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Investigation of the Track Gauge in Curved Sections, Considering Hungarian Railway Lines

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Abstract: In this paper, the authors examined the change in track gauges in curves for several railway lines with low and high traffic in Hungary (i.e., secondary lines and main lines). They covered the processing of raw data as well as statistical calculations. The considered curved sections were transition curves (TCs) and circular curves (CCs), as well as—in some cases—entire curves (ECs), including TCs and CCs, but not dividing them into parts. The change of track gauge parameter as a function of elapsed time was analyzed based on the distribution functions by calculating the Vaszary-type shape number. A statistical test with the Kolmogorov–Smirnov test was performed, in which the question as to whether the measurement data of the railway lines followed a normal or lognormal distribution was examined; additionally, the skewness and kurtosis parameters were calculated and analyzed. The authors also took into account the impact of the track system and the sleepers. For the selected curves, the authors observed how the average track gauge changes and categorized them according to tolerances. In presenting and summarizing the tests, the authors formulated a conclusion for each study fulfilled. Despite higher traffic loads, the value of track degradation over time is lower for mainline curves than for secondary line curves. It is because the main line has stricter tolerances due to the higher speeds allowed, and more maintenance work is carried out on these lines. The authors concluded that the type of the track system and the sleeper type also influence the change in track gauges in curves. The accurate deterioration ratios for all analyses are contained in the paper.

Keywords: railway track; track gauge; statistical analysis; time-series analysis; distribution; circular curve (CC); transition curve (TC); entire curve (EC)

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1. Introduction

The authors need to explain the Introduction's unusual structure. The authors prepared a three-part Introduction. Section 1.1 provides preliminary thoughts on transportation as well as fixed-rail transportation in a more detailed manner. Section 1.2 discusses an international literature review on track gauge parameter. Finally, Section 1.3 discussed this study's novelty, essence, and structure.

1.1. General Introduction

Transport can be divided into three broad areas: land, water, and air transport [1–3]. In this division, air transport should be added to space transport. People have been traveling since ancient times, covering short and long distances. In the case of transport on foot and/or on horseback (or the back of any animal), the first major development was in water transport about 9000 years ago, when the first boat is thought to have appeared, and the first major step in land transport was the invention of the wheel (about 7500 years ago). The next huge step was the industrial revolution in the 18th and 19th centuries with the steam engine and steam-powered vehicles (the names of James Watt, Richard

Trevitchik, Robert Fulton, etc., are worth mentioning), followed by the invention and use of the electric motor and internal combustion engine in vehicles (as a driving mechanism) in the 1700s and 1800s. The next major milestone in air transport occurred in the early 1900s with the invention of the airplane (the Wright brothers). In parallel, land transport, dating back to antiquity, required the construction of suitable roads; in the case of shipping, harbors and docks were required [4–8]. Finally, the construction of railways and airports also became necessary because of modern inventions [1–3,9,10].

In parallel with transport, transport and logistics also became, and still are, of paramount importance [11–13].

This paper is about railway track gauges. As an introduction to the topic and as a prelude to the topicality of the subject, it is helpful to present the development of fixed-rail transportation because it is essential to mention the path that had to be traveled to reach the present state. Initially, in the mining industry, fixed-rail tracks were applied for the track of wagons that could be pushed or hauled onto and from the ground. The big step forward was the steam locomotive, designed and perfected by George Stephenson after "horse-drawn locomotives". The first steam railway was operated between Stockton and Darlington, opening in 1825. After the advent of the steam locomotive, rail transport developed considerably.

The first Hungarian public railway line (with steam hauling) was constructed and announced in 1846, which was the Budapest-Vác railway line with a 33 km length [3]. Seeing the development of the railways, states also became involved in railway development. State-owned railways appeared in 1867. Nevertheless, the financial difficulties of private companies led to more and more railways being nationalized. The Royal Hungarian State Railways ("Magyar Királyi Államvasutak", in Hungarian) took over the railways of private companies [3].

For the "official" first steam locomotive (the Rocket), George Stephenson used a track gauge of ~1422 mm (i.e., 4 feet 8 inches), and later widened it by ~13 mm. It was performed to favor the lateral forces on the wheel flanges [3].

Archaeological excavations in Pompeii and elsewhere have revealed that this may have been the track gauge of Roman road vehicles. At that time, everything was measured against something. The 1435 mm dimension allowed two people to sit comfortably on either side of a passageway [3].

Thus, the gauge value has been covering the nominal track gauge (or, in other words, the so-called standard track gauge) of 1435 mm for decades.

Measured in a cross-section, the track gauge is the smallest distance between points P_1 and P_2, and parallel with the top tangent of the rail heads. The considered Z_P distance is below the top tangent of the rail heads (see Figure 1). The value of Z_P in the harmonized European Standard (EN 13848-1 [14]) is 14 mm. (In the case of grooved rails, Z_P is 9 or 10 mm).

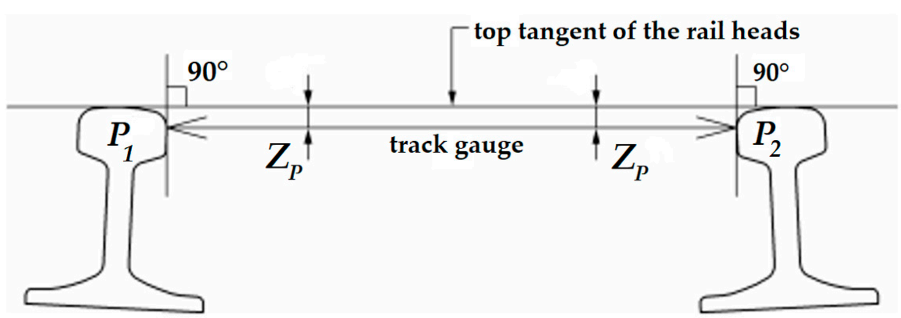

Figure 1. The measurement principle of the railway gauge parameter (drawn based on EN 13848-1 [14]).

1.2. Literature Review

For this article, an international literature review was carried out on the subject of railway track gauges, which of course, could not be exhaustive due to space constraints; in any case, an attempt was made to summarize the most relevant and most cited literature and its main findings, which are presented in the following paragraphs. The authors collected the paper categorized them into main topics: (i) measurement possibilities of track gauge(s) (it has to be mentioned that only the non-commercial and non-standardized methods are overviewed and detailed here, in the Introduction; the standardized methods have been dealt in Section 2.3); (ii) deterioration of track gauge in different fixed-rail applications (tramways, railways, etc.); (iii) special areas and special results related to track gauges.

In the following paragraphs, the authors represent the above (i) group, i.e., measurement possibilities of track gauge.

Zheng et al. [15] have developed a portable mobile trolley method for measuring track gauge and rail wear on railway tracks. The essence and details of the method are that a so-called laser vision inspection model and a system calibration method are used. The procedure requires the use of machine vision in three dimensions. It is also essential and necessary to ensure that the measured rail track (left and right track in the case of a double-track railway line) can be placed in a correct and accurate 3D world coordinate system after the measurements have been taken. Using the improved closest point algorithm, comparing the measured data point set and the standard rail point set results in calculating the rail width and wear rate. The compiled measurement system was tested, and it was found that the maximum measurement error of the method is less than 0.1 mm. Therefore, it satisfies the track maintenance requirements.

Pay et al. [16] have designed and manufactured an IoT-DTG (Internet-of-things-enhanced digital track gauge), a device for measuring track gauge and superelevation (in other words: cant, or cross-level). It offers a higher measurement capacity than the currently available manual track gauge measurement device, with the same or higher accuracy. The device consists of an Arduino microcontroller, a light and distance sensor, an angle sensor, a 12-button dial, an LCD, a red and a green LED, and a Wi-Fi module with ThingSpeak IoT cloud platform. The new device developed has resulted in 50% labor savings, a 60% increase in work efficiency, and annual cost savings of SGD 19,200 (Singapore dollars). Future improvements include the inclusion of a SIM card with 4G/5G mobile connectivity, the use of color and sound alerts for certain measurement conditions, and the use of software to filter out outliers.

Yilmazer et al. [17] have developed a drone-based method for measuring the track gauge using optical and image analysis. The drone must fly at a predetermined height, utterly independent of the vehicles on the line. Any vibrations can be filtered out during the image analysis. The tracks can be identified in the images using Gaussian filters and unique detection algorithms. It was performed using MATLAB programming. The measurement was calibrated and could accurately determine the measured gauge values from the camera images. Measurements were also taken under different lighting conditions, and 80–87% accuracy was achieved.

Zhang et al. [18] developed a relative track gauge measurement method based on the relative transverse motion of the wheel and rail. The method uses a combination of two laser sources and two cameras to dynamically collect images of the inner side of the rail head. Variable settings are required depending on the rail profile. Then, the track gauge is calculated from the lateral displacement of the wheel and the vertical displacement of the laser point on the rail head. The experimental results show the system's advantages in simple hardware design, small data computation, high measurement accuracy, and the ability to measure the gauge spacing value without contact.

Shi et al. [19] developed a tracking system based on the laser triangulation principle, which was mounted on a track detection trolley. They mounted two 2-D laser scanners to collect left- and right-track profile data. An iterative closest point (ICP) algorithm was used to calibrate the sensor data, and a so-called adaptive filter algorithm was used to smooth the contour. A least squares method was applied to the track gauge to fit the curve of the top of the rail head to improve positioning accuracy. The research has resulted that the proposed method improves the track gauge measurement adequately and efficiently, with an achievable accuracy of ±1 mm.

Tsubokawa and Ishikawa [20] have developed a measuring system for railway tracks that can be easily mounted on a motor car, registers loaded track conditions, and measures track gauge and twist. The device is a laser-based, non-contact measurement system that “scans” the rails in two dimensions at a given track cross-section. The maximum measuring speed is 40 km/h. The measurements were repeated several times on a motor car over a 400 m radius curve with a 30 mm superelevation. The rail fastenings were removed from four sleepers, and the variation in the track gauge parameter was measured. In addition to the previous one, a standard railway wagon was mounted to measure a 120 m site radius track section with 107 mm superelevation and 1067 mm gauge at speeds of 10–40 km/h with multiple repetitions. The measurements showed that the repeatability was 0.3 mm for the track gauge parameter and 1.0 mm for the 5 m base length twist parameter.

Tang et al. [21] developed a measurement instrument for grooved rail on tramway tracks using a 2D laser scanner solution. The method achieves a measurement accuracy of about +/–0.6 mm. The measurement principle is based on laser “triangulation”. Mathematical data filtering is first performed on the measured rail head profiles. The measuring range is between 1428 and 1470 mm. The rail head detection and gauge measurement have been tested under laboratory conditions.

In the following paragraphs, the authors represent the above (ii) and (iii) groups, i.e., the deterioration of track gauges in different fixed-rail applications (tramways, railways, etc.) and the special areas and special results related to track gauges.

Németh et al. [22] investigated how the track gauge varies with time on five low and five high-traffic Hungarian railway lines, considering only straight track sections. The analyses included calculating the through-rolled axle tons (i.e., the track loading, MGT—million gross tons). The measurement data were provided by the FMK-007 track geometry measuring car owned and operated by MÁV CRTI Ltd. (MÁV Central Rail and Track Inspection Ltd., Budapest, Hungary, where abbreviation MÁV means the Hungarian State Railways, Budapest, Hungary). Track geometry measurements of 25 cm were used in raw form. Mathematical statistical methods were applied to the data analysis including calculating mean, standard deviation, skewness, kurtosis, and Vaszary-type shape numbers of distribution functions. In addition, a spectral analysis of the ten railway lines studied was carried out. It was found that no significant correlation could be detected between the change of the track gauge, average and standard deviation values, elapsed time, and traffic loading (i.e., MGT). For the ten lines studied, it was demonstrated that the distribution functions for the gauge values were neither Gaussian nor lognormal. For lower track speeds, the distribution functions are flatter, while for higher speeds, they are steeper and have a narrower range.

