and (vii) vehicle engineering However, in reality, these fields often entirely overlap, or overlap to a lesser or greater extent.

One of the most critical areas of land transport is fixed-rail transport. It includes: (i) railways, (ii) tramways and detached railways, and (iii) specialized railways, e.g., rack railways, cableways, funicular railways, etc. From the early 1800s, rail transport became one of the world's most dominant land transport modes. James Watt's invention of the steam engine in 1769 revolutionized this part of mechanical and vehicle engineering, and, after many attempts, the first railroad vehicle for public use was George Stephenson's Rocket steam locomotive of 1825, according to the history of engineering [27]. Rudolph Diesel invented the diesel engine. The diesel engine was invented by Rudolph Diesel in 1958, which further boosted the development of the railway from 1840 to 1850. The first electric locomotive was designed in 1837 by Robert Davidson, a Scottish engineer. In 1879, Werner von Siemens built the first electrically powered tram. It was first shown at an exhibition in Berlin. In 1881, the first 3 km- long electrified tramway line was built in Berlin. The power and tractive effort of diesel locomotives could be significantly enhanced by electric traction, which is still the dominant feature of the 21st century. Electric traction uses environmentally friendly, clean energy—provided that it is not produced using fossil fuels, which have a significant carbon footprint—and its transport can be easily managed using the established electricity grid. The issue of regenerative braking energy [7,24,28] is also crucial for electric traction. In the 20th and 21st centuries, we should also expect to see hybrid (mainly diesel–electric hybrid) and even fuel cell and hydrogen-based propulsion. The use of solar energy is also an option, of course. In addition, the possibility of nuclear trains cannot be ruled out. Battery power is also an important trend in electric propulsion [27]. Railways are one of the most prominent transportation options worldwide, carrying large volumes of freight and bulk cargo and many passengers over short and long distances. According to European statistics [29,30], i.e., in the EU-28 (the 28 countries of the European Union), in 2018, passenger kilometers traveled by rail amounted to 407.2 billion passenger kilometers (a total of 5915.9 billion), while domestic freight kilometers traveled by rail amounted to 423.3 billion tonne-kilometers (a total of 2371.2 billion).

This article deals with tramways and is based on the civil engineering discipline (it should be mentioned that tramways use mainly electric hauling with catenary systems or third rail sunk systems). In the next paragraph, the authors introduce the relevance of the public railways, starting from far and focusing on details.

It is important to develop and maintain an appropriate public transport infrastructure in Europe's largest cities [31] and, of course, worldwide [32]. The well-developed public transport systems not only reduce environmental pollution but also make cities more livable, and they are beneficial from an economic point of view [7]. Nowadays, electric energy consumption is also a key issue all over the world; in this way, the energy efficiency and the electric, electric– hybrid service of fixed-rail vehicles are vital [7,22,28,33]. The backbone of urban public transport in most cities is guided land transport [34–37]. As more and more people live in cities, the infrastructure must work together with those who participate in public transport. Thus, it is also imperative to develop and implement safety-promoting systems that allow the detection, recognition, and tracking of pedestrians, vehicles, and cyclists near the tramway [38–45].

In the years 2021–2023, a significant increase in electricity and fuel prices [46] (e.g., gas oil, kerosene, etc.) will cause serious problems and difficulties for countries, public and private (large) public transport companies (the same can, of course, be said for private transport, where the prices of petrol, gas oil, electricity, natural gas, etc.,). The reasons are, of course, many and varied: some explanations and justifications include the ongoing war in Eastern Europe [47], others include the prolonged COVID epidemic [48], the cyclical and proven boom and bust of the world stock market [49], etc. The most likely explanation, however, is a combination of the above to a greater or lesser extent, i.e., no single factor can be neglected entirely.

Another essential component of the safe and acceptable coexistence of infrastructure and people is to make the noise generated by urban rail as bearable as possible. Although rail dampers are cost-effective and reduce noise, nevertheless, the parameters influencing their effects are not well known [35,50,51].

In Budapest, the capital of Hungary, traveling by tram is one of the most critical parts of public transport [34,52,53]. The fixed-rail transport is realized for nearly 300 km, with six types of vehicles and seven types of superstructure systems in this city. The seven different superstructure systems can be divided into two main groups: "open" and "paved" tracks. "Open" superstructure systems are also used in railway transport, representing about 45% of Budapest's tramway tracks. However, it is essential to mention that tramway transits are not equivalent to (traditional) railways (or railroads) because they have different speeds and axle loads of vehicles [34].

The deterioration of "open" tramway tracks can be described in two ways: observing the condition of structural elements or the geometric parameters. In the case of "open" tracks—such as ballasted tracks—the change of geometric parameters appears first: the deterioration of track gauge, alignment, and longitudinal level. It is followed by structural deterioration: the condition of structural elements, like rails, fastenings, and sleepers [6,23,54–57].

The geometrical condition of railway tracks can also be inferred from sudden changes in the vehicle's acceleration speed. The measured acceleration data are currently also used to classify passengers' travel comfort and check the condition of railway tracks. Therefore, traditional methods and tools, as well as measured acceleration data, are helpful for recording deviations in track parameters [58].

Early detection of track deterioration and planned repair and maintenance interventions are the preconditions for a longer service life of the superstructure systems [11,12,59]. Nowadays, the lifecycle of railway tracks is already known, and much recent research and studies have been done about this subject. In general, there are four lifetimes: technical (planning) lifetime, economic lifetime, service lifetime, and moral lifetime. In addition, in several countries, including Morocco, extraordinary research is being done about how satisfied passengers are with tramways, so they examine the moral lifetime [60].

Comparing them, it can be said that the average lifetime of an "open" ballasted railway track is approximately 30 years. However, it must be mentioned that each structural element has its (own) lifetime, too. Therefore, these values can be equal; however, they can also be different [61–63].

Unfortunately, in contrast to the results of railway tracks, only a few research studies are available about tramway tracks' lifetime. Although there are several cities where the issues are addressed, in most cases, the track gauge and its variations are primarily studied. For example, in the case of the Melbourne tramway network, track deterioration is predicted by considering track gauge variation, traffic data, and structural parameters [64]. In Melbourne, researchers developed a machine learning method to forecast the future Track Degradation Index (TDI) based on their measurements and analysis. Determining the future TDI is essential because it becomes possible to determine when and where the maintenance and operation activities should be carried out [65].

In Budapest, the geometrical deterioration, lifecycle, and lifecycle cost of the tramway tracks are not accurately known; their selection and application are currently mainly based on experience. In the future, it will also be important—from a technical and national economic point of view—so that the newly built superstructures can be selected, considering the geometric properties, the possible load, and the future maintenance and operation tasks. Due to the economic problems of recent years, it would also be a specific goal that the estimated costs do not increase. To be able to achieve this, risk management must play a key role throughout the project's entire life. A country's economic and social development depends not only on expanding the transport infrastructure but also on its proper maintenance [66].

In the field of railway track life, the Graz University of Technology in Austria has significant research [67–70]. A research team led by Professor Peter Veit was involved in the research project Strategie Fahrweg from 1997 to 2003. Life cycle costs were calculated for railway lines and sections of railway tracks in different conditions, geometries, and loads, based on a survey of the entire ÖBB (Austrian State Railways) network [67–70]. It was shown that for substructures in good and medium to poor condition, the lifecycle costs could be in a ratio of 1:3 up to 1:9 (for substructures, one of the most critical parameters is the adequate drainage, the load capacity of the substructure, etc.). The result was that a railway siding with a radius of 500 m, roughly 42 m long, corresponds to a lifecycle cost of roughly 450 m running track. Traffic disruption costs (particularly for single track) and depreciation costs are the most significant for a railway track section, accounting for up to half or even two-thirds of the total cost. The curvature of the railway track is also a critical parameter. The lifetime cost of a small radius curve can be twice or even three times the lifetime cost of a straight section of track.

In this article, the authors investigated the geometrical change of seven "open" tramway tracks. The measurements were made, on average, every third month from July 2021. During the evaluation of measurements, relationships between traffic load, age, and track deterioration were examined. Section 2 deals with the "Materials and Methods", Section 3 presents the results, Section 4 presents the discussion, and Section 5 presents the conclusions.

2. Materials and Methods

2.1. Examined "Open" Superstructure Reference Sections

Four of the seven examined reference sections are ballasted track superstructures, and three are concrete slab tracks.

The ballasted track superstructure system is the most commonly applied in railway and tramway tracks. The lowest layer is ballasted bed on which the sleepers (made of reinforced concrete, wooden or synthetic material) rest. The fastening can be direct or indirect systems with screws or rail clamps, and the rail systems are usually grooved rails or flat-bottom rails (i.e., so-called Vignole rail profiles) [71].

In the case of the concrete slab track superstructure systems, the lowest layer is a reinforced concrete slab or reinforced concrete beam. Rails are stabilized by anchor bolts, bonded (direct), or spring rail fastening. The rail profiles are grooved rails or flat-bottom rails [71].

Section #1 is a 476-m-long ballasted track built in 1985 (Figure 1). The applied rail profiles are flat bottom rails called MÁV48, with a reinforced concrete sleeper, a GEO-type rail fastening system (so-called K-type rail fastening), and a ballast bed. There is one level crossing and one turnout in the section. The geometrical configuration (alignment) is mainly straight; there is a 50-m long (R = 240 m) right direction curve, a 28-m long (R = 108 m) left direction curve, a 70-m long (R = 250 m) left direction curve, and another 33-m long (R = 275 m) left direction curve. Each curve has no transition curve or superelevation. In the first 100 m of the selected section, the track has a 9.4‰ (i.e., per-mile) gradient; the rest has a 12.8‰ gradient.

