ORIGINAL ARTICLE
DOI: https://doi.org/10.30932/1992-3252-2022-20-6-3

World of Transport and Transportation, 2022, Vol. 20, Iss. 6 (103), pp. 138–146

Additional Criteria of Change of Curvature and Temperature of Rails for Monitoring the Pre-Failure State of a Continuous Welded Rail in Plan

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ABSTRACT

The article discusses proposals referring to a new way to control the state of a continuous welded rail.

The main factors that have the greatest impact on the state of a continuous welded rail are displacement of rail and the state of a continuous welded rail in plan. This group of factors describes the temperature-stressed nature of operation of a continuous welded rail. Evaluated factors determining the properties which prevent displacement include the state of rail fastenings, the width of the shoulder of the ballast prism, the presence of hanging and unsupported sleepers, and fulness of the ballast cribs, space between the sleepers.

The combination of these factors makes it possible to identify a complex coefficient with a high degree of reliability to assess the pre-failure state of a continuous welded rail associated with the risk of loss of stability of a continuous welded rail, the degree of danger of violation of train traffic safety.

In order to assess the state of a continuous welded rail and the degree of its deterioration, the paper presents evaluation criteria. They allow getting a comprehensive picture of the state of any section of a continuous welded rail based on the results of its inspection by diagnostic tools and creating a list of recommendations to eliminate the identified violations.

The paper highlights also the shortcomings of the existing methodology for assessing the state of a continuous welded rail in plan, which is based on the analysis of changes in the curvature of welded rails in plan in time. The retrospective analysis carried out by the author shows that there are cases of a sharp change in the state of a continuous welded rail in plan, which are currently not considered by the existing evaluation criteria. To increase detectability of such sections of a continuous welded rail, it is proposed to supplement the existing algorithm with additional evaluation criteria referring to changes in curvature of welded rails and in rail temperature, which allow timely identification of the places of a sharp change in the state in plan.

Subsequent studies are suggested to establish the relationship between the rail temperature and the sites of a sharp change in the state of a continuous welded rail in plan.

Keywords: railways, pre-failure state, curvature, control and analysis of pre-failure state of continuous welded rail, temperature stresses, ranking matrix, continuous welded rail, coefficient.

For citation: Atapin, V. V. Additional Criteria of Change of Curvature and Temperature of Rails for Monitoring the Pre-Failure State of a Continuous Welded Rail in Plan. World of Transport and Transportation, 2022, Vol. 20, Iss. 6 (103), pp. 138–146. DOI: https://doi.org/10.30932/1992-3252-2022-20-6-3.

The text of the article originally written in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

INTRODUCTION

In the world practice of railway operation, the design of a continuous welded rail is considered as one of the advanced structures of the track superstructure, which is confirmed by the accumulated experience and its advantages. In the existing realities, it can work under almost any operational and climatic conditions[1].

These advantages of the design of a continuous welded rail have allowed to ensure a constant increase in the rate of railway network with continuous welded rails as compared with traditional jointed track. The extension of the part of the network where continuous welded rails are laid is associated with implementation of the following tasks[2]:

- Improvement of working conditions of the railway track and rolling stock.
- Increasing the service life of the railway track structure and enhancing reliability of its operation.
- Improvement of technical and economic performance of the railway track.
- Ensuring smooth running of rolling stock.
- Reduction in the number of shock-dynamic zones, thus contributing to the improved operation of automatic centralised traffic control and interlocking systems.

To date, the length of continuous welded rails makes up more than 75 % of the total length of main tracks in Russia. This fact indicates that the entire network of JSC Russian Railways has switched to operation of the track of this design.

Many postulates and assumptions that have been accepted since the time of the first laying and initial operation of a continuous welded rail are still used today. As a rule, these principles were based on little experience of operating a continuous welded rail, as well as on insufficient knowledge and outdated approaches to its maintenance. One of the main drawbacks inherent in maintenance of a continuous welded rail is manifested in terms of diagnosing its actual state. As a result, not all the features of this design, especially those related to the temperature regime of its operation, are fully taken into account.