Aharkov et al. [23] investigated the gauge stability of different rail track reinforcements considering the solutions used in the Ukrainian railway network, namely KB-75, KKP-1, and KPP-5. Measurements on the railway track compared each solution, and the measurements were analyzed by mathematical statistical methods. The measurements were made every 3 months and covered 3 years, thus covering 12 data sets for the research. The section of line selected for the study is a straight line only with a mixed traffic load (passenger and freight trains) of 60 million MGT per year.

Ahac and Lakusic [24] dealt with gauge degradation modeling in the field of maintenance planning for tramways. They developed a mechanistic-empirical degradation model, i.e., a mixed-combined method based on theoretical and practical principles. Their research was based on the tracks of the 1000 mm gauge tramway network in Zagreb, where the track gauge changes (mainly widening) were investigated. One of the leading causes of this is rail wear, which is significantly dependent on track geometry (horizontal curve radius), rail quality (rail hardness), and support stiffness. Their paper investigated Ri-60 "grooved rail" rail profiles and R200 and R260 rail grades for R ≥ 200 m and R < 200 m site radii. Two basic rail reinforcement schemes were considered as follows: tracked and direct rail reinforcement solutions. In this publication, a complete 4.5 km section of 25 segments of the Zagreb tramway, built and rehabilitated in the period 1997–2004, was analyzed. The homogeneous characteristics of the sections were track geometry (only straight sections were considered), traffic characteristics (only "open track" sections with separated track structure, no tram stops and level crossings, with an average constant speed of 15 km/h were considered) and the previously mentioned combinations of rail quality and rail reinforcement (18 sections were designed with R200 rail quality and indirect rail reinforcement and seven sections with direct rail reinforcement). Considering the results of the tests, it was concluded that the stiffness of the rail reinforcement in the initial degradation stage is negligible during the gauge degradation process up to 35 MGT traffic load. After 35 MGT, the degradation rate decreases significantly for indirect rail reinforcement systems, which develops from 45 MGT for direct rail reinforcements. Above 45 MGT, the model is not suitable for accurate prediction of gauge degradation, in which case additional measurements are required.

Akkermann and Akkermann [25] dealt with the rail gauge trajectory and the micro- and macro-profile of the tracks. In their paper, they proposed the creation of a digital clone to monitor track gauge parameters.

Falamarzi et al. [26] conducted research on track gauge deviation prediction for electrified tracks using artificial neural network (ANN) and support vector regression (SVM) methods. The coefficient of determination (R^2) and mean squared error (MSE) parameters were used to characterize the goodness of fit of each model. As a case study, the Melbourne light rail network was considered, which in this case was a 250 km long double-track section with 25 lines. Measurement data was collected in 2013 and 2014, and measurements were made using non-contact optical measuring instruments, taking into account a 10 m string length. The operator, Yarra Trams, provided the data. First of all, the measurement data had to be sorted and filtered, including removing outliers and noise through appropriate mathematical filters. In general, both methods (ANN and SVM) gave similarly promising results, but for straight track sections, the degradation model based on the ANN method gave a more accurate prediction, while for curved-track sections, the opposite was found to be true.

On the basis of the presented exhaustive literature review, it can be asserted that a significant number of international publications investigate the gauge parameter of the superstructure structure of fixed rail transport systems. Due to space constraints and a lack of direct logical connections, the current literature does not provide a thorough analysis of the historical evolution of track gauge parameters. The authors compiled the papers and grouped them into three main categories: (i) measurement possibilities of track gauge(s); (ii) deterioration of track gauge in various fixed-rail applications (tramways, railways, etc.); and (iii) special areas and special results related to track gauges. In group (i), the authors showed and detailed how there are a lot of up-to-date techniques and instruments for measuring fixed-rail systems' track geometry, including track gauge. This means both contact and non-contact devices, manual and mechanized, as well as automatic solutions (or their combinations). The main issue besides measurement methodology is data storage and data processing. There are manual, automatic, as well as modern, e.g., artificial intelligence solutions. In groups (ii) and (iii), the authors collected literature on the deterioration process of track gauge parameter on fixed-rail transport systems as well as special areas related to them. There are a lot of parameters that can influence the deterioration speed, e.g., the through-rolled axle ton values, the type of superstructure, the age of structural elements, etc. For example, entire tramway networks, or only big part of them, were considered during the analyses. Structural set-ups and superstructural solutions were investigated and the authors of these publications tried to derive general conclusions based on their research. Of course, it is not an easy task because each section can differ from the other(s), and it is very difficult and complicated to formulate fully general scientific statements on this subject.

1.3. The Novelty and Structural Set-up of the Current Paper

The novelty of this paper is the detailed analysis of ten railway tracks related to ten years of measurements in the past. The measurements contained more track geometry parameters simultaneously; however, only the track gauge parameter was considered. In this study, the curved sections were analyzed. The prior research was the paper [22]. Three of the authors of [22] conducted additional investigation. The considered railway lines were the same. The authors thought that after having analyzed the straight sections of the ten railway lines, the curved sections are also important and interested. To be able to do that, further filters and additional track geometry data were needed. With these details no one has published results on this topic, yet. The considered time interval is ten years, i.e., it can be stated that it is quite a long-term analysis. The applied methods are classic mathematical statistics methodologies; however, the special shape number is also taken into consideration.

The content and the structure of the paper can be summarized as follows: Section 2 deals with the "Materials and Methods". Section 3 is the "Results and Discussion". Section 4 details the "Conclusions".

2. Materials and Methods

In the following sections, certain terminology is applied as fikkiws: transition curve (TC), circular curve (CC), and the entire curve, which does not divide them into transition curves and circular curve parts (EC).

2.1. Short Introduction of the Investigated Railway Lines

Figure 2 introduces a map of the ten examined railway lines [22]; Table 1 summarizes their main base characteristics.

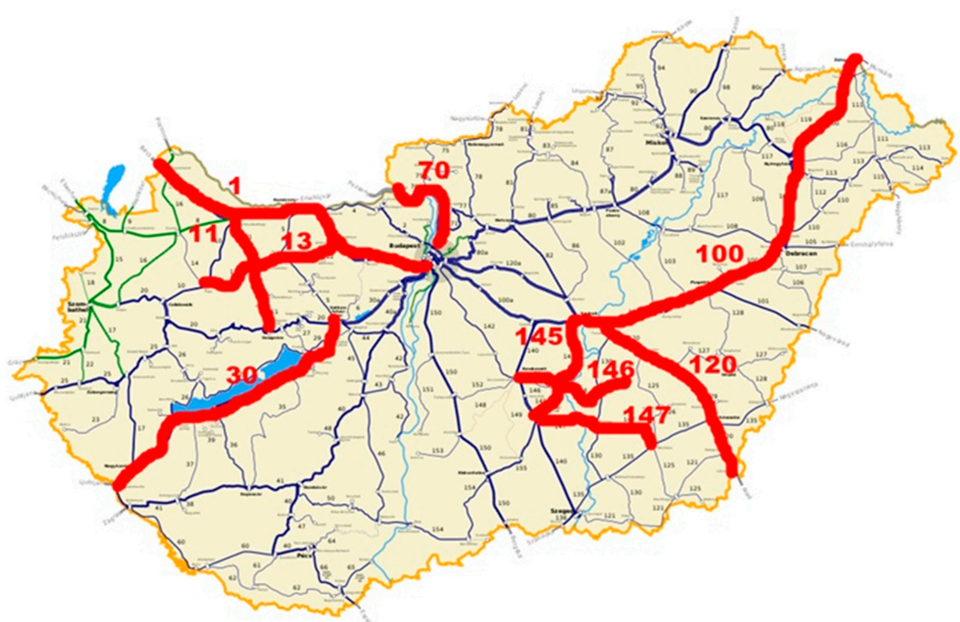

Figure 2. Map of Hungary's railway network highlighting the ten examined railway lines in red color and adding their ID numbers.

Table 1. Description of the ten examined railway lines.

No. of Railway Line	Description
Railway line #1	**Path:** from Budapest to Hegyeshalom state border. **Length:** 189.95 km. **Track gauge:** 1435 mm. **Maximum allowed speed:** varies between 120–160 km/h (between Kelenföld and Budaörs is 120 km/h, and between Budaörs and Tata, 140 km/h). **Double track or single track:** double track. **Electrified or non-electrified:** electrified. **Main line or branch line:** main line. **Text description:** The Budapest-Hegyeshalom border railway line is important, as it connects the Budapest "Déli" and "Keleti" railway passenger terminals and the Hungarian–Austrian/Hungarian–Slovakian state borders. The hourly suburban trains and bi-hourly domestic and international InterCity, EuroCity, EuroNight, and Railjet services illustrate the line's capacity utilization. The railway line plays a vital role in international connectivity, as it is part of the transcontinental transport route across Europe from the Bosphorus to the Dover Strait. It makes Vienna, Bratislava, northern Austria, Switzerland, Germany, and western Europe accessible by rail. The other main line connects from the north at Hegyeshalom to the Baltic Sea and by ferry across Scandinavia to the Arctic Circle.
Railway line #11	**Path:** from Győr to Veszprém. **Length:** 72.32 km. **Track gauge:** 1435 mm. **Maximum allowed speed:** varies between 40–100 km/h (between Győr and Győr-Szabadhegy is 100 km/h, between Győr and Veszprémvarsány 60 km/h, between Veszprémvarsány and Bakonyszentlászló 50 km/h, on the Bakony section 40 km/h, between Zirc and Veszprém 60 km/h). **Double track or single track:** single track. **Electrified or non-electrified:** non-electrified. **Main line or branch line:** branch line. **Text description:** The line can be known as the Bakonyvasút (Bakony railway), crossing the Bakony and thus reaching isolated settlements. It was initially used for mining purposes. It is Hungary's steepest and most beautiful railway line, with 20‰ gradients. It is operated as a branch line.
Railway line #13	**Path:** from Tatabánya to Pápa. **Length:** 82.21 km. **Track gauge:** 1435 mm. **Maximum allowed speed:** varies between 50–80 km/h (the track allows 80 km/h but is not authorized. Between Környe-Kisbér, Bakonybánk-Pápa 50 km/h). **Double track or single track:** single track. **Electrified or non-electrified:** partially electrified (between Tatabánya and Környe). **Main line or branch line:** branch line. **Text description:** Passenger services between Környe and Pápa stations were discontinued in March 2007. However, it is maintained as a bypass and freight line.
Railway line #30	**Path:** from Székesfehérvár to Gyékényes. **Length:** 235.99 km. **Maximum allowed speed:** varies between 90–120 km/h (between Székesfehérvár and Szántód is 120 km/h, which is reduced to 100 km/h between Szántód and Balatonszentgyörgy, between Balatonszentgyörgy and Zalakomár, the speed limit is 90 km/h; between Zalakomár and Murakeresztúr, the speed limit is 100 km/h again). **Double track or single track:** single track. **Electrified or non-electrified:** electrified. **Main line or branch line:** main line.

