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Research Article

Sensitivity of Geometric Parameters in the Sustainability Development of Continuous Welded Rail

Katarzyna Dybeł [1,*], Arkadiusz Kampczyk [1]

[1] AGH University of Science and Technology,
Faculty of Geo-Data Science, Geodesy, and Environmental Engineering,
Department of Engineering Surveying and Civil Engineering,
al. A. Mickiewicza 30, 30-059 Krakow, Poland
*e-mail: kdybel@agh.edu.pl, katarzynadybel@gmail.com

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Abstract: Continuous Welded Rails (CWR) are a key infrastructure element in the safety and efficiency of rail transportation. Their correct exploitation (operational) requires surveying and diagnostic monitoring based not only on the results of rail displacement measurements, but also on the geometric parameters of the track in the horizontal (H) and vertical (V) planes. Many researchers have proposed different approaches for surveying and diagnostic monitoring of CWR. However, they do not refer to the determination of railway track defectiveness (parametric defects, track defectiveness) respectively on straight and curvilinear segments. Research topics involving CWR constitute a continuous openness to research with particular application of synergy effects in the optimization of monitoring of CWR geometry shaped by exploitation processes. In this study, based on real measurement data of six geometric parameters (H: track gauge, gradient of track gauge, horizontal irregularities and V: cant, twist, vertical irregularities), the most sensitive parameters in sustainable development CWR are defined. The research answered that the most sensitive parameters in the sustainability development of CWR belong in the range of the plane H: gradient of track gauge and horizontal irregularities, and in the plane V: vertical irregularities. These escalate especially on curvilinear sections, requiring more significant maintenance capacity. Due to the growing importance of rail transportation as a sustainable, environmentally friendly, and mass transit mode, the research results provide a basis for life cycle management of CWR.

Keywords: Continuous Welded Rail; CWR; Geometrical parameters; Railway track defectiveness; Surveying

I. INTRODUCTION

Developments in infrastructure technology provide new ways to solve existing problems in an efficient and cost-effective manner [1], [2], [3]. Investments in rail transport infrastructure often in the technical field are related to replacement of conventional railway tracks (track) with Continuous Welded Rails (CWR) in order to increase passenger comfort, reduce train running time and thus make rail more competitive in the transport sector. Research on ensuring the stability of CWR and improving its condition monitoring systems is an active area of research that is of great importance and constantly evolving [4], [5], [6]. Sabato and Niezrecki in [7] note that it is important to monitoring the construction condition (Structural Health Monitoring, SHM) of aging railway tracks. Mrówczyńska et al. in [8] aptly state that regardless of the results and their interpretation, we should remember that in the case of geodetic measurements and continuous or periodic geodetic monitoring, the choice of the measurement method and methods of data processing is determined by the nature of the object and specific terrain conditions. In turn, Shvets in [9] notes that experimental studies, while sufficiently reliable, are resource-intensive, time-consuming and cannot cover all situations that may occur during exploitation. Theoretical and experimental research are complementary and should be conducted together.

The major feature of CWR design is the presence of temperature stresses in the rails, which affect the stability parameters during its operation (exploitation). Violations committed during the construction of a CWR, as well as in the process of current maintenance, together with the impact of train load and natural and climatic factors, create conditions for the growth of temperature stresses in rails and changes in the temperature regime of their operation [10]. The combination of these factors can finally lead to deformation or damage to the railway track structure, consequently risking the safety of operations. An important role in preventing damage propagation in CWR is the regular monitoring of the geometry and temperature condition of the rails [11], [12]. Kukulski et al. in [13] presented an effective analytical method for diagnosing the condition of CWR based on experimental measurements. Supporting the decision process in the area of track repair or maintenance. In addition, in [13] they recognise that in the case of a CWR, the costs of its maintenance are about 25% lower than those of a classic track. There is also significantly less wear and tear on vehicles and traction energy consumption, with better ride smoothness and less noise. The interest in the issue of CWR is connected, among others, with the change in operating conditions of modern railway by increasing the speed of passenger trains and the permissible axle loads on the rails. The CWR, in comparison with the classic track, provides better ride smoothness together with a reduction of the acoustic wave emission associated with the passage of the train [13].

Most railways are described in terms of piece-wise curves [14]. The application of appropriate geometry is particularly important for tracks in operations, modernization, revitalization and during repair work. Directly reflected in the comfort and safety of transportation and in the maintenance needs and sustainable cycle of their life management. Hasan in [15] derived formula to determine the threshold value: the temperature limits at which hot-weather or cold-weather patrolling is to be enforced if the radius happens to be sharper than the threshold radius. Doyle and Thomet in [16] note that passenger comfort is an important constraint on high-speed operation in curves and transitions. A detailed analysis of methods of track stability estimation for small radius curves is presented in papers [15], [17]. Conditions for the safe exploitation of CWR require monitoring their geometric parameters, especially in plane:

1. horizontal (H):
- track gauge,
- gradient of track gauge (track gauge gradient),
- irregularities of track rails in the horizontal plane (horizontal irregularities),

2. vertical (V):
- cant (superelevation),
- twist,
- irregularities of track rails in the vertical plane (vertical irregularities).