As it is known, besides failures caused by the actual geometry of the rail track, as well as the defects in the elements of the track superstructure, the change in temperature of welded rails during operation can also cause failures due to poor quality maintenance and diagnosis of the state of a continuous welded rail. Examples of such failures as «buckling», «longitudinal displacement», «track shift» are presented below. Such failures are usually classified as dangerous and are associated with the loss of stability of the assembled rails and sleepers. Besides, there may be also failures associated with formation of rail defects, rail breakage.

In this regard, the *objective* of this work is to develop and improve a method for determining the state of a continuous welded rail. Main research methods were those of comparison, direct measurements, and observation.

RESULTS

History of Development of Methods of Identifying Stability of Continuous Welded Rail

The analysis has shown that the initial methods for determining stability of a continuous welded rail appeared in 19th century. At that time, all the developed methods were aimed at studying a certain stage of the operation of the structure, and most of which were carried out empirically.

The starting point for theoretical studies of stability of a continuous welded rail is considered to be 1913 [1]. Subsequently, already existing methods continued to develop and new methods for determining stability of a continuous welded rail appeared, for the most part based on the calculation of critical forces in welded rails:

- Energy method.
- Method of differential equilibrium equations.
- Simulation modelling method.

One of the most modern ways to determine the state of a continuous welded rail is the finite element method (FEM), which, despite the complexity of creating a model, has a high accuracy of the results and the possibility of their graphic visualisation [2].

It should be noted that in recent years, a completely new method for assessing stability of a continuous welded rail, obtained from the

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[1] Instructions for design, laying, maintenance, and repair of a continuous welded rail, approved by order of JSC Russian Railways dated December 14, 2016, No. 2544/r. [Electronic resource]: https://tgarantproekt.ru/Documents/2544р%20Инструкция%20по%20устройству%2С%20укладке%2С%20содержанию%20и%20ремонту%20бесстыкового%20пути.doc. Last accessed 27.12.2022.

[2] Strategy of scientific and technical development of Russian Railways holding company for the period up to 2025 and an outlook up to 2030 (White Book), approved by order of JSC Russian Railways dated April 17, 2018, No. 769/r. [Electronic resource]: http://cipi.samgtu.ru/sites/cipi.samgtu.ru/files/belaya_kniga.pdf. Last accessed 27.12.2022.

data of diagnostic tools, has acquired special significance. It is based on the analysis of changes in the pre-failure state of a continuous welded rail [3].

This method in Russia was born thanks to the joint research of experts from INFOTRANS Research and Production Centre and JSC VNIIZhT, which resulted in the development of the Methodology for monitoring and assessing the state of a continuous welded rail based on data obtained from the results of measurements by track measuring equipment equipped with subsystems for monitoring stability of a continuous welded rail, initially intended for experimental application[3].

Based on the results of practical testing, the methodology was improved, re-approved and validated for permanent operation in 2017 (later it was further amended)[4]. Its implementation was supported by the developed software «Comprehensive analysis of the pre-failure state of a continuous welded rail» (CAPS CWR), which was installed at all sectors of the continuous welded rail of infrastructure directorates [4].

The Existing Algorithm of Assessment of the State of Continuous Welded Rail in Plan

The CAPS CWR software was based on the data regularly received from diagnostic tools and accumulated in RCDM (regional centre of diagnostics and monitoring of infrastructure equipment) and track divisions, and information and analytical databases. However, among the variety of data obtained, to solve the problem of reliably identifying problem areas of a continuous welded rail, it turned out to be necessary to identify the most significant factors for subsequent evaluation. The factors were classified according to the following principle:

- Identification and evaluation of thermal stresses in welded rails.
- Identification and evaluation of the holding properties of the assembled rails and sleepers as of several factors that as a rule try to hold the rails and sleepers and, in the presence of thermal stresses, weaken.