	Text description: It connects the southern shore of Lake Balaton with Budapest, making it a significant section from a tourism point of view. Intercity trains run every hour to Keszthely and Nagykanizsa and every two hours between Székesfehérvár and Siófok. In addition to passenger traffic, there is also significant freight traffic in the section. In the summer, passenger trains run according to an extended timetable.
Railway line #70	**Path:** from Budapest to Szob. **Length:** 63.61 km. **Track gauge:** 1435 mm. **Maximum allowed speed:** varies between 60–120 km/h. (The permitted speed varies between 60 and 120 km/h. Between Nyugati railway station and Rákosrendező, trains run at 60 km/h, while on the Rákosrendező-Rákospalota-Újpest section, they run at 80 km/h. The maximum speed of the line has been allowed between Rákospalota-Újpest-Vác, while between the Vác and Szob state board, the speed has been reduced again, from 120 km/h to 100 km/h.) **Double track or single track:** double track. **Electrified or non-electrified:** electrified. **Main line or branch line:** main line. **Text description:** It runs between Budapest and Szob in the Danube valley. It was built in 1846 as the country's first public steam railway line. It is built between the Rákospalota-Újpest and Vác stations, with CWR tracks and 60 kg/m rails. The line between Vác and Szob is also a CWR track, but this section is built with 54 kg/m rails. Line #70 has proportionally more curved sections from the ten railway lines examined, with curve values generally below 40%. In the present case, it exceeds 40%. It is also important to note that the ratio between the transition and circular curves is different on this line, while for the other lines, the circular curve part is usually 2–3 times the transitional curve sections
Railway line #100	**Path:** from Cegléd to Záhony. **Length:** 328.59 km. **Track gauge:** 1435 mm. **Maximum allowed speed:** varies between 120–140 km/h (the permitted speeds have been increased to 120 km/h on the Kőbánya-Kispest-Albertirsa section, 140 km/h between Albertirsa-Cegléd, and the track between Cegléd and Szolnok stations has been upgraded to 160 km/h but is not permitted). **Double track or single track:** double track. **Electrified or non-electrified:** electrified. **Main line or branch line:** main line. **Text description:** During the track renewals between 2005 and 2009, MÁV installed UIC 60 rails with elastic, modern Pandrol Fastclip rail fasteners. Passenger trains depart every half hour, every hour. The Záhony express train runs every two hours. InterCity trains run every hour in the direction of Debrecen-Nyíregyháza.
Railway line #120	**Path:** from Szolnok to Lőkösháza. **Length:** 328.59 km. **Track gauge:** 1435 mm. **Maximum allowed speed:** varies between 100–120 km/h. (The permitted speed varies between 100 and 120 km/h. The speed on the Szolnok-Békéscsaba section is 160 km/h, but this is not permitted for traffic.) **Double track or single track:** double track. **Electrified or non-electrified:** electrified. **Main line or branch line:** main line. **Text description:** The section between Szolnok and Szajol is part of railway line #100. The line is used by passenger, high-speed, InterCity, EuroNights, international, freight, and RoLa trains ("rolling road" trains).
Railway line #145	**Path:** from Szolnok to Kecskemét. **Length:** 64.12 km. **Track gauge:** 1435 mm. **Maximum allowed speed:** 60 km/h.

	Double track or single track: single track. **Electrified or non-electrified:** non-electrified. **Main line or branch line:** branch line. **Text description:** Railway line #145 branches off from Lines #100 and #120. Its alignment mostly follows the line of the Tisza river. There are relatively few curves between Szolnok and Kecskemét: less than 15% of the line.
Railway line #146	**Path:** from Kiskunfélegyháza to Kunszentmárton. **Length:** 51.67 km. **Track gauge:** 1435 mm. **Maximum allowed speed:** 40 km/h. (However, most tracks have been built in disused condition so that trains run at 40 km/h instead of the 60 km/h that is possible.) **Double track or single track:** single track. **Electrified or non-electrified:** non-electrified. **Main line or branch line:** branch line. **Text description:** Traffic on the railway line #146 started in May 1952. Its starting point is in Kiskunfélegyháza, which branches off the Cegléd-Szolnok line 140. Although it is a branch line, the traffic between Kecskemét and Lakitelek is quite good. In the other sections, however, traffic is low, as the settlements are small, and the stops are relatively far away from the villages. The ballast bed is alternately crushed stone, gravel, or clay, and there have been sporadic substructural replacements and rebuilds.
Railway line #147	**Path:** from Kiskunfélegyháza to Orosháza. **Length:** 76.81 km. **Track gauge:** 1435 mm. **Maximum allowed speed:** varies between 30–60 km/h (There are speed restrictions on the track, and sections are not rebuilt). **Double track or single track:** single track. **Electrified or non-electrified:** non-electrified. **Main line or branch line:** branch line. **Text description:** Regarding passenger traffic, the line can be divided into two sections, the first being the Kiskunfélegyháza-Szentes section and the second the Szentes and Orosháza section. It was built as a local railway for local freight and passenger transport. The Tisza bridge on the line played an important role in the crossing until the parallel road bridge was built. The line has undergone several upgrades and reconstructions in recent years but is primarily used by passenger traffic. As a result, it has been considered uneconomic, and several initiatives have been taken to eliminate rail traffic partially, but none have been implemented so far.

2.2. Statistical Data of the Considered Railway Lines

In addition to a general description of the railway lines studied, the straight-curve ratio of the lines, including the distribution of circular and transition curves, is illustrated in Figures 3–5 and Table 2; they also contain statistical base data about the ten examined railway lines.

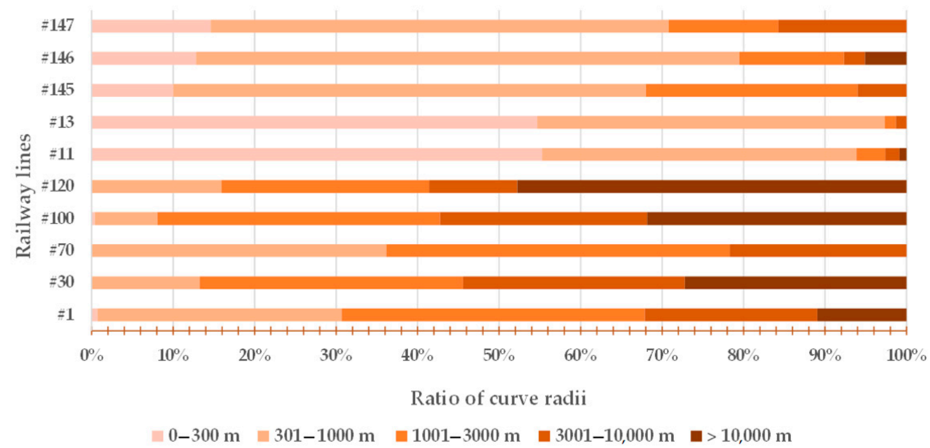

Figure 3. The ratio of curve radii related to the examined ten railway lines.

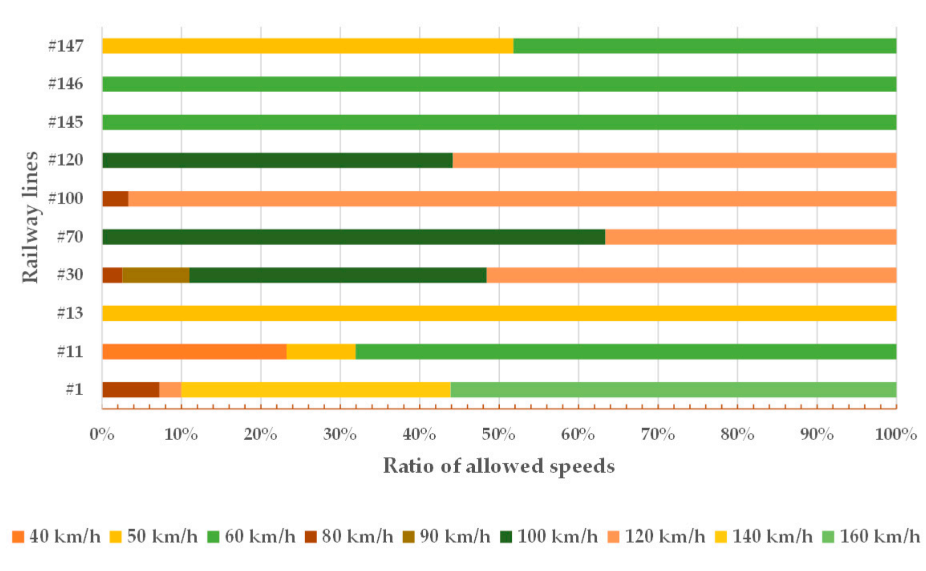

Figure 4. The ratio of allowed speeds related to the examined ten railway lines.

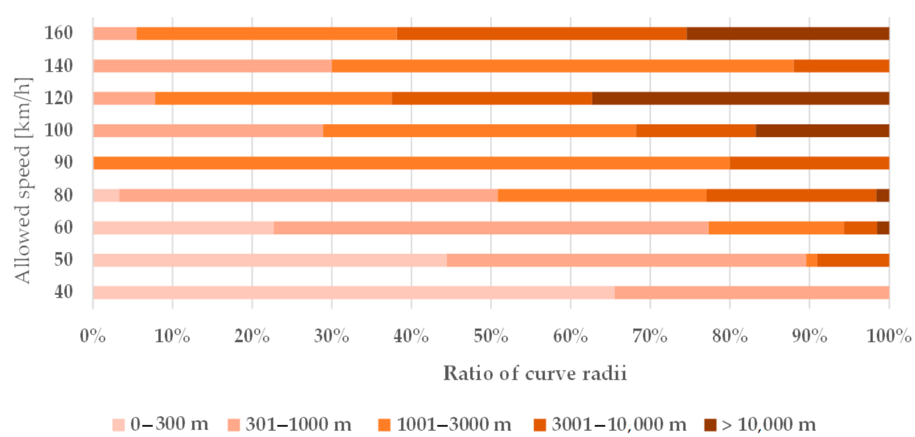

Figure 5. The ratio of allowed speeds considering the allowed speeds related to the examined ten railway lines.

Table 2 represents the horizontal track geometry elements distribution in the investigated ten railway lines in percentages, and Figure 6 shows the annual loading values (MGT).

Table 2. Length and track gauge values of the examined railway lines.

Line No.	Line #1	Line #11	Line #13	Line #30	Line #70	Line #100	Line #120	Line #145	Line #146	Line #147
Straight sections [%]	68.29	63.39	74.01	76.08	57.87	76.09	79.17	85.02	74.97	80.19
Circular curves [%]	22.53	28.35	18.25	19.38	24.93	17.17	14.36	10.58	17.48	14.68
Transition curves [%]	9.18	8.27	7.74	4.53	17.19	6.74	6.47	4.40	7.55	5.13
Total [%]	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

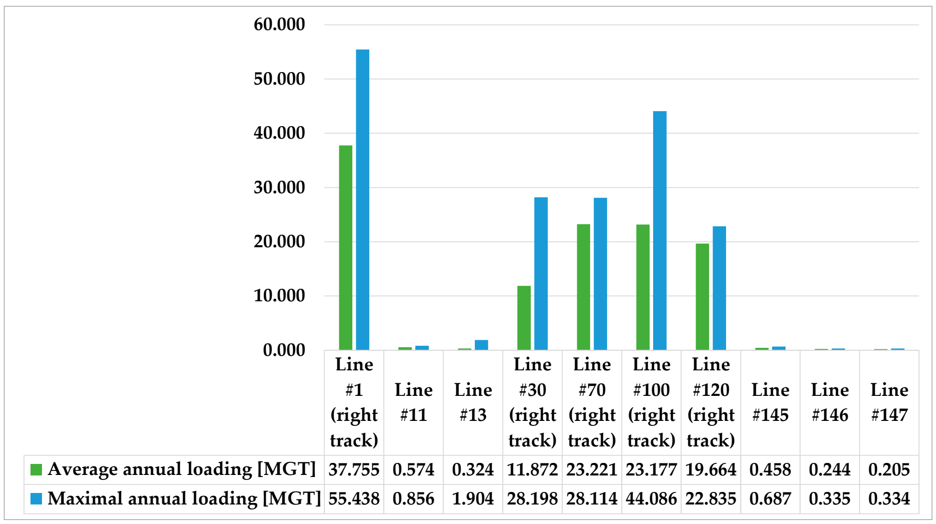

Figure 6. Annual loading values of the examined railway lines between 2013 and 2019.