To the factors threats to the stability of the CWR include, among others:

- temperature spikes,
- longitudinal displacements of the rails (creeping of the rails, pl. pełzanie toków szynowych),
- incorrect technical condition,
- operational impacts.

Failure to comply with normative construction conditions and maintenance of the CWR combined with the effects of operational influences and weather conditions can lead to disorders balance of forces inside the railway track structure. Increasing the risk of deformation. A key role in providing CWR stability and driving comfort of rolling stock is played by surveying and diagnostic monitoring. The sustainability development of the research topic undertaken is a development that meets the needs of scientists, researchers, end users, industry and branch-users, decision makers from many countries and professional backgrounds without compromising the ability of future generations, and especially in correspondence of ensuring the CWR needs that occur. The idea of sensitivity of geometric parameters in the sustainability development of Continuous Welded Rail is to support sustainable decision making for rail infrastructure. One of the main challenges facing the world today in terms of the development of transport components is sustainability development. The most current challenge to be met for a fully functional rail transport is seamlessly connected infrastructure components in a sustainable development system. The main pillar of rail transport infrastructure is the railway track, which requires measures to ensure safe exploitation.

The main objective of this research is to define the most sensitive geometric parameters in the H and V plane escalating especially in straight and curvilinear segments in the sustainability development of CWR. The research included analysis and evaluation defectiveness of geometric parameters in straight and curvilinear segments (transition curves/spirals, circular curves, compound curve). Based on real measurement data of six geometric parameters (H: track gauge, gradient of track gauge, horizontal irregularities and V: cant, twist, vertical irregularities).

Railway track defectiveness (parametric defects, track defectiveness) is a relative measure of railway track condition. It depends on the maximum speed of the trains V_{max}. Its formula represents the ratio of the railway track length − on which the permissible deviations are exceeded − to the total length considered. Railway track defectiveness refers to the individual geometric parameters in the H and V planes. Railway track defectiveness is grounded in regulation Id-14 (D-75) [18]. It define the defectiveness of each parameter on the baseline segment being evaluated as the ratio of the sum of the lengths of the segments where allowable deviations are exceeded to the total length of that segment. For each measured railway track parameter, the defectiveness is (1) [18]:

$$W = \frac{n_p}{n} \qquad (1)$$

where:

n_p – number of signal samples exceeding the permissible deviations in the analyzed segment,
n – number of signal samples on the analyzed segment.

Research was conducted on three real objects – railway lines, including five research objects – railway tracks characterized by different geometric features in plan and profile as well as operational elements of transportation engineering (**Table 1 - 3**):

Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$ Track no. 1
Object no. $R_{143\_1\_2}$ Track no. 2
Object no. R_{144_1} Track no. 1
Object no. R_{161_1} Track no. 1
Object no. R_{161_2} Track no. 2

Table 1. *Technical and exploitation specification of research objects*

Technical and exploitation parameters of research objects	
Name	***Values***
Exploitation load T	$10 \leq T < 25$
Speed of passenger trains V_{max}	$80 < V_{max} \leq 120$
Speed of freight trains V_{ft}	$60 < V_{ft} \leq 80$
Permissible axle loads P	$210 \leq P < 221$

where:

T – in [Tg/per year]
V_{max} – in [km/h]
V_{ft} – in [km/h]
P – in [kN]

Table 2. *Characteristics of selected railway track - permanent way elements of research objects*

Research object	***Rail type***	***Sleeper type***	***Type of rail fastening***	***Historic inauguration***	***Type of refurbishment***
Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$	60E1	wooden (along the 'protective section' length)	Skl (along the 'protective section' length)	1884 1) 1890 3)	RM – 2014
		PS94	SB		
Object no. R_{143_2}	60E1	wooden (along the 'protective section' length)	Skl (along the 'protective section' length)	1896 1) 1890 3)	RM – 2015
		PS94	SB		
Object no. R_{144_1}	UIC60	wooden	K	1857 2) 1964 3)	RM – 1980 RR – 2019
Object no. R_{161_1}	60E1	PS83	SB	1874 3)	RM – 2020
Object no. R_{161_2}	60E1	PS83	SB	1874 3)	RM – 2020

where:

RM – refurbishment – master repair
RR – refurbishment – running repair
1) – opening for exploitation (put into service)
2) – technical acceptance
3) – on the basis of the railway infrastructure quantity evidence (records) – fixed asset

The identification of real objects preserves their anonymity so that no direct identification can be made for a given building object.

Results at all research objects include one measurement period – 2021. The authors verified hypotheses related to the sensitivity of geometric parameters in the sustainability development of Continuous Welded Rail, i.e:

- the possibility to inadequate maintenance of CWR may affect the track defectiveness,
- the possibility to indicate CWR segments most vulnerable to exceeding permissible deviations,
- the possibility to select the most sensitive geometrical parameters of CWR.