Figure 1. Photo of Section #1 (own photo).

Section #2 is a 1715-m-long ballasted track built in 1987 (Figure 2). The applied rail profiles are MÁV48, with reinforced concrete sleepers, GEO-type rail fastening systems, and a ballast bed. There are two level crossings and no turnout in the section. The geometrical configuration (alignment) is variable, mainly straight; however, there is a 64-m long (R = 502 m) right direction curve, a 212-m long (R = 605 m) right direction curve, a 225-m long (R = 502 m) left direction curve and another 145-m long (R = 309 m) left direction curve. Each curve has no transition curve or superelevation. In the selected section, the track has a 4.9‰ elevation on average.

Section #3 is a 1090-m-long ballasted track built in 2002 (Figure 3). The applied rail profiles are 49E1, with reinforced concrete sleepers, (Vossloh) SKL-type rail fastening systems, and a ballast bed. There are five level crossings and no turnout in the section. The geometrical configuration (alignment) is mainly straight; there is a 14-m long (R = 278 m) left direction curve and another 34-m long (R = 250 m) right direction curve. Both curves have no transition curve or superelevation. In the first half of the selected section, the track has a 4.4‰ gradient; in the second half: a 2.4‰ and a 3.6‰ elevation.

Section #4 is a 496-m-long ballasted track built in 2018 (Figure 4). The applied rail profiles are flat bottom rails called MAV48, with reinforced concrete sleepers, (Vossloh) SKL type rail fastening systems, and a ballast bed. There is no level crossing and no turnout in the section. The geometrical configuration (alignment) is also mainly straight; there is a 123-m long (R = 302 m) right direction curve, a 58-m long (R = 1050 m) right direction curve, and another 63-m long (R = 1150 m) left direction curve. The first curve has a transition curve, but the other one has not got it or superelevation. The downgrade of the track is 3.9‰ alongside; the line layout is primarily straight.

Figure 2. Photo of Section #2 (own photo).

Figure 3. Photo of Section #3 (own photo).

Figure 4. Photo of Section #4 (own photo).

Section #5 is a 660-m-long concrete slab track built in 1986 (Figure 5). The applied rail profiles are 54E1, and they are stabilized by METRO III. type rail fastening [72] on a reinforced concrete slab (Figure 6). There is no level crossing and no turnout in the section. The geometrical configuration (alignment) is straight; there is an R = 1150 m left direction curve at the end of the section. The curve has a transition curve, and the superelevation is m = 65 mm. The gradient profile of the selected section is very variable: in the first 80 m, the track has an 8.4‰ elevation; the next 280-m long section has an 8.9‰ gradient, then there is a 110-m long 2.2‰ gradient, a 130-m long 8.0‰ gradient, and finally, a 60-m long 3.5‰ gradient.

Figure 5. Photo of Section #5 (own photo).

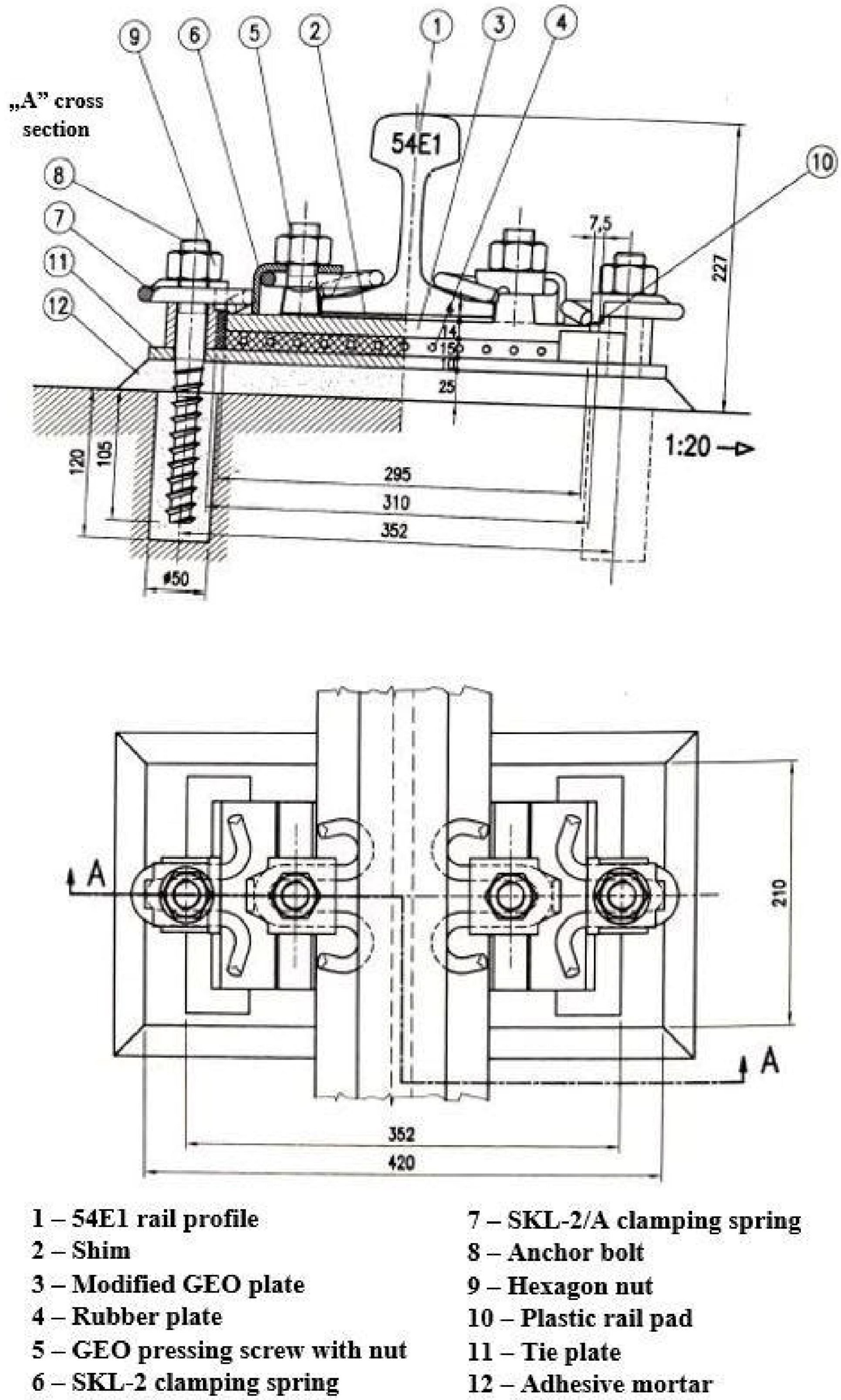

Figure 6. METRO III. type rail fastening (on the basis of [72]).

Section #6 is a 370-m-long concrete slab track built in 2001 (Figure 7). The applied rail profiles are flat- bottom rails called MAV48, stabilized by GEO, and an embedded-type rail- fastening system on a reinforced concrete slab. There is no level crossing and no turnout in the section. The geometrical configuration (alignment) is mainly straight; there is a 91-m long (R = 240 m) right direction curve with a transition curve and a 116-m long (R = 1125 m) right direction curve, which has no transition curve. Both curves have not got superelevation. According to the measurement direction, the track has a 33.5‰ gradient; after the lowest point, the elevation is 39.3‰.

Figure 7. Photo of Section #6 (own photo).

Section #7 is a 450-m-long concrete slab track built in 2010 (Figure 8). The applied rail profiles are 49E1, stabilized by GEO and embedded- type rail- fastening system on a reinforced concrete slab. There is no level crossing and no turnout in the section. The geometrical configuration (alignment) is variable; alternately, straight sections and curves exist. The curves are regularly short and have a high radius. Each curve has not got a transition curve or superelevation. The section is a tunnel, the track has an average 20.9‰ gradient, and after the lowest point, the elevation is 27.6 ‰.

Figure 8. Photo of Section #7 (own photo).

2.2. Traffic Load and Age

In Hungary, several aspects are known to classify a tramway line in the capital city. The most often used characterization depends on the annual through-rolled tonnages. The through-rolled axle tonnage is the mass of all crossing vehicles on a given line in one direction in one year. It is determined by multiplying the total number of crossing vehicles on the line and the average of the T0 loading (serviceable vehicle without crew and passenger) and T3 loading (serviceable vehicle with staff and maximum passenger capacity) [71–75]. Based on these, four traffic load classes can be differentiated (Table 1).

Table 1. Traffic load classes in the case of Budapest's tramway lines [71].

Traffic Load Class	MGT [1]/Year/Direction
I./A. extremely heavy loaded line	>7.5
I./B. heavily loaded line	5.0 . . . 7.5
II. medium loaded line	2.5 . . . 5.0
III. low loaded line	<2.5

[1] The abbreviation MGT means million gross tons, i.e., the annual through-rolled tonnages.

In addition to the traffic load, the other important parameter that must be considered. It is the reference sections' age. Unfortunately, it is impossible to know the exact age of each section by day, but they are known precisely by year. Therefore, in this article, the ages are relative to 2023. Table 2 shows the age and the average traffic load of the examined reference sections between 2017 and 2021.

Table 2. Characteristics of examined reference sections.