2.3. Applied Methods for the Data Analysis

In this paper, the authors applied measurement data provided by railway track geometry measuring and recording cars of MÁV CRTI Ltd., namely the FMK-004 and FMK-007.

There are different measurement possibilities related to track gauge measurement; see [22,27–31].

The investigation used statistical analysis, for which MÁV Ltd. provided the data. The traffic loading data (i.e., MGT) were taken from the official MÁV database. The track data and track geometry measurements were exported from the PÁTER system (railway maintenance and economic assessment system and software in Hungary) and were received in Excel and text (*.txt) format. The track geometry and traffic load data included ten years of measurements (2011–2020). The measurements were made with the track geometry measuring trolleys FMK-004 and FMK-007 owned by MÁV CRTI Ltd.

The measuring systems of FMK-004 are track geometry measuring system as well as clearance gauge measuring system. In the following paragraphs only the first one is introduced and detailed. The summary is prepared according to MÁV CRTI Ltd.'s webpage [32].

In several central European nations, the FMK-004 measuring car performs track geometry and clearance gauge measurements, which is a self-propelled and diesel-powered vehicle. The customer has access to the measurement results in both printed and electronic formats immediately following the completion of the measurement. The clearance measurement requires office post-processing prior to delivery. The measuring systems order data and GNSS coordinates for the measuring results section. A workplace system aids in displaying, evaluating, and analyzing measurement results. The length is 15 m, the axle load is 130 kN, the maximum measuring speed: 100 km/h.

The track geometry measuring system is contact-based, meaning that the majority of measurement results are derived from the movement of the wheels on the rail (altogether 18 smaller or larger wheels on 9 axles). In addition, the measuring system is able to generate alignment and longitudinal level (sinking) diagrams on distortion-free and original chord bases. Using a gyroscope, the cross section is calculated. The twist can be determined for various bases. Measured track geometry characteristics are as follows:

- Gauge;
- Cross level/superelevation/;
- Twist on five different bases;
- Longitudinal level/sinking/on original chord, and in D1 or D2 wavelength range;
- Alignment on original chord, and in D1 or D2 wavelength range;
- Gauge change on any base;
- Average gauge on any base;
- Curvature;
- Twist-differences on five different bases;
- Longitudinal level/sinking/moving standard deviation on any base.

Main services:

- Measuring graphs (different measuring limits with objects);
- List of local defects (taking into account different measuring limits);
- General track condition judgment measuring and qualification numbers (at any length).

The measuring systems of FMK-007 are track geometry measuring system as well as vehicle dynamic measuring system. In the following paragraphs, only the first one is introduced and detailed. The summary is prepared according to MÁV CRTI Ltd.'s webpage [33].

In a number of central European countries, the FMK-007 measuring car conducts track geometry and vehicle dynamics measurements. It is not self-propelled; it was constructed in Hungary in 2001 by repurposing an IC wagon.

Immediately upon completion of the measurement, for which section data and GNSS coordinates are requested by the measuring system, the customer has immediate access to the measurement results in both printed and electronic formats. A workplace system aids in displaying, evaluating, and analyzing measurement results. The length is 26.4 m, the axle load is 140 kN, the maximum measuring speed: 160 km/h.

The track geometry measuring system is non-contact, so measurement results are provided by laser measuring units or inertial units attached to the bottom of the wagon.

The measuring system is also capable of generating alignment and longitudinal level (sinking) diagrams on distortion-free chord bases as well as on the original chord base or any other chord base. The cross section is measured using an inertial unit. The twist can be determined for various bases.

Measured track geometry characteristics:

- Gauge;
- Cross level/superelevation/;
- Twist on five different bases,
- Longitudinal level/sinking/on original or on any chord, and in D1 or D2 wavelength range;
- Alignment on original or on any chord, and in D1 or D2 wavelength range;
- Gauge-changing on any base;
- Average gauge on any base;
- Curvature;
- Twist-differences on five different bases;

- Longitudinal level/sinking/moving standard deviation on any base.

Main services:

- Measuring graphs—different measuring limits with objects;
- List of local defects—taking into account different measuring limits;
- General track condition judgment measuring and qualification numbers—at any length.

In order to start the analysis, preliminary work was performed on the raw data series. The authors combined several days of measurement data and overlapping data in several places to ensure accurate measurement. In this case, they always overwrote the older values with the newer data. Since the authors are looking at curved sections of the trajectory in this paper, straight sections were unnecessary. The measurement data for straight sections were removed by filtering in Excel. The data for TCs and CCs were examined separately, so the next step was to separate the filtered data based on the curves. Then, the analyses were started. It has to be mentioned that in the case of double-track lines (Line #1, #30, #70, #100, and #120), only the right tracks were considered in the calculations and the analyses.

Distribution functions were constructed from the filtered data for statistical time series analysis of the gauge parameter (see Section 3.1).

For each railway line, it was examined whether the data series showed a normal or lognormal distribution. For the lognormal distribution, 10 mm was added to the data to make the logarithm more meaningful, which was also just a transformation parallel to a horizontal axis. The Kolmogorov–Smirnov test was performed using the MS Excel program. The analysis was performed for the sections with transition curves (TC), circular curves (CC), and the entire curves without dividing them into transition curves and circular curve parts (EC) (see Section 3.2).

Section 3.3 investigated the effect of the superstructure on the change in gauge spacing over time. Two railway lines were investigated. Line #13 is built with fishplated rail joints, and Line #1 is a CWR track. In addition to the track system, whether the type of sleeper influences the track gauge was also investigated; the two railway lines were Line #1 and Line #11.

In Section 3.4, selected given curves were analyzed in a detailed manner. Line #1 and Line #11 were selected for this calculation. The track gauge parameter was examined only in the section interval between the beginning points of the transition curves.

It has to be mentioned that all the values published in Sections 3 and 4 are the sign differences in track gauge values, i.e., −2.0 mm means 1435.0 − 2.0 = 1433.0 mm, etc.

2.4. Standards and Regulations

The authors applied the standards and regulations of Hungary based on national specifications [34–36] and harmonized European standards [14,37–39]. Next to them, the so-called "Technical Specification of Interoperability" (TSI) of the European Union (EU) is also relevant [40]. It has to be mentioned that in curves with small radii, track gauge widening can be applied—if needed— and there must be a transition of track gauge parameter from the nominal to the prescribed. These limits are given by [36].

Table 3 contains the specifications of the TSI related to the track gauge [40].

Table 3. Immediate action limits of track gauge [40].

Speed (*V*) [km/h]	Dimensions [mm]	
	Minimum Track Gauge	Maximum Track Gauge
$V \leq 120$	1426	1470
$120 < V \leq 160$	1427	1470
$160 < V \leq 230$	1428	1463
$V < 230$	1430	1463

Tables 4 and 5 give the requirements of the regulation of EN 13848-5 [39].

Table 4. Requirements of track gauge in EN 13848-5 [39].

Speed (*V*) [km/h]	Alarm Limit (AL) [mm]		Intervention Limit (IL) [mm]		Immediate Action Limit (IAL) [mm]	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
V ≤ 80	−7	+25	−9	+30	−11	+35
80 < *V* ≤ 120	−7	+25	−9	+30	−11	+35
120 < *V* ≤ 160	−6	+25	−8	+30	−10	+35
160 < *V* ≤ 230	−4	+20	−5	+23	−7	+28
230 < *V* ≤ 300	−3	+20	−4	+23	−5	+28
300 < *V* ≤ 360	−3	+20	−4	+23	−5	+28

Table 5. Requirements of average track gauge (considering 100 m length) in EN 13848-5 [39].

Speed (*V*) [km/h]	Alarm Limit (AL) [mm]		Intervention Limit (IL) [mm]		Immediate Action Limit (IAL) [mm]	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
V ≤ 80	N.A [1].	+25	N.A [1]	N.A [1]	N.A [1]	N.A [1]
80 < *V* ≤ 120	−6	+25	−7	N.A [1]	−8	N.A [1]
120 < *V* ≤ 160	−5	+16	−6	+20	−7	N.A [1]
160 < *V* ≤ 230	−3	+16	−4	+20	−5	N.A [1]
230 < *V* ≤ 300	−3	+16	−2	+20	−3	N.A [1]
300 < *V* ≤ 360	N.A [1]	+16	−1	+20	−2	N.A [1]

[1] No specified requirement available/prescribed.

Table 6 represents the requirements of MÁV D.54 [36]. There are other different categories in MÁV D.54, i.e., average track gauge and deviation of track gauge; however, in this paper, they are not introduced.

Table 6. Requirements of track gauge in MÁV D.54 [36].

Speed (*V*)	A1 New	A2 Used	B	C1	C2	C3	D
[km/h]	[mm]						
	Track gauge widening						
not specified	N.A.						+45
V ≤ 80	+4	+5	+7	+25	+30	+35	
80 < *V* ≤ 120	+4	+5	+5	+20	+25	+30	
120 < *V* ≤ 160	+4	+4	+5	+15	+20	+25	
160 < *V* ≤ 200	+4	+4	+5	+10	+15	+20	
	Track gauge narrowing						
V ≤ 80	−3	−3	−3	−7	−8	−9	
80 < *V* ≤ 120	−3	−3	−3	−7	−8	−9	
120 < *V* ≤ 160	−2	−2	−2	−6	−7	−8	
160 < *V* ≤ 200	−2	−2	−2	−5	−6	−7	

In Table 6, the abbreviations have the following meanings:

- A: categories related to construction
  - A1: Category of size limit category of track gauge not to be exceeded by the geometric dimensions of track of new material (rail, sleeper, rail fastener, new or renewed ballast in entire cross-section) on a new or renewed substructure;

    - A2: Category of size limits whose limits shall not be exceeded by the geometric dimensions of the track constructed of used (reclaimed) material (rail and/or sleeper are not new and/or ballast not new or renewed);
    - A1 and A2: Values not exceeding the construction size limit shall be required for 90 frost-free (air temperature above 0 °C) days from the date of the first track measurement result that shows the track to be suitable for the given construction speed.
- B: category related to maintenance
    - B: The size limit category, whose limits must not be exceeded by values achieved by maintenance. The assessment of the maintenance work carried out to a B limit provides its rating.
- C: categories related to intervention
    - C1: Alarm limit category (AL) indicating the progressive deterioration of the track geometry. The evolution of the number of defects shall be monitored by comparing the current and previous measurements;
    - C2: Intervention limit category (IL), which, if exceeded, requires corrective maintenance work if the evaluation indicates that the local defect size is expected to exceed C3 by the next track inspection measurement;
    - C3: Immediate action limit category (IAL), which requires action if exceeded: introduction of a speed restriction within a maximum of three days. Thereafter, corrective maintenance of the track geometry must be carried out to remove the speed restriction;
    - If the measured value in a speed range exceeds the C3 limit, the applicable speed shall be set so that the measured value is within the C3 limit;
    - If the value of the fault/defect also exceeds the C3 value for 40 km/h, a speed limit value lower than 40 km/h shall be introduced depending on the structural condition of the track.
- D: category related to closing the railway service on the track
    - D: The speed class-independent size limit category above which the track shall be closed. (This size limit is only for the track geometry characteristics of track gauge widening and twist parameters).

3. Results and Discussion

This section details four different analyses, parallel with Section 2.3.

3.1. Statistical Time Series Analysis of the Gauge Parameter

Distribution functions were prepared from the filtered data for the statistical time series analysis of the track gauge parameter.

Figures 7–9 show that the distribution function of Line #1 gives a steeper trend than that of Line #13 (see Figures 10–12). The tangent of the graph gives information about the state (condition) of the railway line; the more values approach 0, the better the track's state. Because of the fact, Line #1 is a main line, and Line #13 is a branch line, so there are differences in track conditions and traffic volumes (loading). Depending on the speeds allowed, the regulation's requirement is stricter for the main line (i.e., Line #1), so it cannot be too extreme.