Table 3. *Characteristics of actual and research objects*

Characteristics of a curvilinear and straight segment	***Kilometer [km]***	***Geometry of the curvilinear segment***	***Characteristics of the research object***		
			Speed [km/h]	***Category of railway line***	***Type of railway line / movement***
Research object: Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$					
Curvilinear segment:			V_{max} = 120 V_{ft} = 100	prime	double-track, single direction
Transition curve Compound curve Transition curve	1+006.22 ÷ 1+036.22 1+036.22 ÷ 1+357.02 1+357.02 ÷ 1+417.02	L_1 = 30.00 m D_1 = 282.80 m R_1 = 1720.00 m D_2 = 38.00 m R_2 = 2050.00 m L_2 = 60.00 m $C_{ant\ t.}$ = 30 mm			
Straight segment:					
Straight	1+417.02 ÷ 2+517.02	D_3 = 1100.00 m			
Research object: Object no. R_{143_2}					
Curvilinear segment:			V_{max} = 120 V_{ft} = 100	prime	double-track, single direction
Transition curve Circular curve Transition curve	0+986.04 ÷ 1+056.04 1+056.04 ÷ 1+304.44 1+304.44 ÷ 1+454.44	L_1 = 70.00 m D_1 = 248.40 m R_1 = 1740.00 m L_2 = 150.00 m $C_{ant\ t.}$ = 30 mm			
Straight segment:					
Straight	1+454.44 ÷ 2+554.44	D_2 = 1100.00 m			
Research object: Object no. R_{144_1}					
Curvilinear segment:			V_{max} = 70 V_{ft} = 70	prime	single-track, double direction
Transition curve Circular curve Transition curve	14+860.00 ÷ 14+980.00 14+980.00 ÷ 15+640.00 15+640.00 ÷ 15+760.00	L_1 = 120.00 m D_1 = 660.00 m R_1 = 1090.00 m L_2 = 120.00 m $C_{ant\ t.}$ = 40 mm			
Straight segment:					
Straight	15+760.00 ÷ 16+860.00	D_2 = 1100.00 m			
Research object: Object no. R_{161_1}					
Straight segment:			V_{max} = 70 V_{ft} = 70	prime	double-track, single direction
Straight	4+411.24 ÷ 4+611.24	D_1 = 200.00 m			
Curvilinear segment:					
Transition curve Circular curve Transition curve	4+611.24 ÷ 4+651.24 4+651.24 ÷ 4+707.02 4+707.02 ÷ 4+747.02	L_1 = 40.00 m D_1 = 55.78 m R_1 = 3300.00 m L_2 = 40.00 m $C_{ant\ t.}$ = 20 mm			
Straight segment:					
Straight Straight	4+747.02 ÷ 4+847.02 9+500.00 ÷ 10+300.00	D_2 = 100.00 m D_3 = 800.00 m			
Research object: Object no. R_{161_2}					
Straight segment:			V_{max} = 70 V_{ft} = 70	prime	double-track, single direction
Straight	4+408.69 ÷ 4+608.69	D_1 = 200.00 m			
Curvilinear segment:					
Transition curve Circular curve Transition curve	4+608.69 ÷ 4+648.69 4+648.69 ÷ 4+706.38 4+706.38 ÷ 4+746.38	L_1 = 40.00 m D_1 = 57.69 m R_1 = 3300.00 m L_2 = 40.00 m $C_{ant\ t.}$ = 20 mm			
Straight segment:					
Straight Straight	4+746.38 ÷ 4+846.38 9+500.00 ÷ 10+300.00	D_2 = 100.00 m D_3 = 800.00 m			

where: L_i – length of the transition curve, D_i – straight or curve length, R_i – radius, V_{max} – speed of passenger trains, V_{ft} – speed of freight trains, $C_{ant\ t.}$ – theoretical cant value

The research has provided the answer that the inadequate maintenance of the shape of the gravel prism layers in CWR are reflected in the railway track defectiveness, especially in the gradient of track gauge. To the most sensitive parameters in the sustainability of CWR belong in the range of the plane H: gradient of track gauge and horizontal irregularities, but in the plane V: vertical irregularities. These escalate especially on curvilinear segments, requiring more significant maintenance capacity. Completed research provides a source of knowledge and support for optimization of Continuous Welded Rails geometry monitoring.

II. Methods and applied materials

The search for innovations in rail transport results in better use of existing potential and shapes new development perspectives. Optimization in maintenance systems CWR contributes to the efficient and sustainable development of transport infrastructure, while creating new opportunities for transport and logistics operators. In order to make measurements and research on the sensitivity of geometric parameters in the sustainability development of CWR, a direct method was used − mobile measuring equipment using electronic self-recording track gauge TEC-1435 N2 (**Fig. 1**, **Fig. 2**) and for measurements of the displacement of CWR rails used a measurement method called the fixed point method.

Figure 1. *Electronic self-recording track gauge TEC-1435 N2*

Figure 2. *Electronic self-recording recorder of track gauge TEC-1435 N2*

The construction of the track gauge is three-point, and direct measurements are made without load. The performed measurements provided the parameters of the track geometry in the plane H: track gauge, gradient of track gauge, horizontal irregularities and in the plane V: cant (position of the track in the cross-section), twist, vertical irregularities.