The first group of factors includes: rail longitudinal displacement (rail creep) and the state of a continuous welded rail in plan. Indirectly, and not directly, by analysing and evaluating these factors, according to the Methodology, sections of a continuous welded rail with thermal stresses are identified. To analyse and develop the coefficients characterising longitudinal displacement (rail creep, $C_{cr.}$) and the state of a continuous welded rail in plan ($C_{pl.}$), the following initial parameters are used: displacements on the «reference» sleepers and curvature of the right and left welded rails (Table 1).

The second group of factors includes those components that hold the assembled rails and sleepers in the longitudinal and transverse directions. These include (Table 1):

- Rail fastenings, the state of which is determined based on the analysis of changes in the unstable pattern.
- Shoulder width of the ballast prism, which is controlled according to the geometric dimensions of the ballast prism [5].
- Ballast crib fullness rate, determined by the presence of ballast in the space between sleepers.
- The presence of unsupported and hanging sleepers, diagnosed by calculating the gaps in the space under the sleepers according to natural irregularities in vertical plane.

The main «technical markers» of problems that show the existence of thermal stresses in a particular section of the welded rails are factors related to the first group. In case of their occurrence and growth over time, there is a threat of accumulation of thermal stresses.

The combination of these indicators with irregularities revealed during the diagnostics of the second group of factors, especially within a small (6–9 m) section, can lead to a violation of transverse stability of a continuous welded rail and subsequent failure [6–7].

The analysis and evaluation of all factors results in determination of the complex coefficient (C_c), which shows the state of the assembled rails and sleepers in terms of formation of a failure due to loss of stability (Pic. 1).

When determining the complex coefficient of the pre-failure state of a continuous welded rail for factors that characterise the holding properties, scale and weight indicators are

[3] Methodology for monitoring and assessing the state of a continuous welded rail based on data obtained from the results of measurements by track measuring equipment equipped with subsystems for monitoring stability of a continuous welded rail, approved by order of JSC Russian Railways No. 3120r dated December 25, 2014.

[4] Methodology for monitoring and assessing the state of a continuous welded rail based on data obtained from the results of measurements by track measuring equipment equipped with subsystems for monitoring stability of a continuous welded rail, approved by order of JSC Russian Railways dated October 17, 2017 No. 2115/r [limited access].

Table 1

Factors assessed in CAPS CWR [developed by the author]

Factors characterising the presence of thermal stresses in welded rails		Factors characterising the holding properties of the assembled rails and sleepers	
Factors	Initial assessment parameter	Factors	Initial assessment parameter
1. The state of a continuous welded rail in plan	Curvature of the right and the left welded rails	1. Holding properties of rail fastenings	Unstable pattern
		2. The presence of hanging and unsupported sleepers	Natural irregularities in vertical plane
2. Rail creep	Displacements at «reference» sleepers	3. Assessment of the shoulder width of the ballast prism	Geometric dimensions of the shoulder width of the ballast prism
		4. Fullness of ballast cribs	Ballast crib fullness rate

considered. The formula for determining the complex coefficient is as follows:

$C_c = max(C_{cr}; C_{pl}) + c_{scale}(c_{w.fast.} \bullet C_{fast} + c_{w.bpr.} \bullet C_{bpr.} + c_{w.hsl} \bullet C_{hsl} + c_{w.bcr} \bullet C_{bcr}),$ (1)