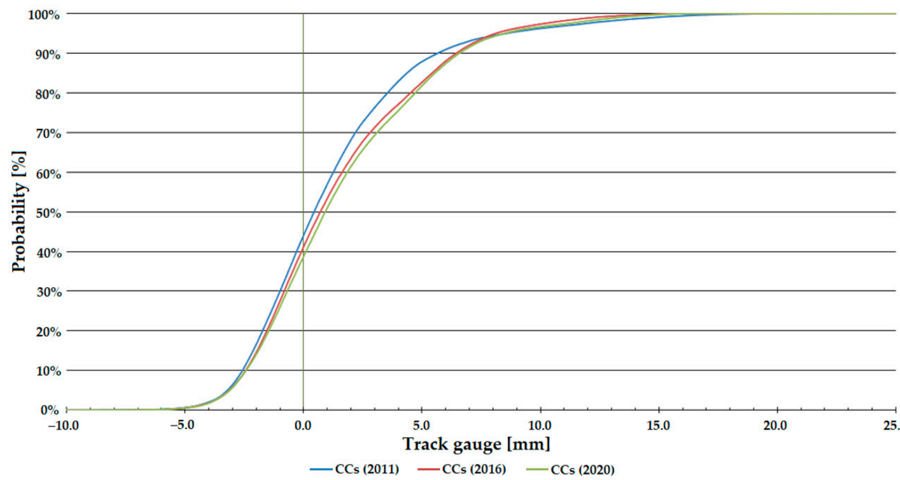

Figure 7. Distribution functions of track gauge parameter on Line #1, circular curves (CCs).

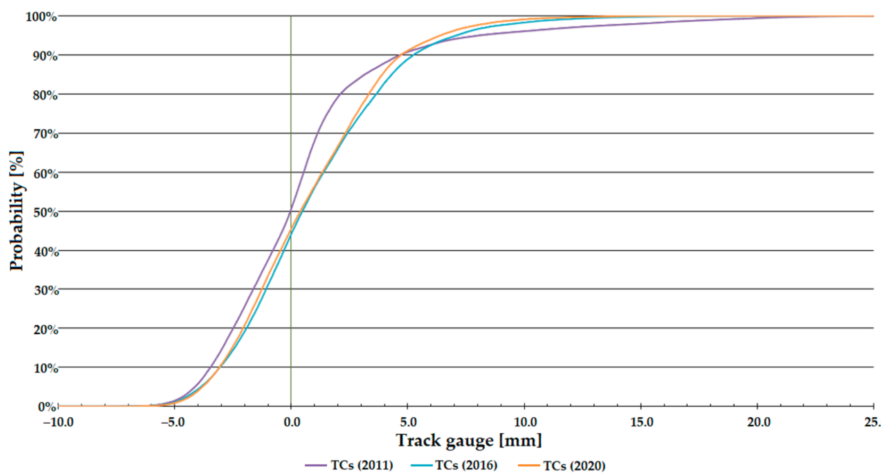

Figure 8. Distribution functions of track gauge parameter on Line #1, transition curves (TCs).

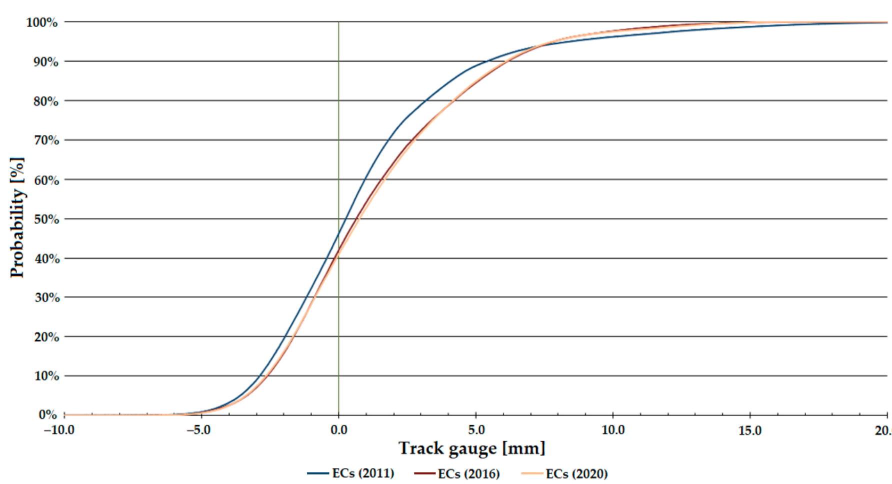

Figure 9. Distribution functions of track gauge parameter on Line #1, entire curves (ECs).

For Line #1, the transition curve sections showed a deterioration from 2011 to 2016, after which there was an improvement on these sections (see Figure 8).

Figure 9 shows that deterioration is visible for the sections with CCs. For the ECs, on the other hand, there is only deterioration from 2011, with no significant deterioration between 2016 and 2020.

For the selected branch line (see Figures 10–12), significant deterioration is observed in the transition curve sections until 2020, but at the end of the line, the track gauge widening of the curve has already decreased. It is likely to be due to rebuilding.

For sections with CCs, a deterioration is observed until 2015, but by 2020, as for the TCs, an improvement is observed, which can also be said for the sections with ECs.

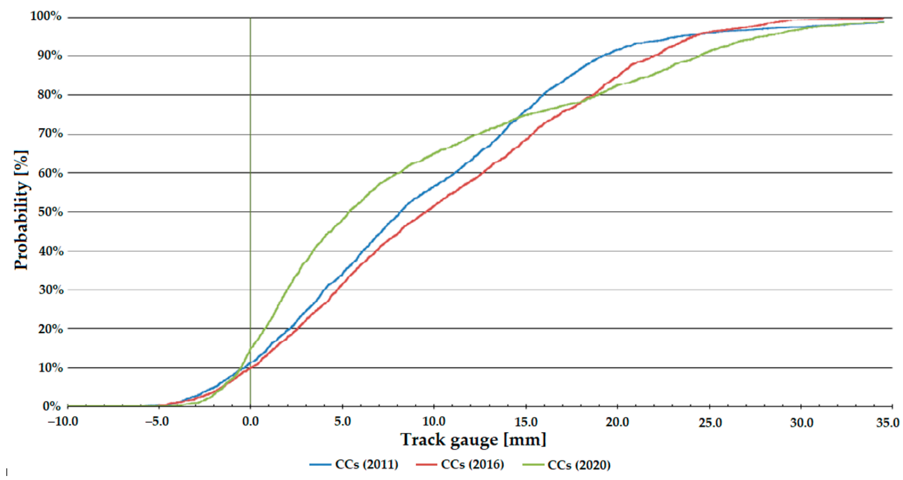

Figure 10. Distribution functions of track gauge parameter on Line #13, circular curves (CCs).

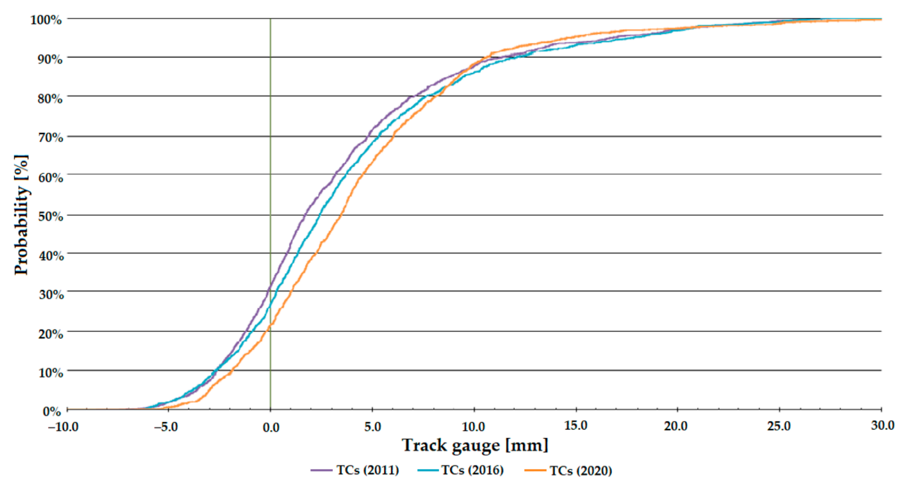

Figure 11. Distribution functions of track gauge parameter on Line #13, transition curves (TCs).

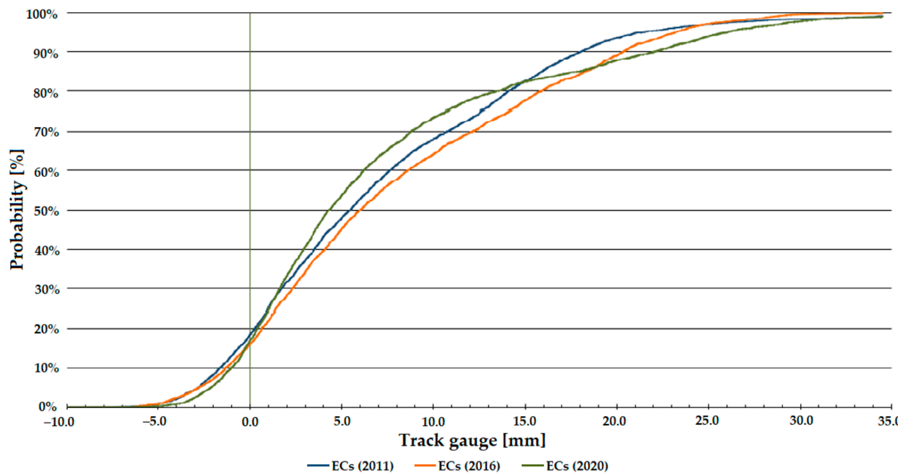

Figure 12. Distribution functions of track gauge parameter on Line #13, entire curves (ECs).

After constructing the distribution functions, the authors determined the quantiles (15%, 50%, and 85%) of the distribution functions needed to calculate the condition characteristic (see Table 7).

Table 7. Quantiles of distribution functions of track gauge parameter on Line #1.

Quantiles	Circular Curves (CCs)			Transition Curves (CCs)			Entire Curves (ECs)		
	Years			Years			Years		
	2011	2016	2020	2011	2016	2020	2011	2016	2020
15%	−2.12	−1.95	−1.92	−2.94	−2.43	−2.54	−2.39	−2.08	−1.73
50%	0.45	0.71	0.87	−0.03	0.49	0.34	0.26	0.65	1.71
85%	4.38	5.44	5.36	3.17	4.32	3.73	4.10	5.10	5.64

An additional 10 mm was added to the values to avoid calculating an absolute value (which would have distorted the value of the parameter(s) calculated from the distribution function). It is only a transformation parallel to the horizontal axis and does not affect the comparability of the values. The Vaszary-type shape numbers were then calculated [22].

The calculation of the Vaszary-type shape number ($I_{track\ gauge}$) is shown in Equation (1), where $i_{15\%}$, $i_{50\%}$, and $i_{85\%}$ are the quantiles for 15%, 50%, and 85% probabilities, respectively [22].

$$I_{track\ gauge} = \frac{(i_{15\%}^2 + i_{50\%}^2 + i_{85\%}^2)}{10}\ [mm^2] \tag{1}$$

The resulting values for the years studied are shown in Table 8.

Table 8. Quantiles of distribution functions of track gauge parameter on Line #1, considering the modification of track gauge values with adding +10 mm.

Quantiles	Circular Curves (CCs)			Transition Curves (CCs)			Entire Curves (ECs)		
	Years			Years			Years		
	2011	2016	2020	2011	2016	2020	2011	2016	2020
15%	7.88	8.05	8.08	7.06	7.57	7.46	7.61	7.92	8.27
50%	10.45	10.71	10.87	9.97	10.49	10.34	10.26	10.65	11.71
85%	14.38	15.44	15.36	13.17	14.32	13.73	14.10	15.10	15.64
$I_{track\ gauge}$ [mm^2]	37.81	41.79	41.94	32.27	37.24	35.11	36.20	40.42	45.01

The calculated values of Vaszary-type shape numbers are summarized in Table 9, separating sections with CCs, TCs, and ECs.