ID. of Reference Sections	Type of Superstructure System	Average Traffic Load [MGT/Year]	Age [Year]
Section #1	Ballasted track	1.92	38
Section #2	Ballasted track	1.24	36
Section #3	Ballasted track	3.91	21
Section #4	Ballasted track	6.49	5
Section #5	Concrete slab track	4.55	37
Section #6	Concrete slab track	6.70	22
Section #7	Concrete slab track	4.30	13

2.3. Geometrical Measurements and Examined Parameters

The geometrical measurements are executed on average every third month at a night standstill. The TrackScan 4.01 instrument is applied to measure the geometrical characteristics of tramway tracks (Figure 9).

This instrument has been developed by the Hungarian company called Metalelektro Méréstechnika Ltd. [73–75]. This instrument is a complex track-measuring device that records the parameters every 25 centimeters and is suitable for continuous measurement of railway and tramway tracks. It can measure and record the following characteristics at the same time [73–75]:

- track gauge [mm];
- flange gauge [mm] (the distance between the guiding surface of the rail on one side and the back of the structure that ensures the guidance of the wheel on the other side, interpreted as the height of the track gauge);
- superelevation [mm];
- alignment [mm] (i.e., lateral track irregularity);
- longitudinal level [mm] (i.e., vertical track irregularity);
- length of the railway section [in meters to the nearest mm];
- twist [mm].

Based on the measured and recorded characteristics, the examined parameters of tracks are the following:

- track gauge: 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 the case of a curved track [71,73,75];
- alignment: shows the horizontal deviations of rails, its base length is 1350 millimeters, and it is symmetrical [71,73,75];
- longitudinal level: shows the vertical deviations of rails from the ideal, the base length of measurement is 1510 millimeters, and it also uses a symmetrical basis [71,73,75].

The average value of geometric characteristics was investigated during the statistical examination of the measured data.

Figure 9. TrackScan 4.01 instrument (own photo).

3. Results

In this Section, the results of the geometric analysis of each reference section are presented separately. In the end, they are summed up, considering the traffic load and the sections' ages.

3.1. Section #1

Figure 10 illustrates that the average values of the measurement results change very minimally concerning each other; there is only one case when the difference between the values is more than 1 millimeter. It is important to note that the change in average values complies with the regulations of [71]. However, based on the trendline of the measurement data, there is a clear increase in track gauge data in the section, which means the broadening of the track gauge. Therefore, it can be assumed that the weather conditions also affect the results.

Examining the change of alignment and longitudinal level parameters is also vital. These values can have negative or positive signs, so the parameter values were examined in absolute terms to avoid errors. The TrackScan 4.01 instrument also measures these characteristics in the right and also left rail(s). In this article, the average of these values has been considered. Figure 11 shows that the trendline of the measurement data of longitudinal level—similar to the track gauge parameter—there is an evident increase. Even so, the trendline of the alignment parameter shows a minimal decrease.

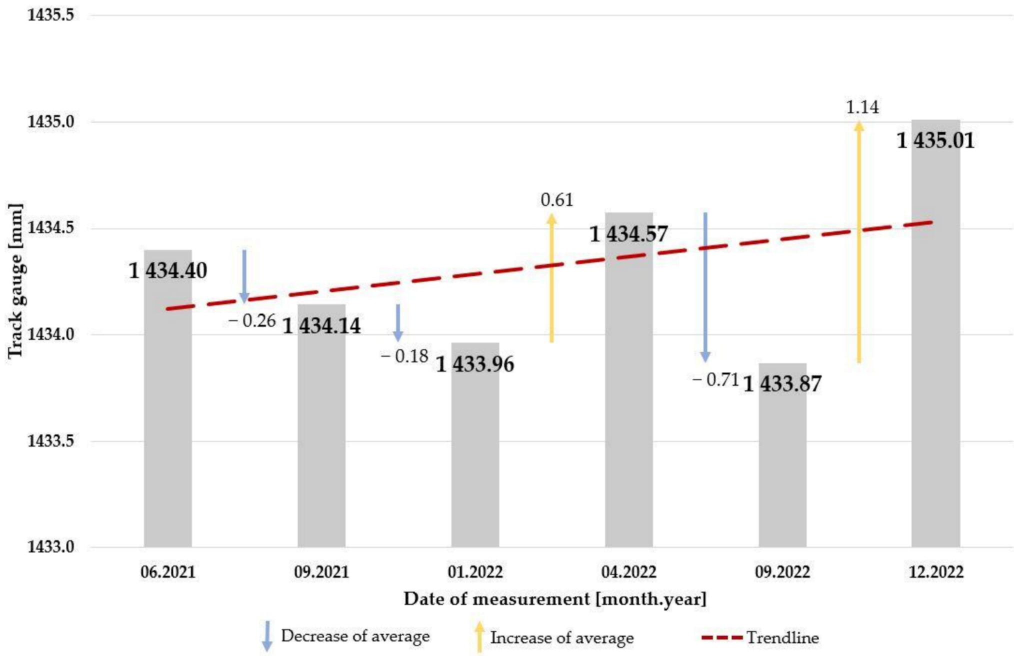

Figure 10. The change of average values of the track gauge in Section #1.

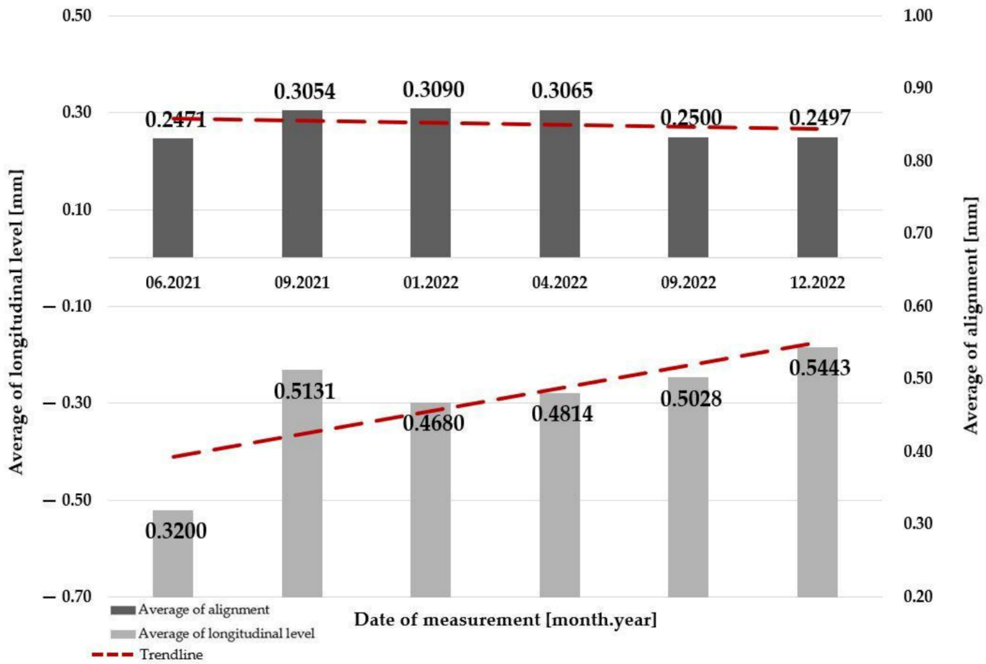

Figure 11. The change of average values of longitudinal level and alignment in Section #1.

3.2. Section #2

As described in Section 2.1., Section #2 is very similar to Section #1. There is only a two- year difference between their ages. Despite that fact, the change of track gauge parameter is the opposite. Figure 12 illustrates an evident decreasing trendline through the measurements, which means the narrowing of the track gauge.

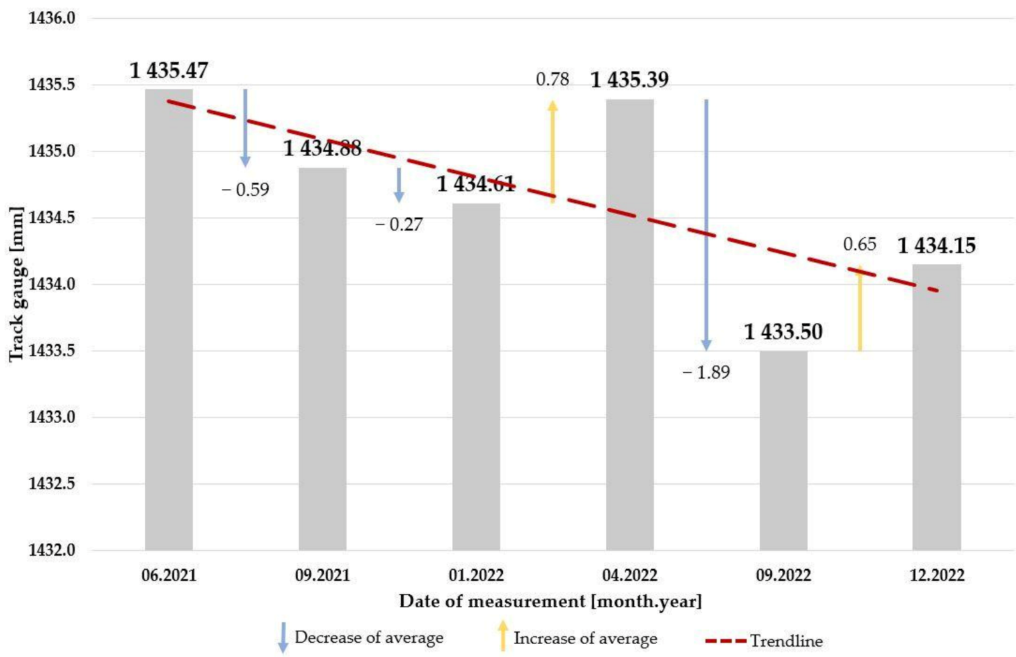

Figure 12. The change of average values of the track gauge in Section #2.