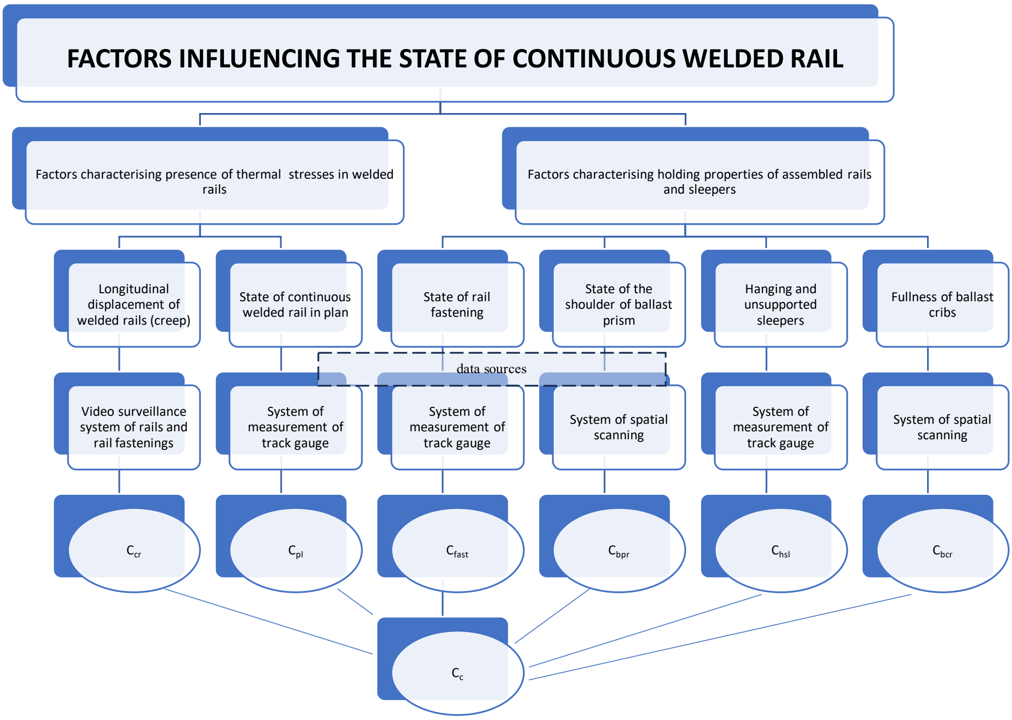
where c_{scale} is scale coefficient, taken equal to 0,25.

$c_{w.fast}$, $c_{w.bpr}$, $c_{w.hsl}$, $c_{w.bcr}$ are weight coefficients that take into account the share of influence of each of the factors belonging to the second group on the total complex coefficient. Their values are assumed as $c_{w.fast} = 0{,}1$; $c_{w.bpr} = 0{,}4$; $C_{w.hsl} = 0{,}3$; $C_{w.bcr} = 0{,}2$.

In addition to the value of the complex coefficient the CAPS CWR software also determines the value of the buckling probability V_2, which characterises the risk of a continuous welded rail failure due to the second critical state.

The assessment of these indicators is carried out based on the threshold values given in the table of states for indicators V_2 and C_c (Table 2). When assessing, the state of each section of the continuous welded rail is analysed and the final ranking matrix per each distance between train milestones is formed (Pic. 2). It reflects the overall integral assessment of a given structural division with an indication of the number of distances between train milestones in a particular state [8].

The traffic is closed for distances between train milestones with impermissible state.



Pic. 1. Algorithm for determining the complex coefficient of pre-failure state of a continuous welded rail [developed by the author].

Ranking matrix based on the comprehensive assessment of pre-failure state of the track

Check:working

Track state	G <30	30≤G<50	50≤G<70	G ≥70
Impermissible				
Pre-failure	1			
Undesirable	15	1		
Permissible	50	8		
Not taken into account	2081	31		
Total distances	2148	40		

Pic. 2. An example of a ranking matrix by C_c [developed by the author].

The ranking matrix, depending on the value of the complex coefficient, provides a detailed description for each of the distances between train milestones, including data on all indicators, as well as information about a distance's attributes, track plan, traffic density, and speed (Pic. 2). Based on the data available in the ranking matrix, the necessary measures are undertaken purposed to restore the state of the continuous welded rail and ensure its stability.

As noted above, one of the key factors that plays a major role in the process of monitoring the thermal-stress state of a continuous welded rail is determining of the dynamics of changes in welded rails in plan.

According to the existing algorithm embedded in the CAPS CWR software the control of the state of welded rails in plan is carried out by measuring changes in their curvature with modern diagnostic tools [9].