Looking at the values as a whole, Line #13 is the worst, and Line #30 is the best since the higher the value of the Vaszary-type shape number, the worse the quality of the track. In addition, the most significant part of Line #30 has been rebuilt during the years under study and is, therefore, in better condition than the other lines.

For Line #145, the authors observed that the values had almost halved by 2020 compared to 2011. This represents an improvement in condition due to the work carried out. Likely, the line has also undergone sleeper replacements, sleeper repairs, and track replacements in recent years. The other lines have also shown an improvement in condition over the years.

Table 9. Vaszary-type shape numbers of the examined curves' distribution functions.

Railway Line	Circular Curves (CCs)			Transition Curves (TCs)			Entire Curves (ECs)		
	Years			Years			Years		
	2011	2016	2020	2011	2016	2020	2011	2016	2020
#1	37.80,813	41.79,002	41.93,729	32.26,934	37.24,074	35.10,801	36.19,897	40.41,589	45.01,266
#30	42.22,022	37.49,758	42.76,129	20.14,109	20.89,973	23.60,162	36.99,414	32.95,545	37.53,841
#70	55.34,870	58.16,905	70.30,706	36.80,361	39.46,925	44.81,850	47.39,224	51.15,014	60.59,141
#100	38.55,849	50.67,965	51.94,522	31.94,962	34.69,323	36.50,474	36.19,150	45.48,753	46.19,585
#120	45.49,683	37.21,421	54.79,674	42.43,445	37.42,395	45.28,941	43.91,962	37.29,669	50.91,306
#11	81.66,073	60.89,739	91.72,283	50.72,246	42.57,699	61.36,859	75.68,402	57.75,698	86.35,739
#13	120.58,179	141.52,299	135.02,942	55.67,074	60.63,091	63.25,931	99.87,926	115.13,571	107.86,011
#145	90.08,387	71.37,074	47.40,699	75.33,099	65.85,854	50.68,027	85.63,910	69.50,259	48.43,979
#146	54.56,115	68.54,331	64.32,299	39.89,555	47.92,235	39.85,875	49.72,931	61.38,579	56.32,779
#147	46.96,067	51.94,494	42.85,939	46.29,994	47.36,891	37.47,059	46.65,315	50.35,179	41.37,131

Comparing the sections with CCs, TCs, and ECs, the authors derived the following results:

- The highest shape numbers are observed in CCs;
- The lowest Vaszary-type shape numbers are in the sections with TCs;
- The ECs are located in between them (see above);
- The reason for the case of CCs is that in these sections, significant lateral forces can act on the vehicles due to the non-compensated lateral acceleration, depending on the vehicles' speed and curve radius (which is proportional to the vehicle speed squared and inversely proportional to the radius of the curve).

3.2. Examination of Normal and Lognormal Distributions

The analysis of the distribution functions was executed by Kolmogorov–Smirnov (KS) tests. During these analyses, the facts were examined as to whether the track gauge parameters' distribution functions are Gauss-distribution (GD) or lognormal distribution (LD). The logarithmic function was the "ln", where the basis is the neutral number "e".

The "Result" column of Tables 10–15 shows that the data do not follow a normal distribution for any lines. The skewness and kurtosis values in the last two columns show how far the track gauge data describing a given track deviate from the normal distribution. In the Result column there are two options, ND means normal distribution, NND means non-normal distribution.

Table 10. The results of the Kolmogorov–Smirnov test for the sections with CCs of the investigated railway lines.

Circular Curves (CCs)		Track Gauge [mm]							
Railway Line	Number of Data in the Sample	Mean	Standard Deviation	$\alpha_{0.05}$	Maximum	$\alpha_{0.05}$ < Maximum	Result	Skewness	Kurtosis
#1	164,538	1.667	3.742	0.003	0.082	TRUE	NND	0.950	1.005
#30	133,436	1.928	3.776	0.004	0.993	TRUE	NND	0.540	3.123
#70	65,502	4.627	4.919	0.005	1.000	TRUE	NND	0.511	0.164
#100	88,245	1.021	3.108	0.005	0.974	TRUE	NND	0.789	2.656
#120	39,771	1.733	4.648	0.007	0.991	TRUE	NND	0.830	0.436
#11	13,458	6.046	4.486	0.012	0.041	TRUE	NND	0.422	0.150
#13	3453	9.012	9.874	0.023	0.859	TRUE	NND	1.026	0.270
#145	20,155	1.643	6.805	0.010	0.891	TRUE	NND	1.111	1.930
#146	36,195	3.803	7.114	0.007	0.998	TRUE	NND	0.903	1.329
#147	14,066	1.286	5.941	0.011	0.725	TRUE	NND	1.372	2.616

Table 11. The results of the Kolmogorov–Smirnov test for the sections with CCs of the investigated railway lines, considering the modification of track gauge values by adding +10 mm.

Circular Curves (CCs)		LN (Track Gauge + 10 mm) [mm]							
Railway Line	Number of Data in the Sample	Mean	Standard Deviation	$\alpha_{0.05}$	Maximum	$\alpha_{0.05}$ < Maximum	Result	Skewness	Kurtosis
#1	164,538	3.062	0.165	0.003	3.705	TRUE	NND	0.483	0.035
#30	133,436	3.075	0.159	0.004	0.099	TRUE	NND	0.894	1.575
#70	65,502	3.184	0.199	0.005	0.999	TRUE	NND	−0.002	−0.267
#100	88,245	3.035	0.146	0.005	0.876	TRUE	NND	0.011	1.383
#120	36,771	3.057	0.206	0.007	0.984	TRUE	NND	0.317	−0.248
#11	13,458	3.245	0.172	0.012	0.038	TRUE	NND	−0.044	−0.233
#13	3453	3.316	0.314	0.023	0.859	TRUE	NND	0.559	−0.763
#145	20,155	3.029	0.302	0.010	0.889	TRUE	NND	0.084	0.285
#146	36,195	3.126	0.297	0.007	0.989	TRUE	NND	−0.222	1.061
#147	14,066	3.024	0.257	0.011	0.985	TRUE	NND	0.503	0.434

Table 12. The results of the Kolmogorov–Smirnov test for the sections with TCs of the investigated railway lines.

Transition Curves (TCs)		Track Gauge [mm]							
Railway Line	Number of Data in the Sample	Mean	Standard Deviation	$\alpha_{0.05}$	Maximum	$\alpha_{0.05}$ < Maximum	Result	Skewness	Kurtosis
#1	8017	2.691	4.181	0.015	0.055	TRUE	NND	0.920	1.110
#30	35,100	−1.169	2.629	0.007	0.992	TRUE	NND	1.459	3.124
#70	42,450	1.996	4.043	0.007	0.999	TRUE	NND	1.352	3.574
#100	171,008	2.836	3.526	0.003	0.925	TRUE	NND	1.056	1.726
#120	39,771	1.733	4.648	0.007	0.991	TRUE	NND	0.830	0.436
#11	10,108	3.860	5.313	0.014	0.094	TRUE	NND	0.536	0.147
#13	2022	4.333	5.889	0.030	0.875	TRUE	NND	1.337	1.384
#145	10,281	2.224	5.571	0.013	0.979	TRUE	NND	0.641	0.429
#146	15,523	0.826	5.720	0.011	0.988	TRUE	NND	0.811	1.784
#147	5839	0.871	5.158	0.018	0.973	TRUE	NND	1.347	2.694

Table 13. The results of the Kolmogorov–Smirnov test for the sections with TCs of the investigated railway lines, considering the modification of track gauge values by adding +10 mm.

Transition Curves (CCs)		LN (Track Gauge + 10 mm) [mm]							
Railway Line	Number of Data in the Sample	Mean	Standard Deviation	$\alpha_{0.05}$	Maximum	$\alpha_{0.05}$ < Maximum	Result	Skewness	Kurtosis
#1	8017	3.105	0.184	0.015	3.594	TRUE	NND	−0.036	−0.623
#30	35,100	2.926	0.132	0.007	0.988	TRUE	NND	0.744	1.099
#70	42,450	3.076	0.172	0.007	0.999	TRUE	NND	0.623	0.872
#100	171,008	3.117	0.148	0.003	0.925	TRUE	NND	0.474	0.979
#120	9771	3.057	0.206	0.007	0.984	TRUE	NND	0.317	−0.248
#11	10,108	3.149	0.211	0.014	0.031	TRUE	NND	0.436	0.017
#13	2022	3.166	0.220	0.030	0.883	TRUE	NND	0.644	1.015
#145	10,281	3.070	0.249	0.013	0.944	TRUE	NND	−0.079	0.021
#146	15,523	2.999	0.278	0.011	0.970	TRUE	NND	−0.383	1.420
#147	5839	3.011	0.229	0.018	0.968	TRUE	NND	0.524	0.504

Table 14. The results of the Kolmogorov–Smirnov test for the sections with ECs of the investigated railway lines.

Entire Curves (CCs)		Track Gauge [mm]							
Railway Line	Number of Data in the Sample	Mean	Standard Deviation	$\alpha_{0.05}$	Maximum	$\alpha_{0.05}$ < Maximum	Result	Skewness	Kurtosis
#1	245,590	1.363	3.597	0.003	0.999	TRUE	NND	0.920	1.110
#30	168,536	1.283	3.783	0.003	0.995	TRUE	NND	1.459	3.124
#70	107,952	3.592	4.771	0.004	1.000	TRUE	NND	0.791	0.747
#100	259,253	2.218	3.497	0.003	0.983	TRUE	NND	0.972	1.990
#120	99,630	2.296	5.081	0.004	0.988	TRUE	NND	0.626	−0.132
#11	15,772	5.462	4.503	0.011	0.061	TRUE	NND	0.536	0.147
#13	5475	7.284	8.910	0.018	0.907	TRUE	NND	1.337	1.384
#145	30,436	1.839	6.421	0.008	0.958	TRUE	NND	0.995	1.712
#146	51,718	2.910	6.863	0.006	0.995	TRUE	NND	0.942	1.581
#147	19,905	1.164	5.725	0.010	0.984	TRUE	NND	1.384	2.739

Table 15. The results of the Kolmogorov–Smirnov test for the sections with ECs of the investigated railway lines, considering the modification of track gauge values by adding +10 mm.

Entire Curves (CCs)		LN (Track Gauge + 10 mm) [mm]							
Railway Line	Number of Data in the Sample	Mean	Standard Deviation	$\alpha_{0.05}$	Maximum	$\alpha_{0.05}$ < Maximum	Result	Skewness	Kurtosis
#1	245,590	3.048	0.162	0.003	0.999	TRUE	NND	0.434	0.076
#30	168,536	3.044	0.165	0.003	0.992	TRUE	NND	0.767	1.318
#70	107,952	3.141	0.196	0.004	0.999	TRUE	NND	0.258	−0.178
#100	259,253	3.089	0.152	0.003	0.922	TRUE	NND	0.288	1.167
#120	9963	3.079	0.223	0.004	0.981	TRUE	NND	0.158	−0.587
#11	15,772	3.222	0.175	0.011	0.032	TRUE	NND	0.096	−0.366
#13	5475	3.261	0.292	0.018	0.902	TRUE	NND	0.742	−0.144
#145	30,436	3.043	0.286	0.008	0.899	TRUE	NND	0.013	0.299
#146	51,718	3.088	0.297	0.006	0.988	TRUE	NND	−0.222	1.095
#147	19,905	3.020	0.249	0.010	0.982	TRUE	NND	0.516	0.488

After the Kolmogorov–Smirnov test, probability density functions were constructed for each line, separating the different sections (CCs, TCs, and ECs). Only one of them is shown in Figure 13 due to the required space. The skewness and kurtosis values of the probability density functions can be seen in Tables 10–15 in the last two columns.