In terms of the measurement work carried out, the research also included monitoring of such elements as: lack of sleepers in a given kilometer of the railway line, weed, breaks – broken rail and local depressions of the running surface (squat), lack of screws, prism condition, etc., and locations of features/events around existing ones, e.g., railway level crossing, bridges, overpasses, tunnels, hectometric points, etc.

The scientific and research work on the topic of sensitivity of geometric parameters in the sustainability development of Continuous Welded Rail was carried out in correspondence with legal regulations:

- Instruction for Measuring, Researching and Assessing Track Condition Id-14 (D-75) [18],
- Technical Conditions for Maintaining Track Surface on Railway Lines Id-1 (D-1) [19],
- Instruction for railway superstructure diagnosis Id-8 [20].

Direct measurements in accordance with regulations Id-14 (D-75) [18] i Id-1 (D-1) [19] are made:

- twice a year (spring and autumn) – for all railway tracks of each category. Direct measurements are not performed when a detour with a measuring vehicle, e.g. a measuring trolley (Measure track motor car, Measuring motor car, Track recording cars, Real time systems for geometry cars), is planned,
- once every six months – measurement of railway tracks in curves with radius 350 ÷ 500 meters on railway lines of all categories,
- once every four months – measurement of railway tracks in curves with radius less than 350 meters on railway lines of all categories.

Measurements of the displacement of CWR rails as places susceptible to creeping of the rail were carried out using a measurement method called the fixed point method [19], [20]. The purpose of this method was to determine the value of the creeping of the rails in relation to fixed points. The measurements were conducted in all railway tracks of the research objects – once a year before the period of increased temperatures.

Results for all objects include one measurement period – spring 2021 r. using the direct method and the fixed point method (**Fig. 3**):

Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$ Track no. 1

Object no. $R_{143\_1\_2}$ Track no. 2

Object no. R_{144_1} Track no. 1
Object no. R_{161_1} Track no. 1
Object no. R_{161_2} Track no. 2

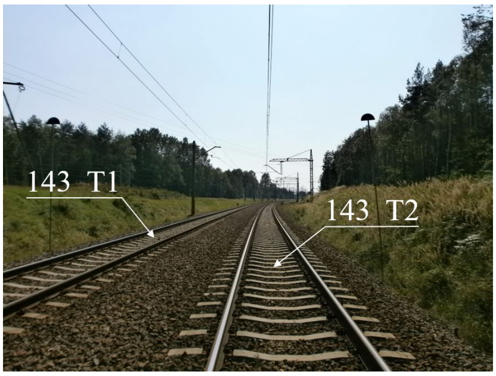

Figure 3. *Actual and research object: Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$ and Object no. $R_{143\_1\_2}$*

III. Results and discussion

Conducting research on the sensitivity of geometric parameters in CWR sustainability development is applicable to rail transportation engineering, while providing effective support for optimizing the monitoring of such structures. It significantly supports the process of correct analysis and assessment of the technical condition of rail transport infrastructure. Implies correct diagnosis and correctness of actions taken to prevent the development of further damage threatening the safe operation of the construction.

The research conducted in this publication, while combining scientific and practical knowledge and correlating with the results of research Shvets in [9], that "theoretical and experimental research are complementary and should be conducted together" are part of the application of synergy effects in optimizing the monitoring of CWR geometry shaped by operational processes.

The reason for the occurrence of a high level of defectiveness of the railway track of particular geometrical parameters may be, for example, the weakening of the construction caused by the slack in the rail fastenings, slight resistance of the ballast, utility damage, lack of ballast − insufficient maintenance of the shape of the ballast prism of the railway superstructure, etc. Research in this direction leads to the identification of CWR segments most exposed to the occurrence of permissible deviation exceedances and to the selection of the most sensitive geometric parameters in the sustainability development of Continuous Welded Rail.

CWR stability in sustainability development requires not only surveying and diagnostic monitoring of longitudinal rail displacements (creep of the rail), but also geometrical parameters in the horizontal and vertical plane. Longitudinal displacements of the rails have an influence on the stability of the CWR. This is confirmed by Towpik in [21], stating that longitudinal displacements of the rails and local horizontal and vertical deformations of the track increasing over time can lead to local accumulation of stresses causing deformation of the track frame leading in extreme cases to loss of stability by the CWR.

The research topic covering the sensitivity of geometric parameters in the sustainability development of Continuous Welded Rail, then its objectives, including specific hypotheses and its relevance are in demand not only in the scientific and research community, but also in the branch. The idea of the Authors is to ensure that the research results are communicated and understood also by researchers and related industry professionals not involved in this publication topic. Therefore, a detailed expression of them in % has been made to enable others to replicate and use the published results. As a result of the analysis and evaluation of the acquired geometric data in the CWR, a histogram of permissible deviation exceedances was developed, distinguishing straight and curvilinear segments (curves and transition curves) of all research objects (**Fig. 4**).