The essence of this algorithm is as follows:

1. After measuring the curvature of welded rails in plan in the CAPS CWR program, the curvature (ρ) is formed in the range of 6–9 m, i.e., within the buckling risk range.

2. Next, a local section is determined, symbolising the presence of thermal stresses by fixing the curvature growth for each welded rail separately in the selected assessed section. As a site of assessment, as a rule, a distance between train milestones (hereinafter referred to as DTM) or a welded rail is taken [3].

3. Then, the calculation of the temperature equivalent characterising the change in the state of the continuous welded rail in plan ($\Delta t_{pl.}$), and formation of intensity of change of this temperature equivalent (($\Delta\Delta t_{pl.(\lambda)}$) is performed, as the difference between the value obtained in the current check ($\Delta t_{pl.(cur)}$), and minimal ($\Delta t_{pl.(min)}$) over the last six months of observation (Pic. 3).

Table 2

Assessment criteria for the values of V_2 and C_c [4]

Criterion name	Indicator value						
	not taken into account	permissible	undesirable		pre-failure*		imper-missible
			$V_{set.}$ = 140 km/h and less	$V_{set.}$ = more than 140 km/h	$V_{set.}$ = 140 km/h and less	$V_{set.}$ = more than 140 km/h	
Complex coefficient of the pre-failure state of a continuous welded rail, C_c	$C_c < 1.5$	$1.5 \le C_c < 2$	$2 \le C_c < 3$	$2 \le C_c < 2.5$	$3 \le C_c < 5$	$2.5 \le C_c < 5$	$C_c \ge 5$
Probability of buckling of the section of a continuous welded rail, V_2, %	$V_2 < 5$ less than 5	$5 \le V_2 < 10$	$10 \le V_2 < 18$	$10 \le V_2 < 14$	$18 \le V_2 < 34$	$14 \le V_2 < 34$	$V_2 \ge 34$

*****Note: when a pre-failure condition occurs:
– for distances between train milestones with values $3 \le C_c < 4$, the speed is limited to 60 km/h;
– for lines with a set speed of more than 140 km/h for distances between train milestones having values $2,5 \le C_c < 3$, speed is limited to 120 km/h;
– for distances between train milestones with values $4 \le C_c < 5$, the speed is limited to 25 km/h.

4. Determination and assessment of the pre-failure condition coefficient is carried out, showing the stability of the continuous welded rail in plan ($C_{pl.}$). Assessment of the coefficient $C_{pl.}$ is performed according to the current criteria, which are shown in Table 2.

It is noteworthy that the entry into force of speed limitations and the work on the discharge of thermal stresses or their adjustment at the identified distances and distances closest to them, as well as the performance of other related works, begin when the complex coefficient $C_c \geq 3$ is detected.

As noted earlier, a formation of an unfavourable complex coefficient is highlu influenced by the factors related to the first group (rail creep and the state of a continuous welded rail in plan) [10; 11]. If information is available on both indicators, to determine the complex coefficient, the one that characterises the worst condition is taken into account.

In case of $C_{pl.}$ coefficient, formation of a complex coefficient symbolising a pre-failure (value of 3 or more with $V_{set.}$ = 140 km/h or less, and 2,5 or more with $V_{set.}$ = more than 140 km/h) or an unacceptable state (value of 5 or more) is possible in the following scenarios.