Based on the results mentioned above, it was expected that opposite trendlines are formed for the alignment and longitudinal level parameters. Nevertheless, Figure 13 shows similar trendlines, such as the track gauge parameter's trendline. However, in the case of the longitudinal level, there is a clear increase. Moreover, in the case of the alignment parameter, there is a minimal decrease.

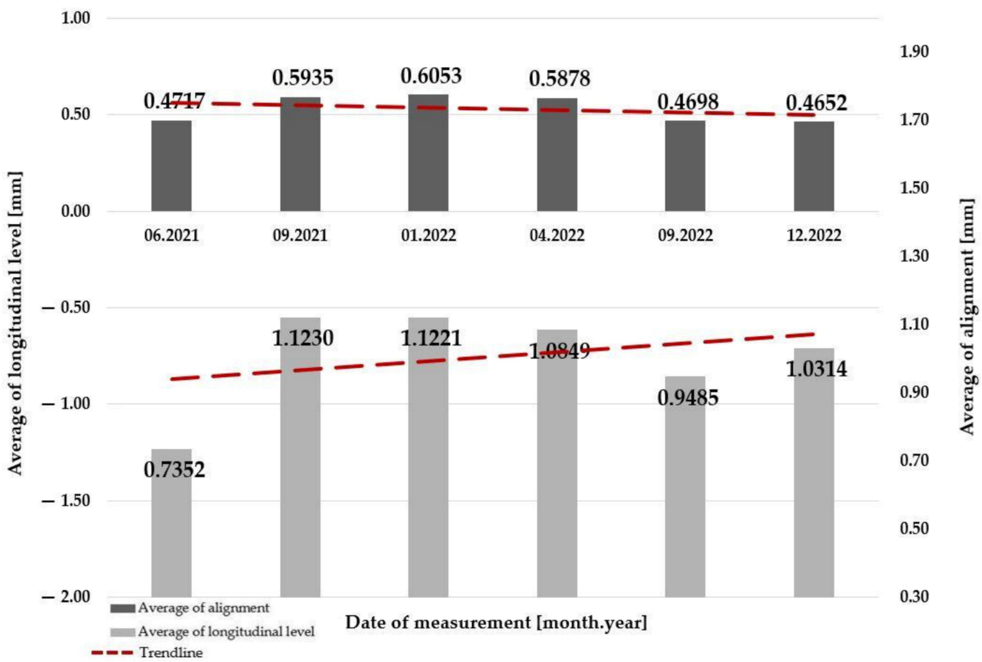

Figure 13. The change of average values of longitudinal level and alignment in Section #2.

3.3. Section #3

Section #3 is younger than the previous ones. In this case, the trendline of the track gauge parameter shows an unequivocal decrease, which means the narrowing of the track gauge (Figure 14). There are more cases when the difference between the values is more than 1 millimeter. The gradient of this trendline is smaller than the trendline of Section #2.

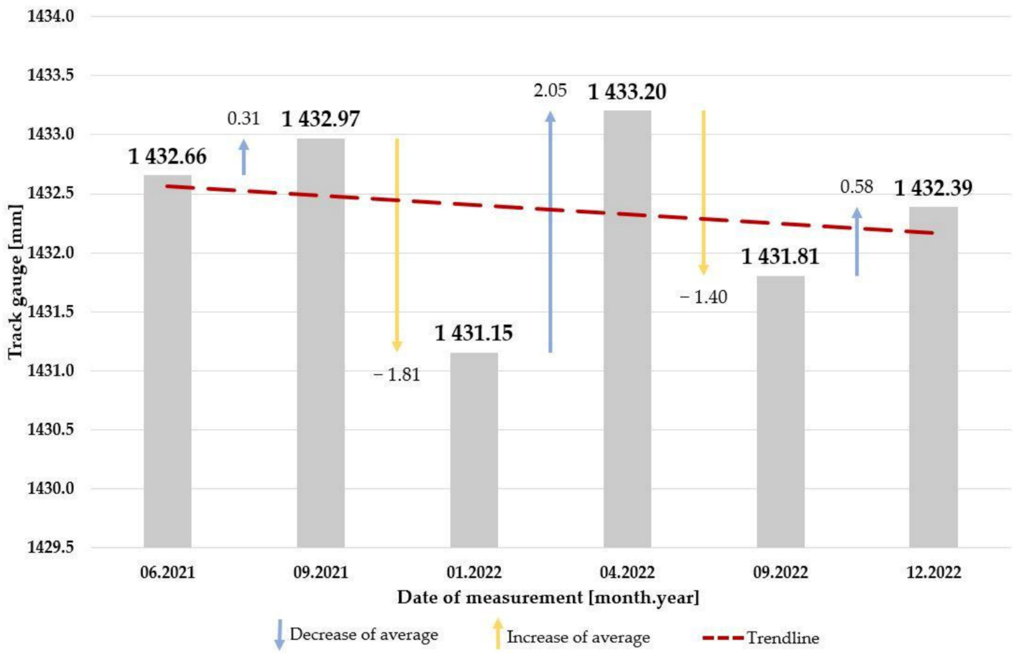

Figure 14. The change of average values of the track gauge in Section #3.

Figure 15 represents the examination of the change of alignment and longitudinal level parameters. The trendline of the longitudinal level—similar to Section #1 and Section #2—is evidently increasing. On the other hand, the trendline of the alignment parameter shows a decrease.

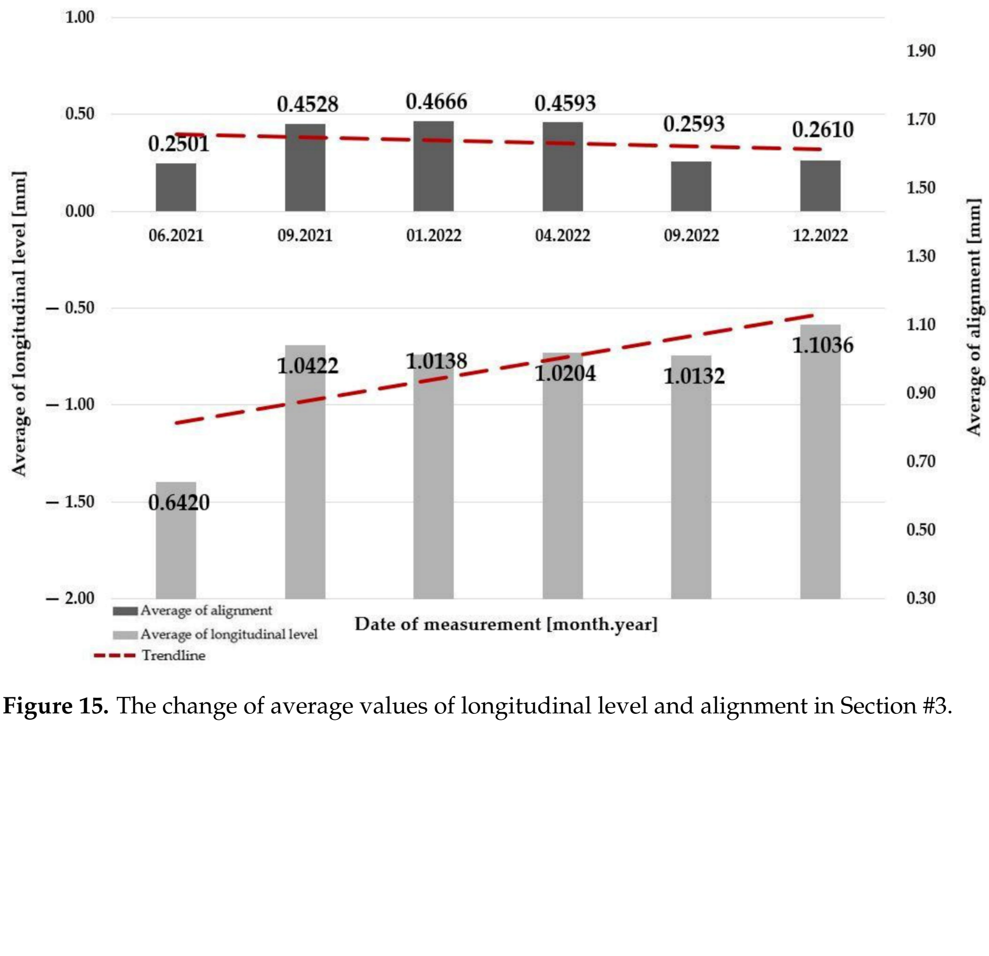

Figure 15. The change of average values of longitudinal level and alignment in Section #3.

3.4. Section #4

Section #4 is the youngest examined ballasted track section. The trendline of the track gauge parameter illustrates an evident but slight increase, which means the broadening of the track gauge. (Figure 16). In the case of the first four measurements, the difference between the values is 1 millimeter on average. The first and the second changes show a decreasing value, and the third and the fourth changes show an increasing value. The rise of this trendline is smaller than the trendline of Section #1.