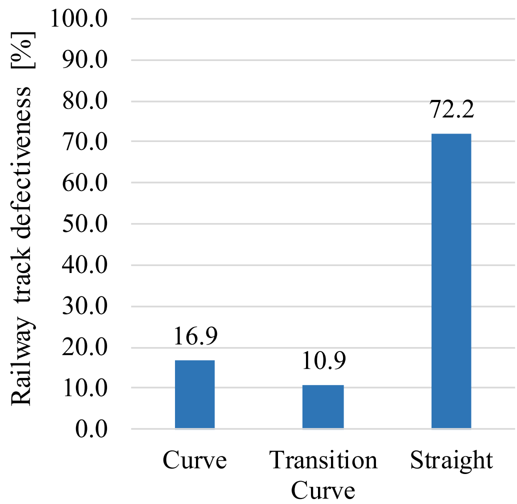

Figure 4. *Histogram of permissible deviation exceedances in the measured data samples all research objects*

Fig. 4 shows a significant spike in the level of railway track defectiveness on straight sections up to 72.2 %. This spike is determined by the number of parametric defects in the gradient of track gauge in Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$. Inadequate maintenance of gravel prism layer formation − lack of ballast in CWR in Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$ is directly reflected in the parametric defects of the whole set of exceeded permissible deviations in all straight segments of the research. Numerous defects in the gravel, up to a value of 23 cm relative to the top surface of the sleeper, contribute to the disturbed geometry of this research object (**Fig. 5**). At the same time having a direct reflection in straight and curvilinear segments of the main aim of the research – which is to define the most sensitive geometric parameters in the H and V plane escalating especially in straight and curvilinear segments in the sustainability of CWR. Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$ disrupted the insights of the research as a whole. Inadequate maintenance of CWR through proper gravel prism profiling has an impact on the track defectiveness. Thus confirming the hypothesis of the possibility that insufficient maintenance of CWR on the track defectiveness.

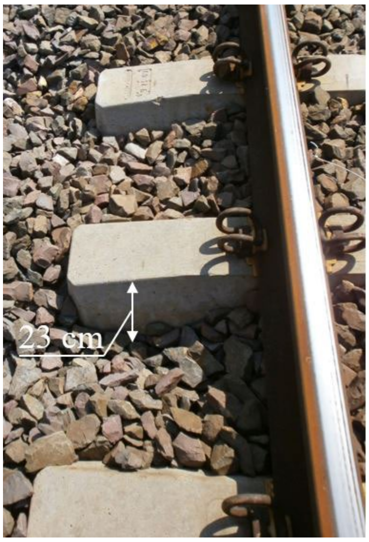

***Figure 5.** Loss of ballast in Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$ – straight segment*

Therefore, in continuing the analysis and evaluation of geometric parameters in CWR, this straight segment was removed – obtaining a histogram of permissible deviation exceedances in the measured data sample without a straight section of Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$ (**Fig. 6**). As a result of removing the disturbed straight segment from research Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$, obtained insights into the totality of all research objects. From which it is concluded that the number of parametric defects in CWR escalates significantly in curvilinear segments, embracing in the curves 16.9 % and in the transition curves 10.9 %, giving a total of 27.8 %. These segments are more susceptible to defects than the straight segments 13.9 %. At the same time, it should be taken into account that the histogram contained in the fig. 6 includes all research objects, excluding only straight segment of Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$. So, at this stage of the research, it represents a certain deficiency in the proportionality of the analogy of straight versus curvilinear segments.

Consequently, in order to properly define and identify the segments CWR the most exposed to the occurrence of exceedances of permissible deviations were completely eliminated Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$ from the overall analysis and evaluation of the sensitivity of geometric parameters in the sustainability development of CWR. De facto, in the final stage of the research, conducting analysis and evaluation on three real objects – railway lines, covering four research objects – railway tracks. The result obtained shows **Fig. 7**, including histogram of permissible deviation exceedances in the measured data sample without Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$.

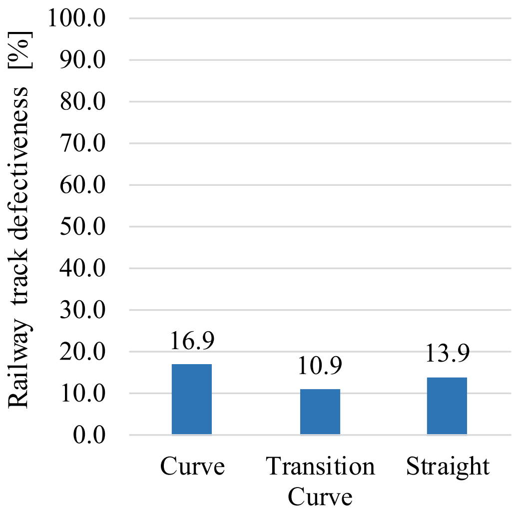

***Figure 6.** Histogram of permissible deviation exceedances in the measured data sample without a straight segment of Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$*