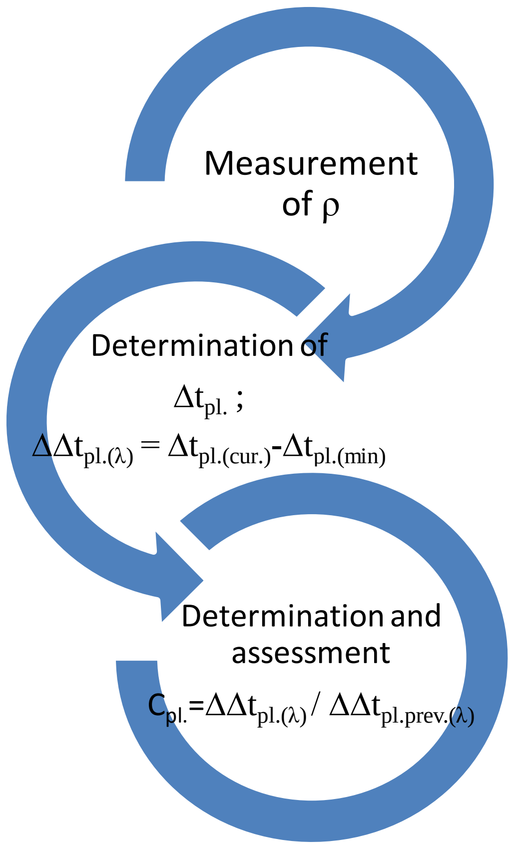
Scenario No. 1. The state of a continuous welded rail in plan, that is, a change in curvature of welded rails in the range of 6–9 m, occurs quite abruptly (within two adjacent checks) (Pic. 4, a).

Scenario No. 2. The state of a continuous welded rail in plan, that is, a change in curvature of welded rails the range of 6–9 m, occurs smoothly over a long period of time (Pic. 4, b).

Consideration of Additional Factors

The existing algorithm for estimating the state of a continuous welded rail in plan, implemented in the CAPS CWR software, in the considered scenarios does not always take into account cases of a sharp change in curvature in plan [12]. Descriptive are examples when the initial value of the coefficient $C_{pl.}$ has rather small values (as a rule, less than 0,5), and then there is a sharp increase, leading to an increase in the coefficient values that are less than those of the pre-failure state (less than 3 or 2,5, depending on the set speed). The manifestation of this growth is clearly displayed on the graph of the curvature of welded rails, obtained in the range of 6–9 m (Pic. 5).

For example, with the initial value of the coefficient $C_{pl.}$ = 0,2 (for control inspection in

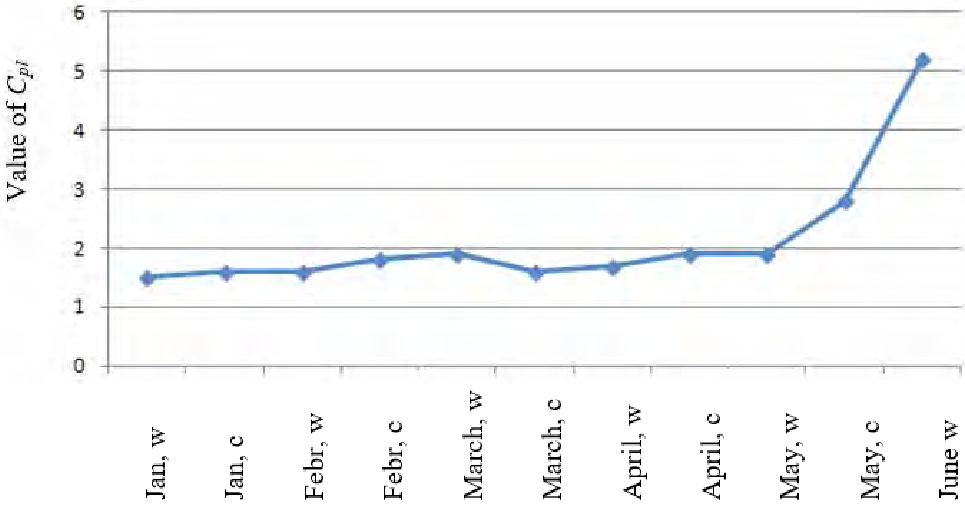


Pic. 3. Algorithm for determining the state of a continuous welded rail in plan [developed by the author].