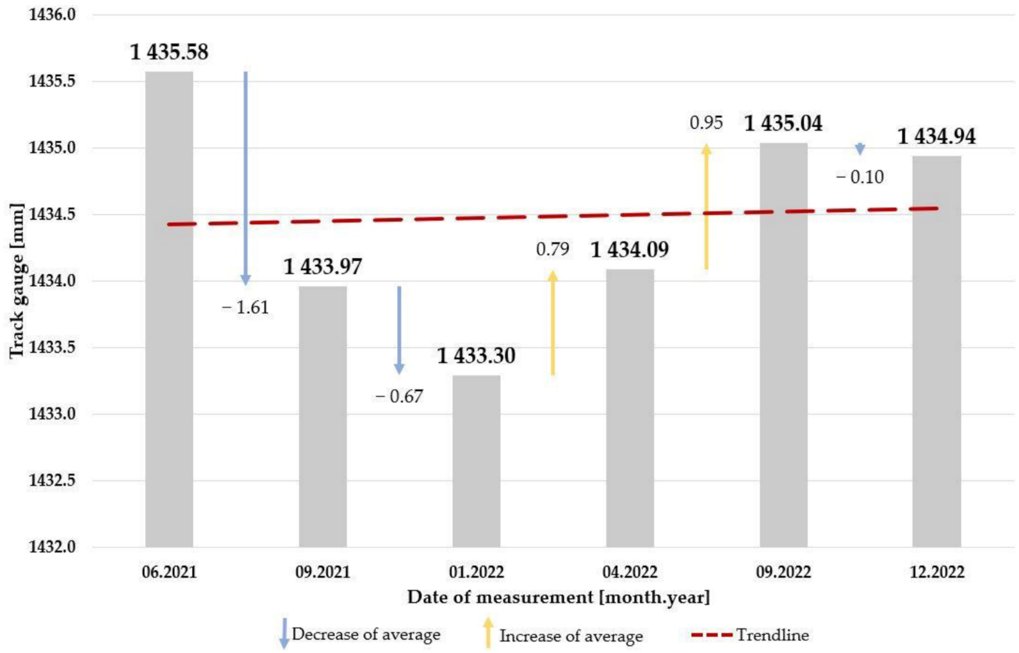

Figure 16. The change of average values of the track gauge in Section #4.

Similar to the previous ones, Figure 17 shows that the trendline of the longitudinal level is increasing, while the trendline of the alignment parameter shows a minimal decrease.

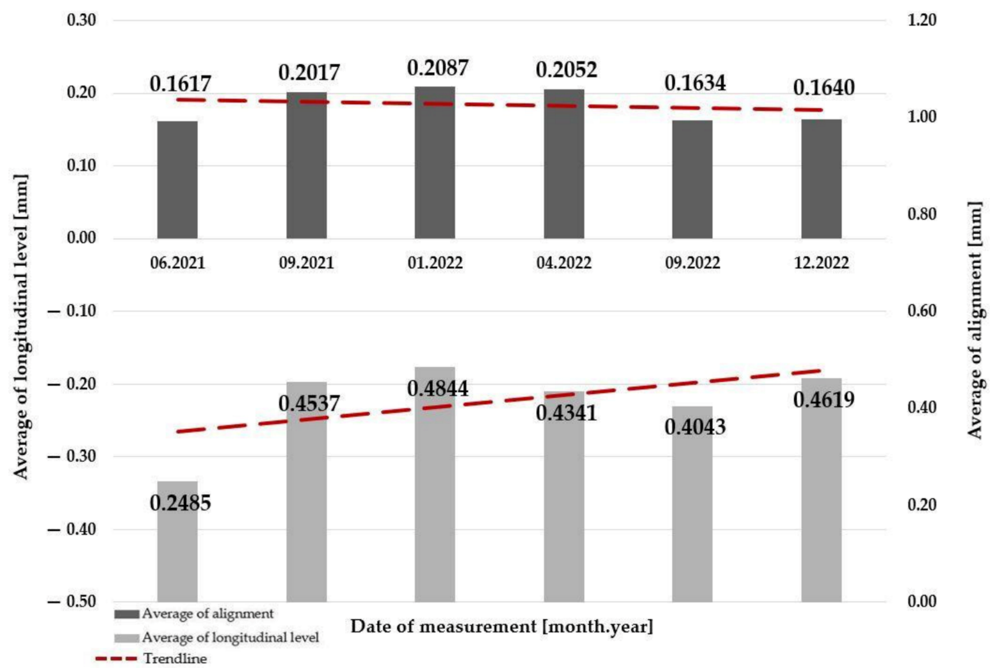

Figure 17. The change of average values of longitudinal level and alignment in Section #4.

3.5. Section #5

Figure 18 represents the average of track gauge parameters in the case of the oldest concrete slab track section in this research. It is crucial to notice the differences between the results of the last three measurements: the decreasing and the increasing values are almost the same.

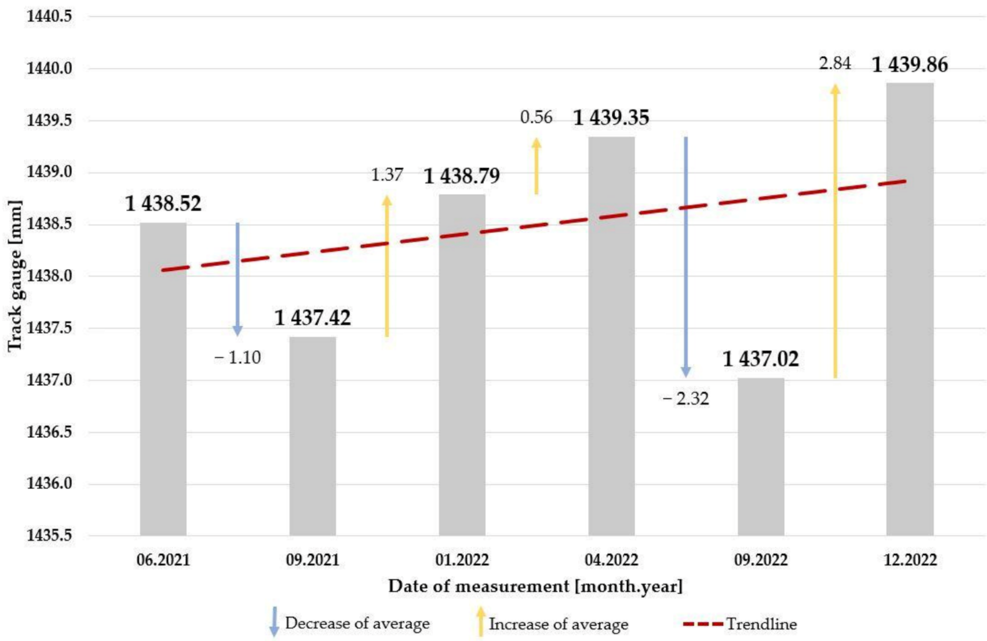

Figure 18. The change of average values of the track gauge in Section #5.

The trendline indicates a pronounced increase, which means the track gauge has been broadened, just as in Section #1.

Figure 19 shows the assessment of the change of alignment and longitudinal level parameters. The trendline of the longitudinal level—similar to the previous sections—is increasing. However, the trendline of the alignment parameter also shows a decrease.

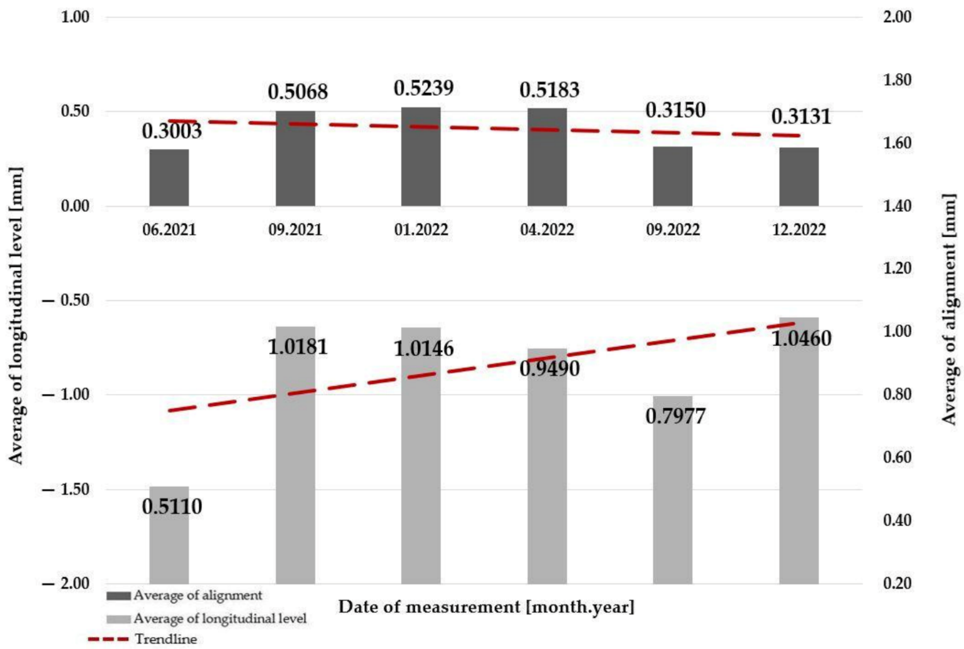

Figure 19. The change of average values of longitudinal level and alignment in Section #5.

3.6. Section #6

Figure 20 introduces the changing of the average of the track gauge parameter of Section #6. In this case, as in Section #5, the trendline of the track gauge parameter shows a noticeable increase, which means the broadening of the track gauge. There are more cases when the difference between the values is increasing. The gradient of this trendline is similar to the trendline of Section #5.