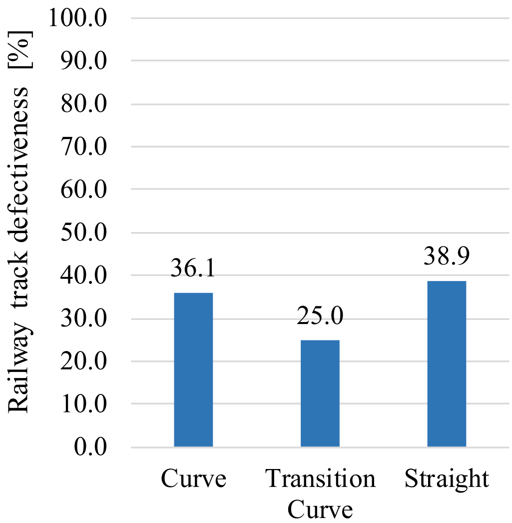

***Figure 7.** Histogram of permissible deviation exceedances in the measured data sample without Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$*

The histogram in **Fig. 7** shows in the whole research on the verification of the hypothesis of the possibility of indicating segments CWR most susceptible to the occurrence of exceedances of the permissible deviations, it is unambiguously that for CWR geometric parameters are more exposed on curvilinear segments than on straight segments. Track defectiveness in segments:

- curvilinear is 61.1 % (of which on curves 36.1 %, on transition curves 25.0 %),
- straight is 38.9 %.

Both figure 6 and figure 7 confirm that the highest level of defectiveness in CWR geometric parameters occurs in curvilinear segments. Conducting verification of the hypothesis regarding the possibility of selecting the most sensitive geometric parameters of CWR the results were interpreted as the percentage distribution of individual parametric defects for all research objects (**Fig. 8**).

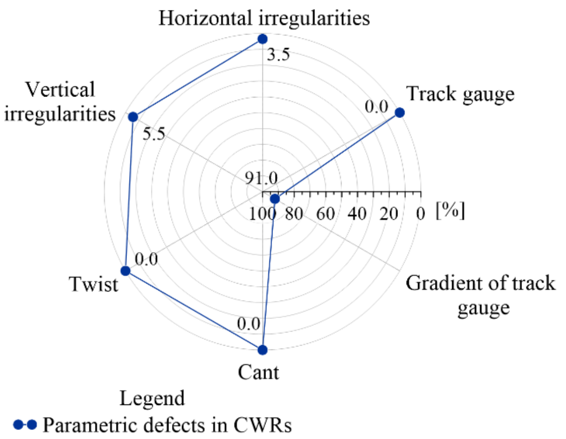

Figure 8. *Percentage distribution of individual parametric defects*

Conditions for safe CWR operation require monitoring of six geometric parameters. In the plane H: track gauge, gradient of track gauge, irregularities of track rails in the horizontal plane. However, in the plane V: cant, twist, irregularities of track rails in the vertical plane. Of the six geometric parameters analysed and evaluated, the most vulnerable to sensitivity escalation is:

- gradient of track gauge 91.0 % ,
- irregularities of track rails in the vertical plane 5.5 % ,
- irregularities of track rails in the horizontal plane 3.5 % .

The research answered that to the most sensitive parameters in sustainability CWR include in the plane H: gradient of track gauge and irregularities of track rails in the horizontal plane, while in the plane V: irregularities of track rails in the vertical plane.

It was also confirmed that most parametric defects exist on curves with smaller radiuses (**Fig. 9**):

- Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$:
  $R_{143\_1\_1}$ = 1720.00 m curve 23.5 %
- Object no. $R_{143\_1\_2}$:
  R_{143_2} = 1740.00 m curve 29.4 %
- Object no. R_{144_1}:
  R_{144_1} = 1090.00 m curve 47.1 %

which indicates that the more complicated the track geometry, the more the probability of defects in the geometry parameters of CWR is higher. It is also rationalized by the type of line and transport engineering. Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$ and Object no. $R_{143\_1\_2}$ is a double-track line carrying single direction movement in each track, but both track no. 1 and 2 carry passenger and freight train movements (**Table 3**). In contrast Object no. R_{144_1} is a single-track line (in the analyzed kilometreage) with two-way movement, mainly freight (**Table 3**).

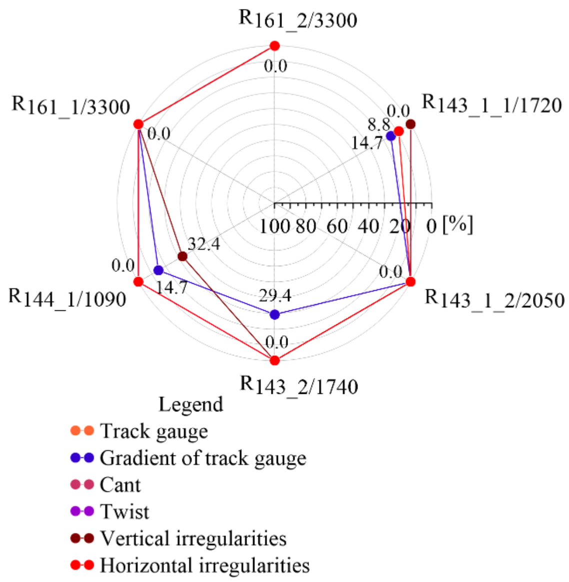

Figure 9. *Percentage distribution of parametric defectivity on a given curve radius, where: $R_{xxx\_x/xxxx}$ – identification of the research object with information on the value of the curve radius (for example: $R_{144\_1/1090}$ – radius of Object no. R_{144_1} in railway track no. 1, value 1090 m)*