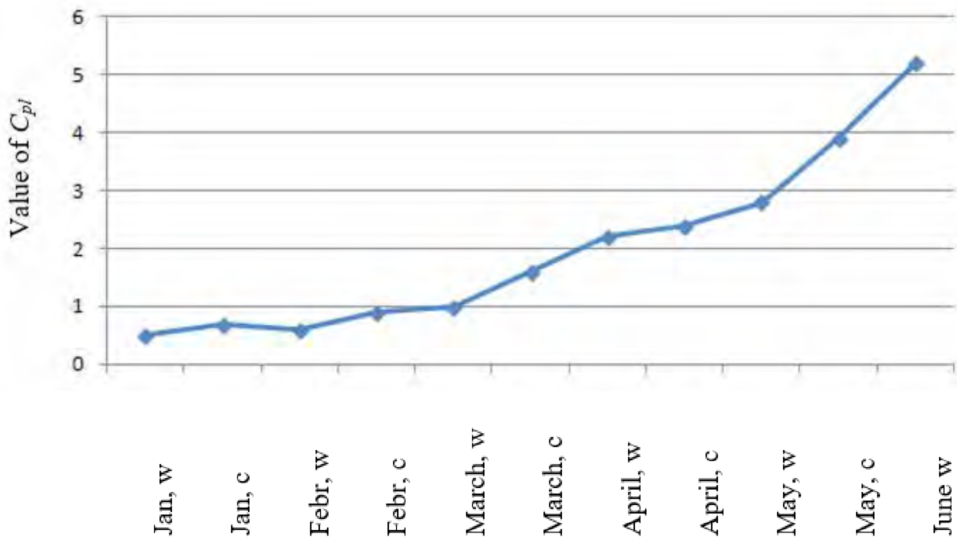
May as shown in the graph in Pic. 6), the value of the coefficient during the next inspection changed to $C_{pl.}$ = 2,8 (June, current work inspection). According to the current assessment criteria, the value of $C_{pl.}$ = 2,8 (at $V_{set.}$ < 140 km/h) corresponds to an undesirable state and not to the inadmissible state and does not therefore require imposing speed limitations, as well as works related to the discharge of thermal stresses or their adjustment.

However, the change itself, equal to $\Delta C_{pl.} = C_{pl.(cur.inspect..)} - C_{pl.(prev.inspect.)}$ = 2,8–0,2 = 2,6, is significant and has happened during a short period of time, therefore it poses a risk of further growth, as well as the transition to a state that corresponds to the state preceding buckling, especially during the period of temperature increase (Pic. 6).

The statistical analysis carried out at the initial stage regarding individual cases, which are similar to the above example, has shown that these changes are indeed dangerous, and require additional control and can lead to a violation of train traffic safety [13].



a)



b)

Pic. 4. Scenarios for development of the state of a continuous welded rail in plan: a – scenario No. 1; b – scenario No. 2 (w – current work inspection; c – control inspection) [developed by the author].

SUGGESTIONS AND CONCLUSIONS

To increase rate of detection of such sections of a continuous welded rail, it is proposed to determine the places of a sharp change in curvature of welded rails in plan within the range of 6–9 m within the framework of successive track inspetctions, using the following formula:

$$\Delta C_{pl} = C_{pl.(cur.inspect)} - C_{pl.\ (prev.inspect)}, \quad (2)$$

where $C_{pl.(cur.inspect)}$ – the value of the coefficient showing the pre-failure state rate during the current inspection;

$C_{pl.(prev.inspect)}$ – the value of the coefficient showing the pre-failure state rate during the previous insptction.