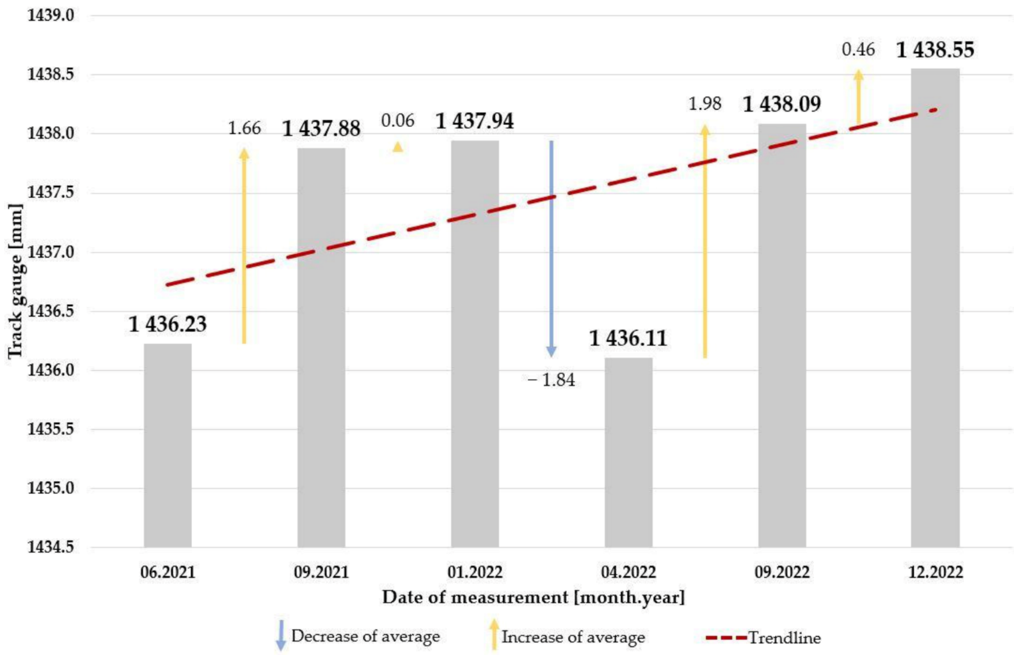

Figure 20. The change of average values of the track gauge in Section #6.

Like all the previous sections, Figure 21 represents that the trendline of the longitudinal level is increasing, while the trendline of the alignment parameter shows a minimal decrease.

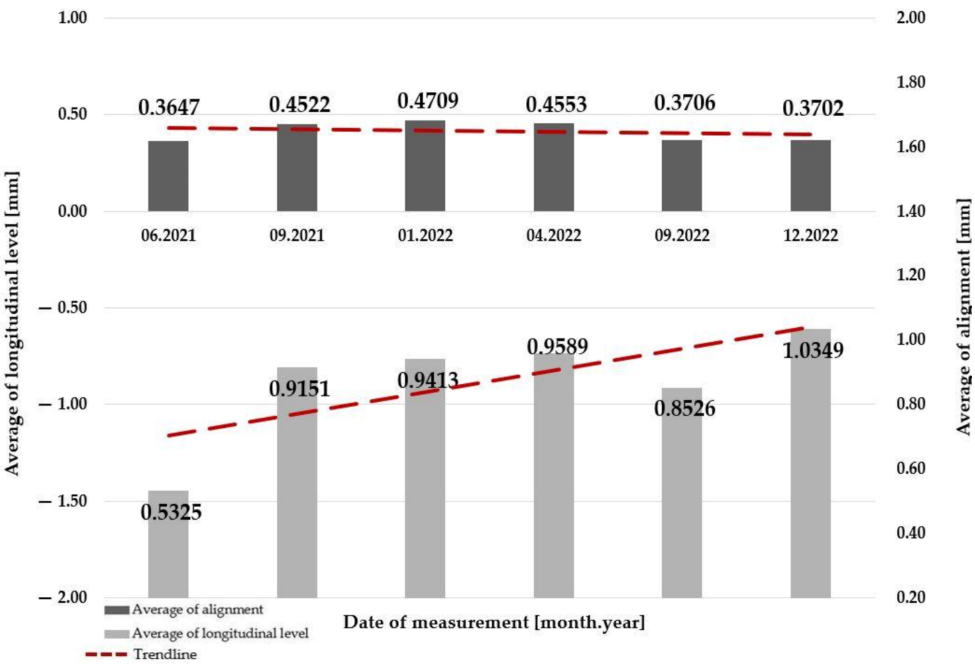

Figure 21. The change of average values of longitudinal level and alignment in Section #6.

3.7. Section #7

Figure 22 illustrates the average of the track gauge parameters in the case of the youngest concrete slab track section related to the present investigation. The differences between the results of the last two measurements are similar, but they are in contrast. The trendline shows an evident increase, which means the broadening of the track gauge, similar to the case of Section #5 and Section #6.

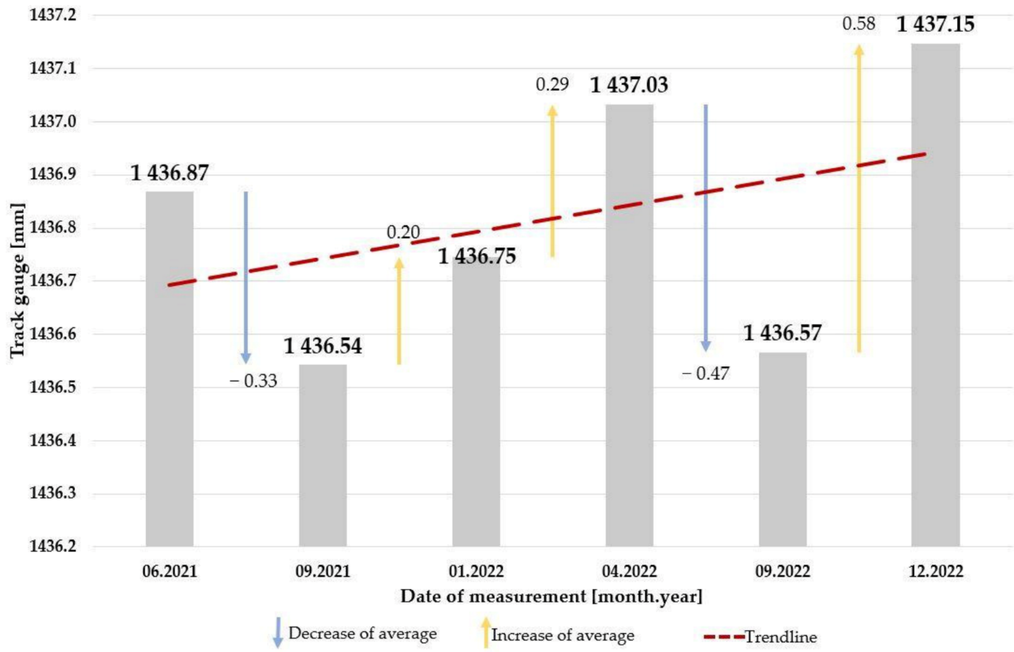

Figure 22. The change of average values of the track gauge in Section #7.

Based on the previous results, it was expected that the trendlines seem to be the same. Figure 23 shows that the trendline of the longitudinal level is increasing, and the trendline of the alignment parameter is decreasing minimally.

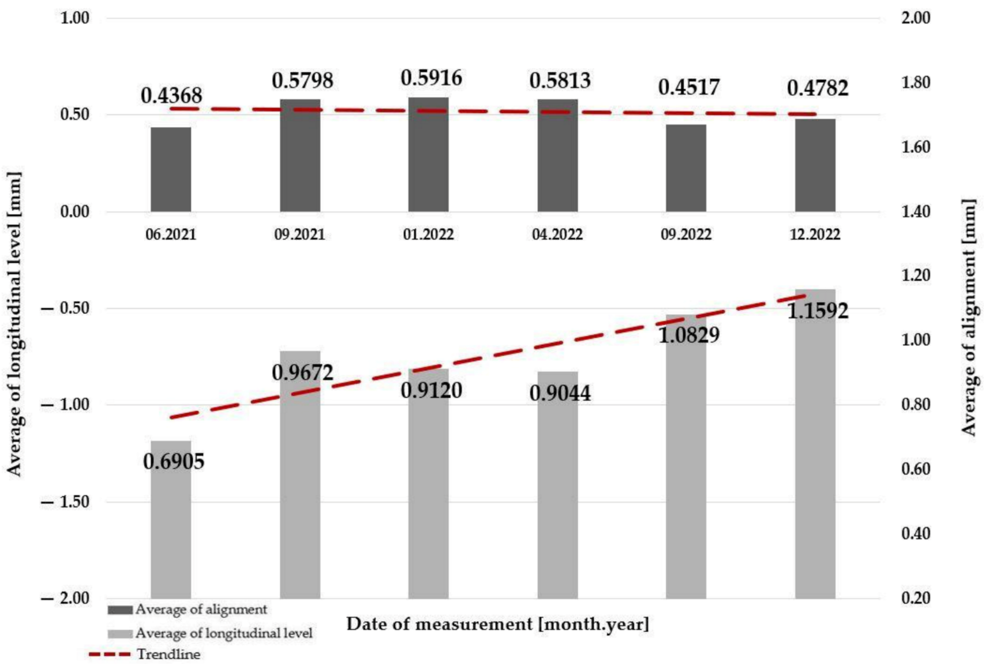

Figure 23. The change of average values of longitudinal level and alignment in Section #7.

4. Discussion

In this Section, the results of the geometric analysis of each reference section are discussed based on each superstructure system.

4.1. Results of Ballasted Track Systems

Figure 24 represents the relationship between trendlines of track gauge changes in the case of examined ballasted track systems and average traffic load values.