Analogously, the research indicated that the highest number of parametric defects occurs on curvilinear segments (curves and transition curves) (**Fig. 10**):

- Object no. $R_{143\_1\_1}$ and $R_{143\_1\_2}$ 21.5 %
- Object no. R_{143_2} 35.7 %
- Object no. R_{144_1} 42.8 %

Uren and Price in [22] state that a transition curve differs from a circular curve in that its radius is constantly changing. As may be expected, such curves involve more complex formulae than curves of constant radius and their design can be complicated. Basak and Nowak in [23] dealing with dynamics of railway vehicles movement on transition curves conclude that the transition curve is a very important element of any road, including a railway road, although it is almost invisible to traffic participants.

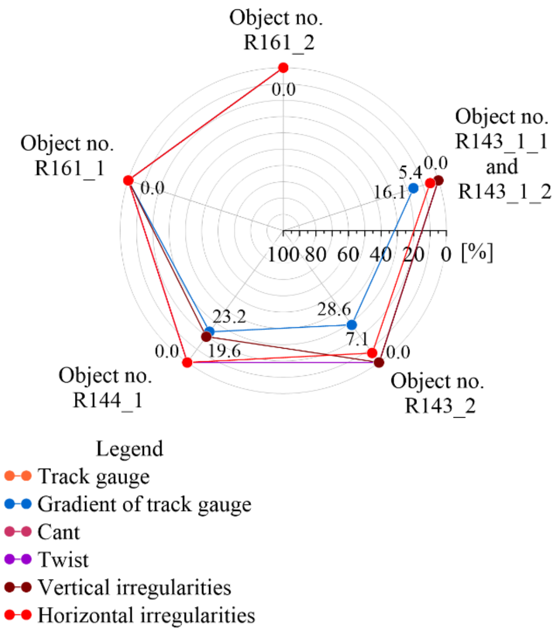

Figure 10. *Percentage distribution of parametric defects on curvilinear objects*

Track layout geometry (TLG), is spatial in nature, comprising [24]:

- the longitudinal horizontal plane (in plan), where straight sections, curvilinear sections, among others, are to be distinguished.
- the vertical longitudinal plane (in profile), where the following should be distinguished railway track segments with the same gradient – slope, vertical circular curves: concave or convex.
- the plane in which, due to railway practice, the system of railway track geometrical parameters comprising the vertical and horizontal railway track position is used: vertical parameters V and horizontal parameters H.

The geometrical layout of the railway track is a set of features that shape the position of the railway track in the vertical and horizontal plane, including straight and curvilinea sections. TLG at both stations and open line is dependent among others from train speeds, kinematic volumes and land availability. Land availability has an influence on the type of curvilinear sections used. At the same time, TLG has a decisive influence on the exploitation parameters of railway lines, especially maximum speed of trains, energy consumption, movement resistances [25], then on the life cycle of individual facilities, exploitation and maintenance costs of the railway track – permanent way (superstructure), and finally on the smooth running (smoothness of driving). The scientific and research work carried out, combined with practice and in-depth discussion, has led to further conclusions:

1. **Identification of the most sensitivity of geometric parameters in the sustainability development of Continuous Welded Rail**

Conditions for the safe exploitation of CWR at each monitored object included the study of six geometrical parameters. Showing that the most sensitive parameters in the sustainability development of CWR include in the H-plane range: gradient of track gauge and irregularities of track rails in the horizontal plane, while in the V-plane range: irregularities of track rails in the vertical plane. These parameters are characterised by one essential element. They are continuous parameters. Parameters such as track gauge and cant do not belong to them - as they are point parameters, the identification of which takes place in a single cross-section of the railway track. In contrast, the most sensitive parameters:

- irregularities of track rail in the vertical plane,
- irregularities of track rail in the horizontal plane,
- gradient of track gauge,

have a common denominator, which is the continuity of their identification basis.

Vertical irregularities, in practice called ‘holes’, are identified on a measuring base equal to 10.0 m in length. Similarly, the measurement base for identifying horizontal irregularities is also 10.0 m. In turn, the gradient of track gauge shall be defined on the basis of a measurement base of 1.0 m.