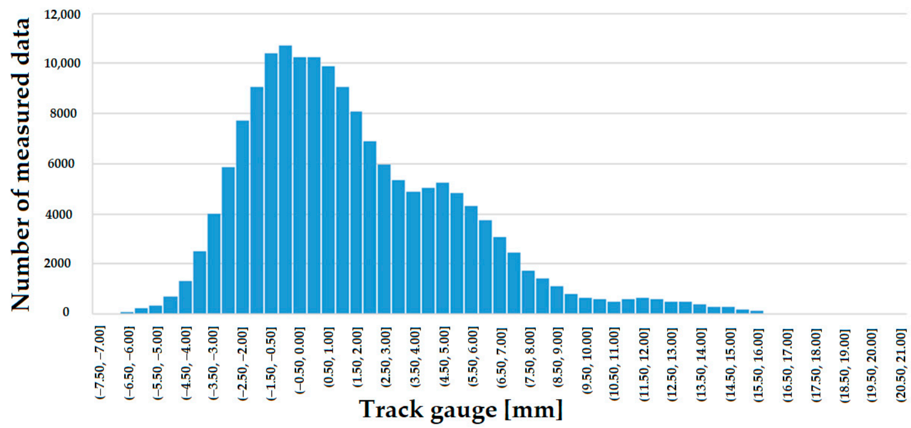

Figure 13. Distribution functions of track gauge parameter on Line #1, circular curves (CCs).

The lines were classified according to the limits of skewness and kurtosis, which shows that Line #11 is the closest to a normal distribution. The transition curves show a more "peaked" picture. For a lognormal distribution function, there is an acceptable degree of asymmetry. Regarding kurtosis, the line distribution functions are higher than the lognormal distribution function.

3.3. Examination of Superstructure Types

The track gauge values are plotted with the sections for the two railway lines studied. For Line #13, comparing the 2012 data set with the 2020 data set, it is noticeable that the track gauge widening has already been transformed into track gauge narrowing in some places over time (see Figures 14 and 15). The reason for this phenomenon has not been clarified. It has been suggested that the section may have been rebuilt, but the track gauge limits related to this speed do not allow for such a track narrowing during rehabilitation.

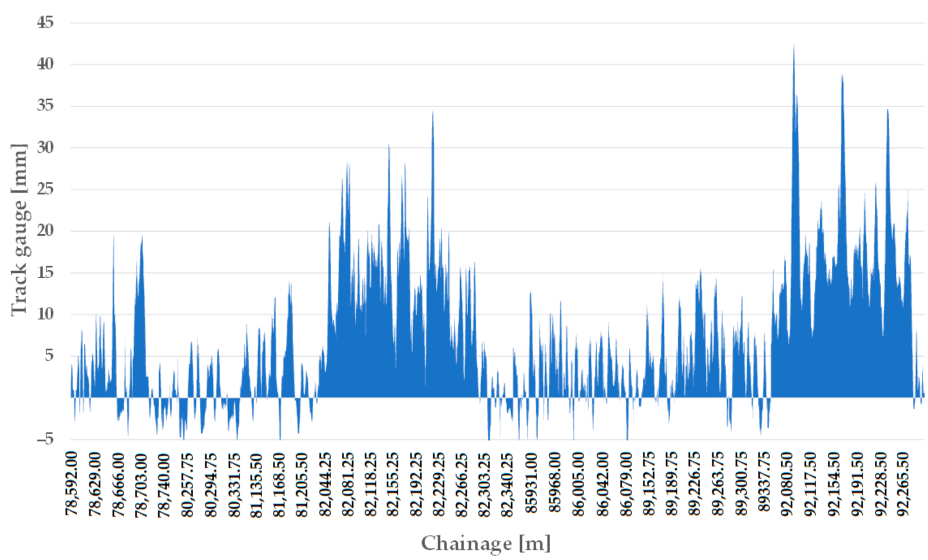

Figure 14. The longitudinal function of the track gauge on Line #13, considering the measurement data in 2012 and the sections with ECs.

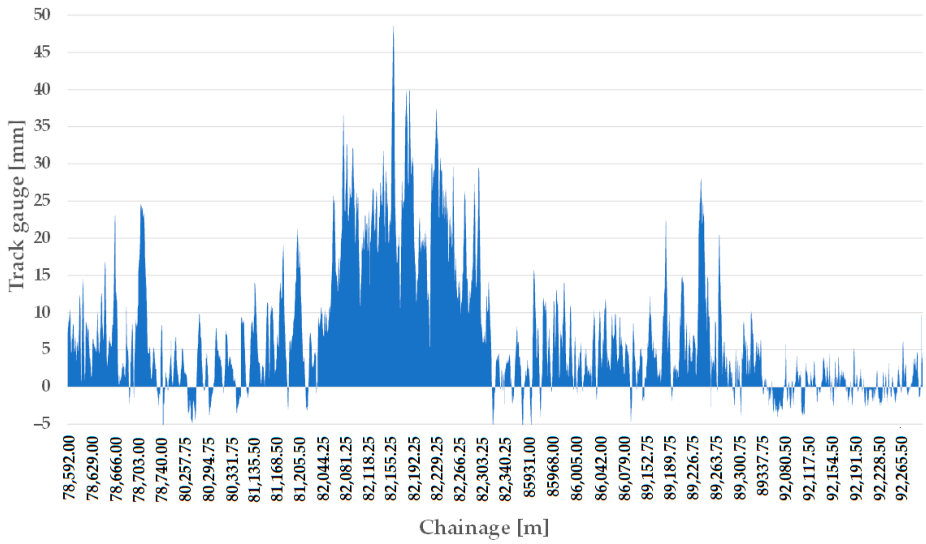

Figure 15. The longitudinal function of the track gauge on Line #13, considering the measurement data in 2020 and the sections with ECs.

Line #1 has typically experienced track gauge widening over the ten years studied (see Figures 16 and 17), but as with Line #13, there is also evidence of track gauge narrowing despite wear from use.

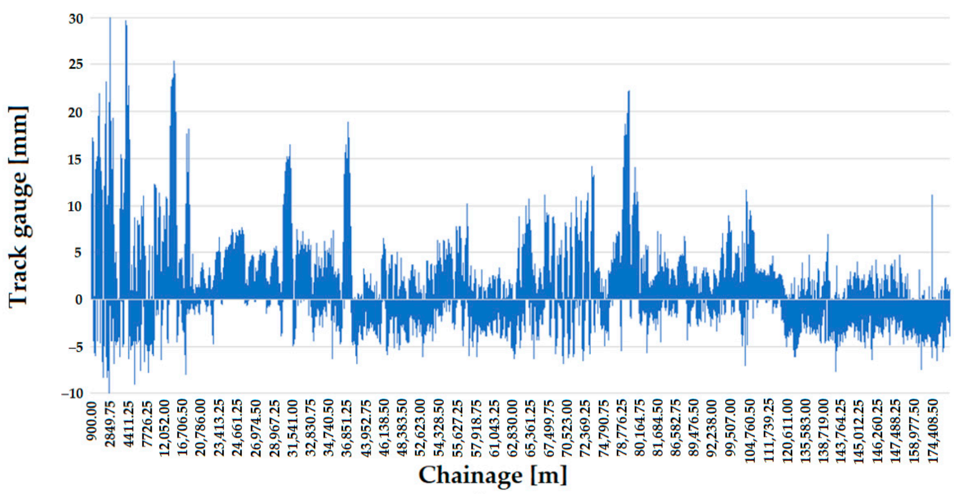

Figure 16. The longitudinal function of the track gauge on Line #1, considering the measurement data in 2011 and the sections with ECs.

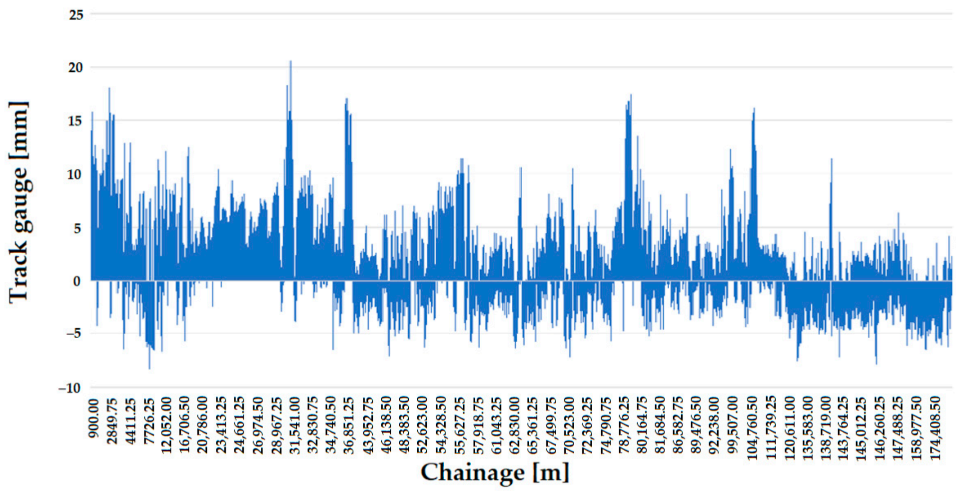

Figure 17. The longitudinal function of the track gauge on Line #1, considering the measurement data in 2020 and the sections with ECs.

In addition to the track system, it was also investigated whether the type of sleeper or not influences the track gauge. In the section of Line #11 under study, wooden sleepers (see Figure 18) were installed, while on Line #1, reinforced concrete sleepers were used (see Figure 19).

Comparing the two figures shows that the values of the track gauge narrowing are almost similar in both cases, but the values of the track gauge widening show a significant difference. Line #1's maximum track gauge widening value is close to 20 mm, while Line #11's is close to 35 mm.

The change over five years is 5 mm for the examined main railway line (i.e., Line #1) and 8–10 mm for the branch line (i.e., Line #11). This variation is significant, and it can be concluded that the sleeper type influences the variation in the track gauge.

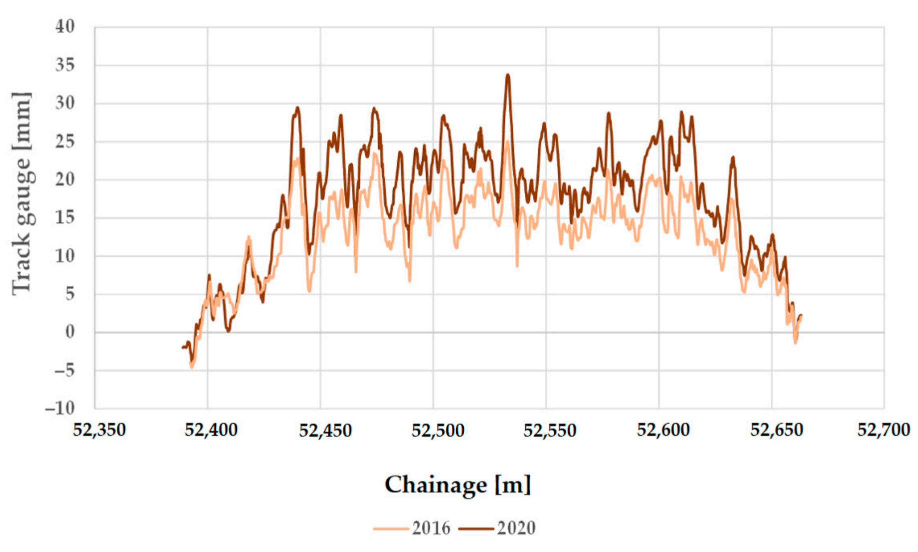

Figure 18. The longitudinal function of the track gauge on Line #11 (between Zirc and Eplény railway stations), considering the measurement data in 2016 and 2020 and the sections with ECs.