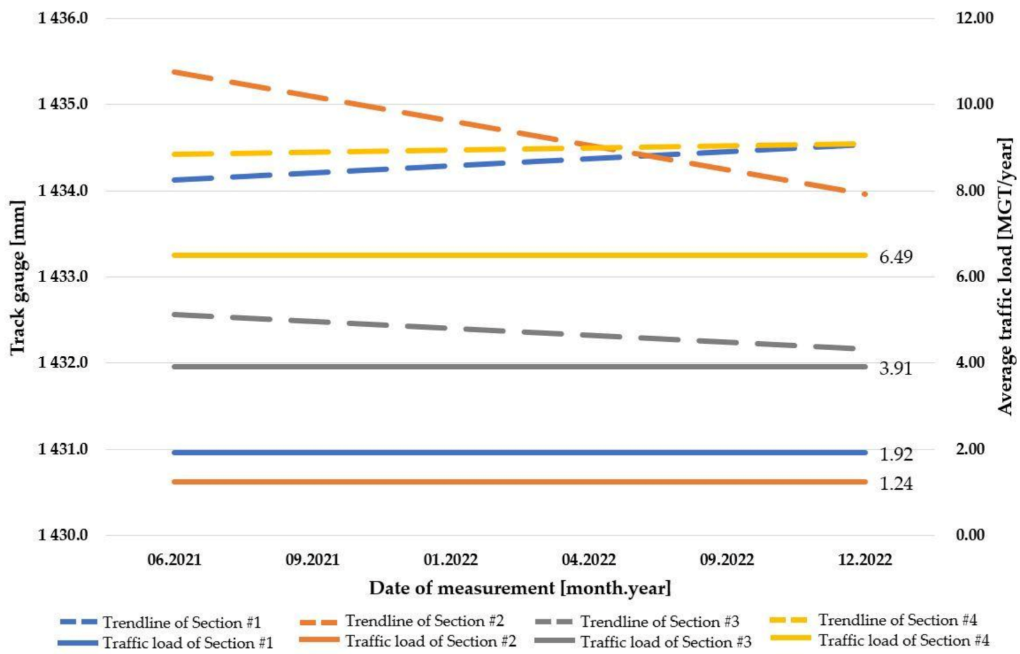

Figure 24. The relationship between track gauge and traffic load in ballasted track systems.

Section #1 and Section #2 are almost the same age and have almost the same average traffic load; despite that fact, their trendlines are opposite. The grade of the trendline in the case of Section #2 is steeper than in the case of Section #1. Section #3 was built 15 years later than Section #2, and its load is three times greater than Section #2's traffic load. Even so, the grade of their trendlines is very similar. Section #4 is the most recent ballasted track, and it has more than three times greater traffic load than Section #1. Despite that, their trendlines are almost the same.

Figure 25 shows the relationship between trendlines of alignment changes in the case of the examined ballasted track systems and average traffic load values.

Regardless of the traffic load level, in each section, the trendlines are decreasing. Section #1 is the oldest ballasted track, and the grade of its trendline is similar to Section #4, which is the newer section. The grade of the trendline of Section #2 is steep, similar to the trendline of Section #3.

Figure 26 shows the relationship between trendlines of the longitudinal level changes in the case of examined ballasted track systems and average traffic load values.

Similar to the results of the alignment parameter, regardless of the level of traffic load, in the case of each section, the trendlines are increasing. Section #1 is the oldest considered and analyzed ballasted track section, and the grade of its trendline is similar to Section #4, which is the considered most younger section. There is also a significant difference between their traffic load values.

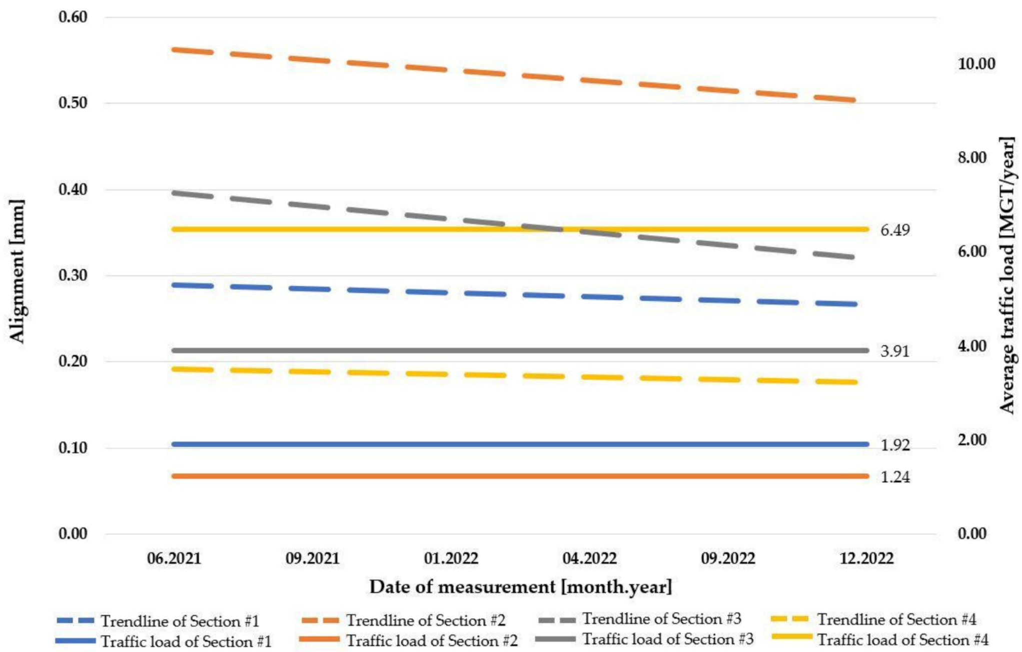

Figure 25. The relationship between alignment and traffic load in ballasted track systems.

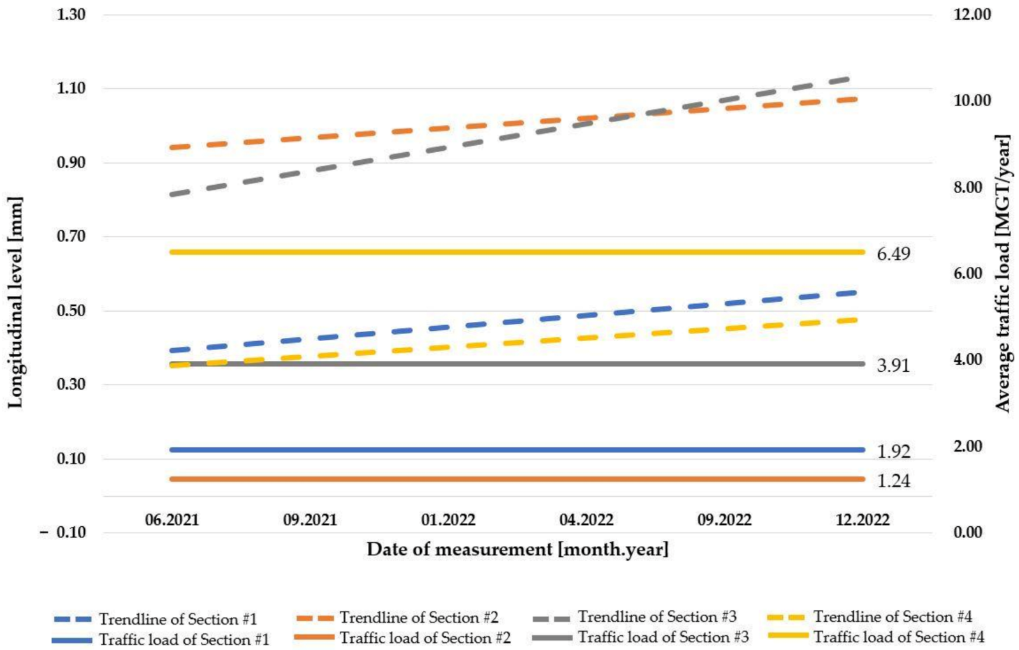

Figure 26. The relationship between longitudinal level and traffic load in ballasted track systems.

The grade of the trendline of Section #3 is steep, similar to the trendline of Section #2.

The results of the examination of the longitudinal level parameter are similar to the results of the alignment parameter but the opposite.

Based on the results, the following statements can be determined about the ballasted tracks:

- when a ballasted track section is at least 1.5-times older but has a lower traffic load, the narrowing of the track gauge is similar to the case when the ballasted track is newer but has a greater traffic load: the deterioration is comparable;
- when a ballasted track section is at least seven times older and has at least a traffic load at least three times higher than another ballasted track, the broadening of the track gauge is similar: the deterioration is comparable;

- regardless of the level of traffic load, the average value of alignment is decreasing;
- when a ballasted track is at least seven times older and has a traffic load at least three times higher than another ballasted track, they have a similar average value of decreasing alignment;
- regardless of the level of traffic load, the average value of the longitudinal level is increasing.

4.2. Results of Concrete Slab Track Systems

Figure 27 illustrates the relationship between trendlines of track gauge changes in the case of examined concrete slab track systems and average traffic load values.