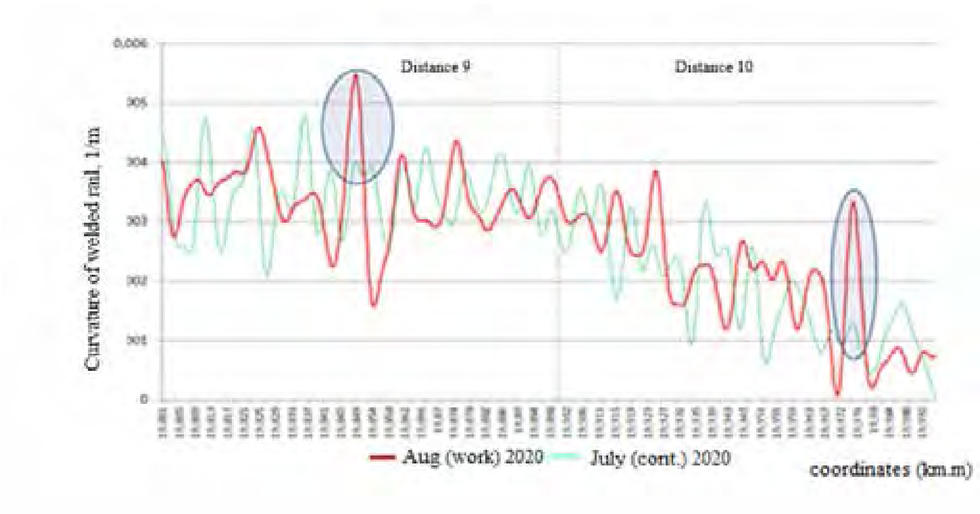
Additionally, it is proposed to consider changes in the temperature of rails, which were recorded by diagnostic tools at the time of measuring the curvature, during the above inspections, according to the formula:

$$\Delta t_r = t_{r(cur.inspect)} - t_{r(prev.inspect)}, \quad (3)$$

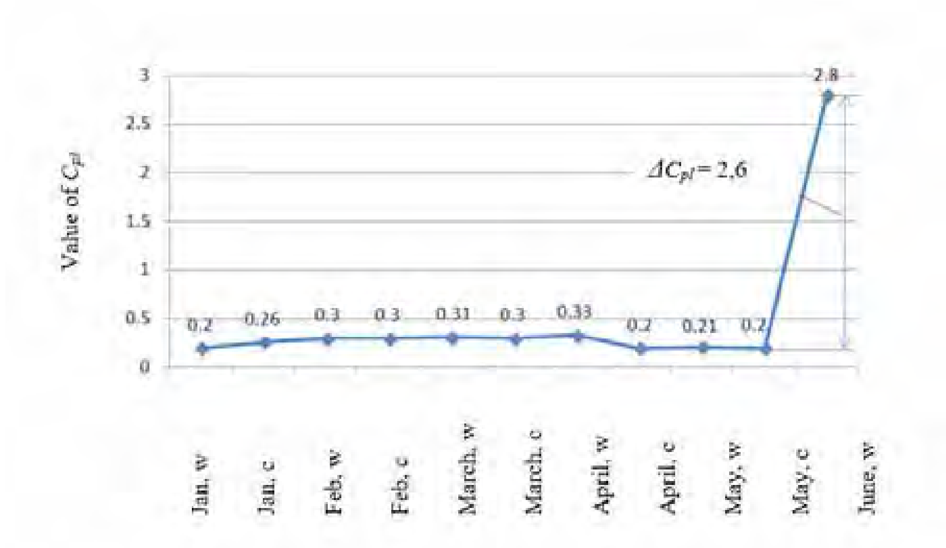
where $t_{r(cur.inspect)}$ – temperature of rails recorded at the moment of curvature measurement during the current inspection;

$t_{r(prev.inspect)}$ – temperature of rails recorded at the moment of curvature measurement during the previous inspection.

Determining threshold evaluation criteria is proposed to be performed on the basis of



Pic. 5. An example of a sharp change in curvature of a welded rail over time [developed by the author].



Pic. 6. An example of a sharp change in Cpl coefficient in time [developed by the author].

Pic. 7. Tree homing [developed by the author].

dependencies obtained in the course of research [14]:

$$f\,(\Delta C_{pl.};\ \Delta t_r), \qquad (4)$$

To rank the obtained evaluation criteria and to make managerial decisions, it is advisable to use the tree homing (Pic. 7) [15; 16].

Thus, the use of additional assessment criteria will make it possible to timely identify sections of a continuous welded rail that pose a high risk of buckling due to a sharp change in the state in plan, especially during a period of rising temperatures.

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Article received 27.11.2022, approved 27.12.2022, accepted 28.12.2022.