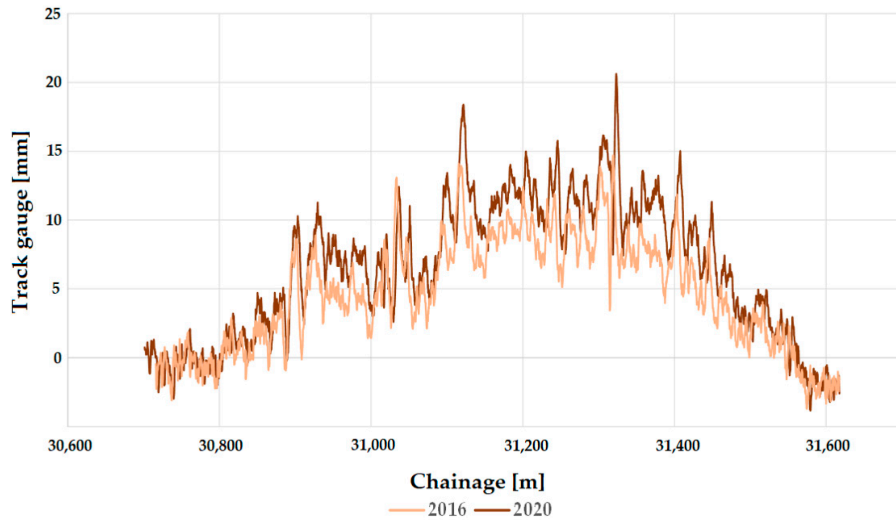

Figure 19. The longitudinal function of the track gauge on Line #1 (between Biatorbágy and Herceghalom railway stations), considering the measurement data in 2016 and 2020 and the sections with ECs.

3.4. Examination of Selected Given Curves

In the selection of the curves, it was observed which curve "stands out" on the line regarding track gauge widening or narrowing. For example, line #1 had the highest value of track gauge widening (see Table 16), so the corresponding curve was analyzed.

Table 16. Outstanding values of track gauge widening and narrowing of Line #1.

Sections	Track Gauge [mm]	
	Years	
	2016	2020
31,323.25	9.93	20.63
7891.00	−5.34	−8.34

The change in track gauge parameter is plotted based on measurements for 2016 and 2020. TCs and CCs are marked and illustrated in Figure 20. A moving average was also created for the data.

The permitted speed on this section of Line #1 is 140 km/h. Therefore, it fits the regulations (see Section 2.4, Table 6).

In the case of track gauge widening, the track gauge value exceeds the C2 intervention size limit category at one point. It falls within the immediate action limit category C3, so a speed limit is required in this section. The transition curve sections are classified as B-C1 (see Section 2.4, Table 6).

Regarding track gauge narrowing, the whole track curve does not exceed the C1 warning size limit category. In addition, the values in the transition curves do not exceed maintenance category B in places (see Section 2.4, Table 6).

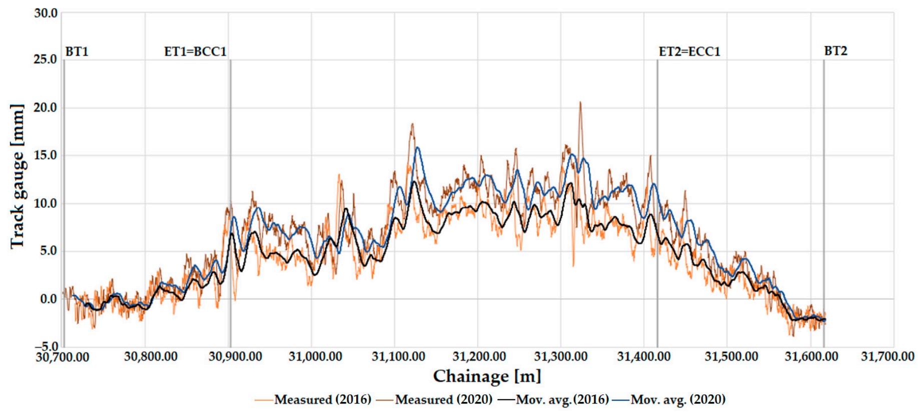

Figure 20. The longitudinal function of the track gauge on Line #1 (between Biatorbágy and Herceghalom railway stations), considering the measurement data in 2016 and 2020 and the sections with ECs. Moving average (mov. avg.) lines are added. The meanings of abbreviations are detailed in "Abbreviations" at the end of the paper.

Line #11 also included a larger value of track gauge widening, so the curve that contains the 605+59.75 section was examined (see Table 17).

Table 17. Outstanding values of track gauge widening and narrowing of Line #11.

Sections	Track Gauge [mm]	
	Years	
	2016	2020
49,797.25	6.90	−10.34
60,589.8	30.22	38.50

The speed limit on this section of the line is 60 km/h. On Line #11, in 2016, there was a section with a category D value, meaning the track must be closed (see Figure 21). However, the track gauge value on this section has been reduced to 2020, placing it in the category C2 intervention size limit. The CC varies between categories B to C3 (see Section 2.4).

Track gauge narrowing has only occurred in the transition curve between sections 604 + 31 and 604 + 69.

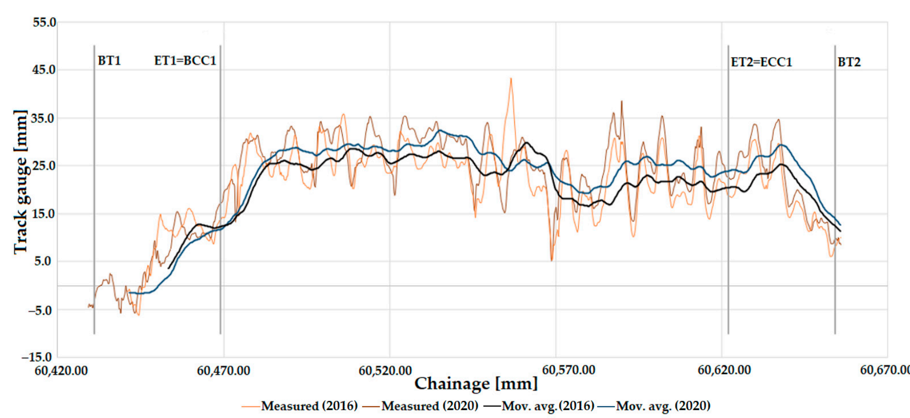

Figure 21. The longitudinal function of the track gauge on Line #11 (between Zirc and Eplény railway stations), considering the measurement data in 2016 and 2020 and the sections with ECs. Moving average lines are added. Moving average (mov. avg.) lines are added. The meanings of abbreviations are detailed in "Abbreviations" at the end of the paper.

4. Conclusions

The authors conclude their examination in the following paragraphs.

1. **Statistical time series analysis of the track gauge parameter**

In the time series analysis, findings were as follows:

- The highest Vaszary-type shape numbers are observed in CCs.
- The lowest Vaszary-type shape numbers are in the sections with TCs.
- For ECs, this parameter lies between the above two results.
- From the straight sections to CCs, the vehicle is guided by the TCs; it was, therefore, to be expected that the track gauge values in the sections with TCs are transitions between the values of the straight lines and CCs, which are almost close to 0, and the CCs' values.

2. **Examination of normal and lognormal distributions**

In the distribution analysis of track gauge parameters in curves, findings were as follows:

- The result of the Kolmogorov–Smirnov test is that the ten railway lines incorporated in the study have neither normal nor lognormal distributions.
- The lines were classified according to the limits of skewness and kurtosis, which shows that Line #11 is the closest to a normal distribution. The transition curves show a more "peaked" picture. For a lognormal distribution function, there is an acceptable degree of asymmetry. Regarding kurtosis, the line distribution functions are higher than the lognormal distribution function.

3. **Examination of superstructure types**

In the investigation of track gauge parameters regarding different superstructure types, findings were as follows:

- First, the track system was examined to see how it affects the variation in the track gauge. For example, on some sections of the branch line, the gauge narrowing has been converted to a gauge widening by 2020, while on other sections, the value of track gauge widening has decreased. It could be due to rebuilding, sleeper replacement, or track replacement, but the required data were unavailable.
- In general, there is a 10–15 mm deterioration between 2012 and 2020.
- For the sections of the main line examined, an average deterioration of 5 mm was observed between 2012 and 2020.
- Thus, the type of track system influences the change in track gauge, with more remarkable changes over the years for fishplate jointed tracks.
- The influence of the type of sleeper on the change in the track gauge parameter was analyzed. This analysis was carried out on branch line curves, as no wooden sleepers are applied on main line curves.
- The curve with concrete sleepers shows a change of 5 mm over 5 years, whereas the curve with wooden sleepers shows a change of 8–10 mm. The reason for this is characteristic of the wood, which is sensitive to weathering. Over time, elastic deformations develop, and when this occurs, the reinforcements may also shift.
- The track gauge narrowing is the same for both lines; however, when the maximum value of track gauge narrowing is considered, there is a difference of 5 mm between the curves with wooden and concrete sleepers.

4. **Examination of selected given curves**

In the analysis of selected given curves, findings were as follows:

- For this parameter, one main line and one branch line were chosen. Then, the variation of track gauge parameters as a function of time and their moving averages are plotted. In terms of moving average, a deterioration of less than 5 mm was generally observed for the main line, while for the branch line, it was close to 10 mm, despite the main line having a higher traffic load.

- In addition, a further set of curves was examined and categorized according to the intervention size limits.
- Overall, regarding the curves on the main line—with the higher traffic load—the deterioration value of the track over time is less than that of the curves on branch lines. This is because the main line, due to the higher speeds, allowed stricter gauge limits, and more maintenance work on these lines maintenance work is performed on these lines.

5. Future research possibilities

The authors formulated ideas for future research as follows:

- During the preparation of this article, some sections have been transformed over time from an already occurring widening to a narrowing. To examine the deterioration, taking into account the curve radius categories, traffic loading, and curve radii;
- To investigate how the track gauge changes for small radius curves at lower permitted speeds or large radius curves at higher speeds under the same traffic load;
- The effect of the maintenance work on the track gauge, with particular reference to sleeper repairs and replacements;
- To consider special track sections, i.e., rail joints, turnouts, etc. [10,41–44].

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Abbreviations

2D or 2-D	two dimensions or two dimensional
3D or 3-D	three dimensions or three dimensional
4G	fourth generation wireless
5G	fifth generation wireless
AL	alarm limit
ANN	artificial neural network
BCC	beginning point of the circular curve
BT	beginning point of the transition curve
CC	circular curve
ECC	end point of the circular curve
EC	entire curve considering it between the beginning points of the transition curves or if there is not any transition curve, between the beginning and the very last point of the curve
ET	end point of the transition curve
EU	European Union
GD	Gauss-distribution or Gaussian-distribution
IAL	immediate action limit
ICP	iterative closest point
IL	intervention limit
IoT	internet of things
IoT-DTG	internet of things enhanced digital track gauge
KS	Kolmogorov–Smirnov

LCD	liquid crystal display
LD	lognormal distribution
LED	light emitting diode
Ltd.	Limited company
MÁV CRTI Ltd.	MÁV Central Rail and Track Inspection Ltd., Budapest, Hungary
MÁV or MÁV Ltd.	Hungarian State Railways Ltd., Budapest, Hungary
MGT	million gross tons
mov. avg.	moving average
MSE	mean squared error
ND	normal distribution
NND	non-normal distribution
RCF	rolling contact fatigue
RoLa	rolling road (trailers are transported on trains, original name: "rollende Strasse" in German language)
SGD	Singapore dollar
SIM	subscriber identity module
SVM	support vector regression
TC	transition curve
TSI	Technical Specification of Interoperability (see [40])
Wi-Fi	wireless fidelity

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