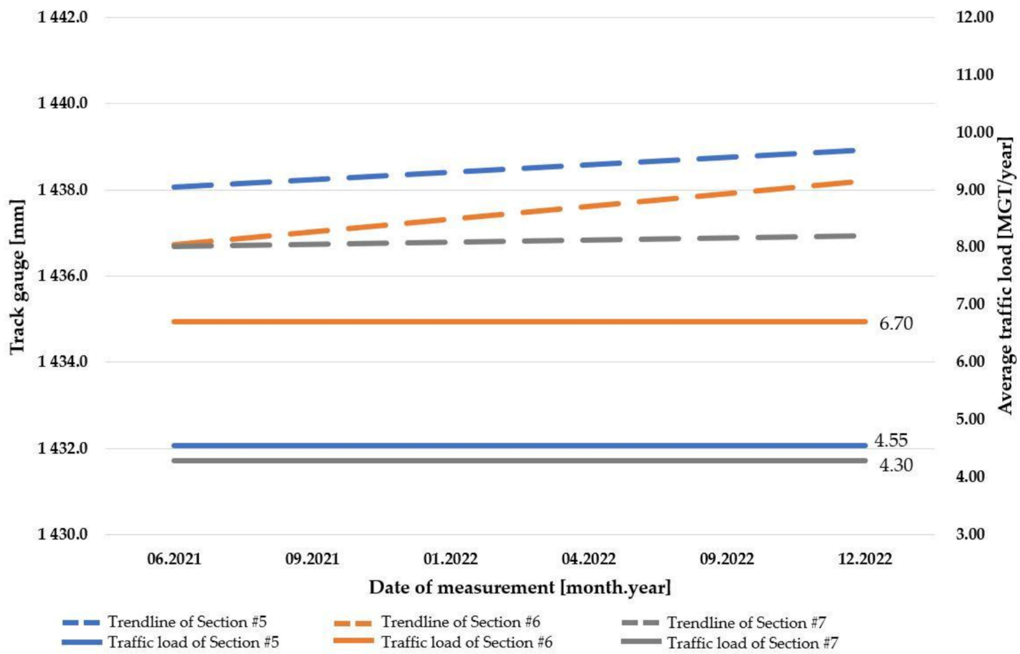

Figure 27. The relationship between track gauge and traffic load in concrete slab track systems.

According to the results, in the case of each examined track section, the trendlines are increasing. Section #6 is much steeper than Section #5 or Section #7. This fact can be explained by Section #6's higher traffic load.

Section #7 was built 24 years later than Section #5, and its load is almost the same; moreover, the grade of their trendlines is also very similar.

Figure 28 shows the relationship between trendlines of the alignment changes in the case of examined concrete slab track systems and average traffic load values.

Regardless of the traffic load level, in each section, the trendlines are decreasing. Section #5 is the oldest concrete slab track section, and its trendline grade is similar to Section #7, which is the newer section.

Figure 29 shows the relationship between trendlines of longitudinal level changes in the case of examined concrete slab track systems and average traffic load values.

Similar to the results of the alignment parameter, regardless of the level of traffic load, in the case of each section, the trendlines are increasing. Section #5 is the oldest ballasted track section, and its trendline grade is not as steep as Section #6 or Section #7.

The results of the examination of the longitudinal level parameter are similar to the results of the alignment parameter but the opposite.

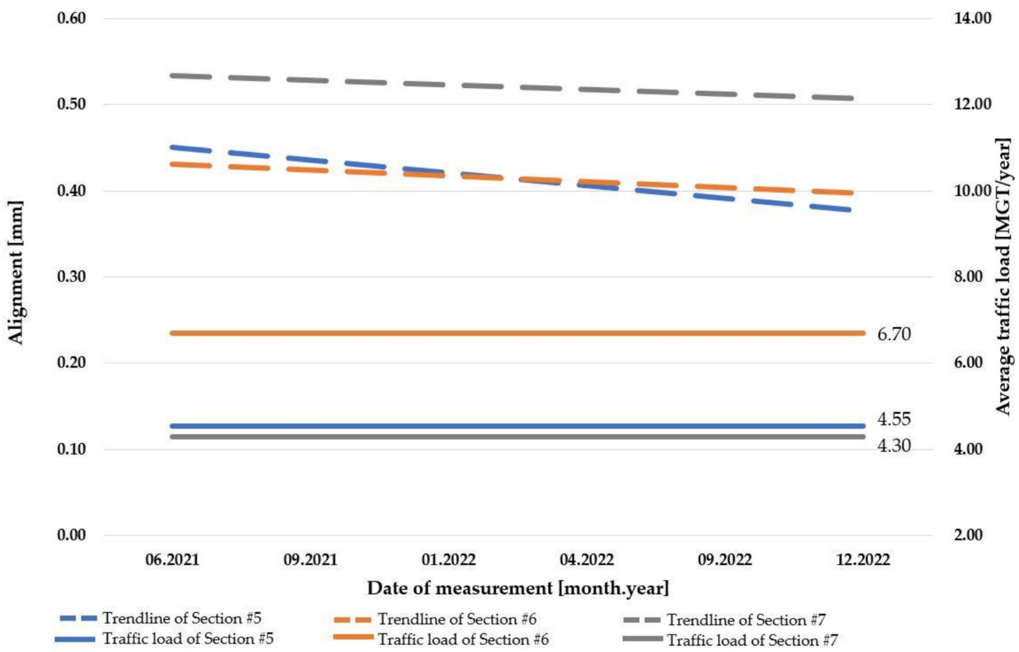

Figure 28. The relationship between alignment and traffic load in concrete slab track systems.

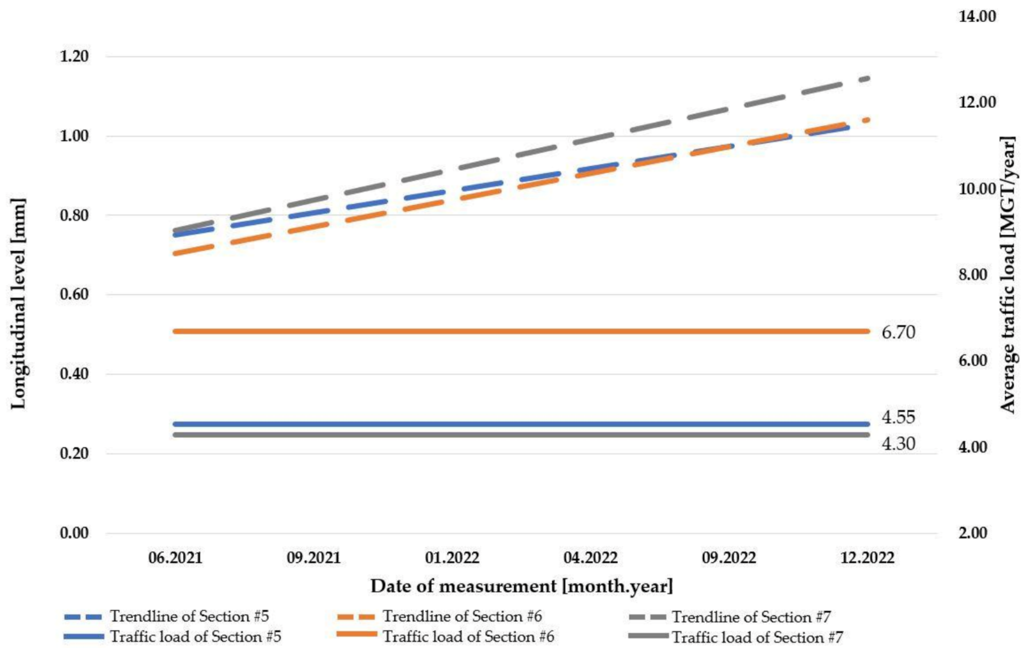

Figure 29. The relationship between longitudinal level and traffic load in concrete slab track systems.

Based on the results, the following statements can be determined about the concrete slab tracks:

- the deterioration of track gauge parameter in the case of concrete slab tracks is clearly described as the broadening of track gauge;
- the more significant the load of the examined concrete slab track section, the steeper the grade of the trendline of the track gauge parameter;
- regardless of the level of traffic load, the average value of alignment is decreasing;
- regardless of the level of traffic load, the average value of the longitudinal level is increasing.

5. Conclusions

Nowadays, when the prices of materials and energy are increasing significantly, the individual urban transport infrastructure elements must be properly planned and maintained.

In the case of tramway tracks in Budapest, the capital of Hungary, there are seven superstructure systems, which can be divided into two large groups: "open" or "paved" tracks. "Paved" superstructure systems, when the pavement zone of the track axis and the pavement zone of the permanent way axis, furthermore, the connected part to the public road and verge are paved. All other superstructure systems, such as ballasted track and concrete slab track are "open" superstructures. As described in the Introduction, unfortunately, the geometrical deterioration, lifecycle, and lifecycle cost of the tramway tracks are not accurately known; their selection and application are currently mainly based on experience. Therefore, this procedure is not the most suitable from an economic and technical point of view.

In this article, the authors investigated the geometrical change of seven "open" tramway tracks. The measurements have been made on average every third month since July 2021 with TrackScan 4.01 instrument. Of the measured and recorded characteristics, the examined parameters of tracks were the track gauge, alignment, and longitudinal level.

Based on the results, the following statements can be determined about the "open" tracks:

- regardless of the "open" superstructure system or the level of traffic load, the average value of alignment is decreasing;
- regardless of the "open" superstructure system level of traffic load, the average value of the longitudinal level is increasing;
- when a ballasted track section is older but has a lower traffic load, the narrowing of the track gauge is similar to the case when the ballasted track is newer but has a greater traffic load;
- when a ballasted track section is much older and has a greater traffic load than another ballasted track, the broadening of the track gauge is similar;
- the deterioration of track gauge parameter in the case of concrete slab tracks is clearly described as the broadening of track gauge;
- the more significant the load of the examined concrete slab track section, the steeper the grade of the trendline of the track gauge parameter.

In the future, the authors aim to examine the presented sections and analyze the changes. The most important thing is to investigate whether the measured and evaluated results show or do not show significant deviations from the current trend lines. It is also advisable to evaluate the measurement results of "paved" tracks and observe whether there is a similarity between the behavior of "open" tracks and the behavior of "paved" tracks.

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