2. **Interaction of defects in continuous parameters with infrastructure elements and its geometry**

The railway superstructure is a construction designed to transfer to the ground the stationary and moving loads associated with the movement of railway vehicles, includes the railway track, which consists of two rails laid at a set distance, being at the same time the basic load-bearing system of the railway superstructure. In the studies conducted on the sensitivity of geometric parameters in the sustainability development, all railway tracks are Continuous Welded Rail. Railway track with welded rails with lengths of 180 m and more is CWR (Table 3) [19]. The components of the railway superstructure, especially rail type, sleeper type, type of rail fastening, ballast (**Table 2**) represent a particular interaction in the sustainability development of Continuous Welded Rail. The railway superstructure elements (including their constituent segments) and the location of the continuous parameter defect - argue the presence of the parameter defect:

- the gradient of track gauge, especially in linear structures with a structural assembly made of wooden sleepers, especially with K-type rail fastenings system. The study revealed the defects and escalation of this parameter also in the structural assembly assembled with wooden sleepers and Skl-type rail fastenings system - applied to CWR protection spans (protective section). The defectiveness of this parameter is also present in the areas of peak values of CWR creeping of the rail, in a place and in the vicinity of crest curve - profile fold (change in gradient, profile bends) and engineering structures represented by culverts and railway level crossings,

- vertical irregularities especially in linear structures, near and at the values climaxes of CWR creeping of the rails, engineering structures represented by culverts and railway level crossings,
- horizontal irregularities especially in linear structures located near and on railway level crossings and transition curves. The research showed an escalation of this parameter also in the structural assembly based on wooden sleepers - applied in the CWR protection spans.

Creeping of the rail can lead to a build-up of stress in certain sections of the railway track and consequently in deformation. Sensitivity of geometric parameters in the sustainability development of Continuous Welded Rail identifies CWR locations requiring maintenance intervention. Especially the defects in the parameters of horizontal and vertical irregularities, even more so when they are in interaction with the symptoms of creeping of the rail.

The most sensitive CWR parameters, which are especially represented by vertical and horizontal irregularities and the gradient of track gauge characterise its newralgic state. Being of considerable importance in its maintenance, exploitation and life cycle management. As a result, it provides support in the design and planning of repairs.

At the same time, it is important to be aware that the geometrical parameters studied in this publication, especially: gradient of track gauge, irregularities of track rails in the horizontal plane, irregularities of track rails in the vertical plane, are among the most sensitive parameters in the sustainable development of Continuous Welded Rails. Especially on curvilinear segment.

IV. CONCLUSIONS

In our current publication, we have distributed research in contributing to the scientific discipline of civil and transportation engineering in the subject area of sensitivity of geometric parameters in the sustainability of Continuous Welded Rail. Based on real measurement data of six geometric parameters (H: track gauge, gradient of track gauge, irregularities of track rails in the horizontal plane and V: cant, twist, irregularities of track rails in the vertical plane) the most sensitive parameters in the sustainability of CWR were defined. The research included defects in each parameter on real objects – a specific case study, characterized by different geometric characteristics in plan and profile and operational elements of transportation engineering. The conducted research confirmed the reasonableness of the hypotheses. An explicit case study provided the determination of the segments CWR the most vulnerable to exceeding permissible deviations and selection of the most sensitive geometric parameters CWR.

The research answered that the insufficient maintenance of gravel prism layer formation in CWR is reflected in the parametric defect especially the gradient of track gauge. For the most sensitive parameters in sustainability CWR belong in terms of the plane H: gradient of track gauge and horizontal irregularities, while in the plane V: vertical irregularities. These escalate especially on curvilinear segments, requiring more significant maintenance capacity.

The conducted research also confirmed that both surveying and diagnostic knowledge, as well as measurement technologies (use of advanced measuring instruments and methods and techniques) combining scientific and practical knowledge, ensure the implementation of the research topic sensitivity of geometric parameters in the sustainability development of Continuous Welded Rail, having a reflection in:

- construction, operation and maintenance,
- design and planning process,
- innovation of surveying and diagnostic technologies,
- life cycle management,

rail transport infrastructure, in order to increase efficiency and availability.

The research also considered the effect of parametric defectiveness depending on the size of curve radius and curvilinear objects. The obtained research results are a novel source of knowledge and support in the analysis and evaluation of this type of construction in the discipline of civil engineering and transportation. Providing particularly new knowledge for enhancing the safety of rail transport infrastructure. This study includes monitoring CWR from the spring 2021 measurement period. This period is representative of a period of strong activity CWR, especially in terms of stability. In our next study, interaction with other measurement periods is predicted. Harmoniously focusing also on movement resistances of rail vehicles on Continuous Welded Rail Curves as a component of synergy in optimizing monitoring of CWR geometry shaped by operational processes.

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AUTHOR CONTRIBUTIONS

K. Dybeł: Conceptualization 50 %; Methodology 50 %; Software 51 %; Validation 50 %; Formal analysis 52 %; Investigation 50 %; Resources 50 %; Data curation 50 %; Writing—original draft preparation 50 %; Writing—review and editing 50 %; Visualization 52 %; Supervision 50 %; Project administration 50 % .

A. Kampczyk: Conceptualization 50 %; Methodology 50 %; Software 49 %; Validation 50 %; Formal analysis 48 %; Investigation 50 %; Resources 50 %; Data curation 50 %; Writing—original draft preparation 50 %; Writing—review and editing 50 %; Visualization 48 %; Supervision 50 %; Project administration 50 % .

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Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID

K. Dybeł http://orcid.org/0000-0003-2213-0562

A.Kampczyk http://orcid.org/0000-0001-9210-9668

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