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# PREDICTIVE ANALYTICS FOR ENHANCING PERFORMANCE AND SAFETY IN CONTINUOUSLY WELDED RAIL

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## Abstract

The modernization of rail infrastructure demands innovative approaches to ensure optimal performance and safety. In present days, railway tracks are increasingly installed with continuous welded rails (CWR) to reduce train vibration and noise. Unfortunately, CWR's are prone to lateral buckling, which is a rather complex phenomenon that is observed in a wide range of physical circumstances. Numerous factors affect track buckling, but the rail temperature and the stress-free (neutral) temperature of the CWR are two of the most important factors. Rail temperatures are closely related to air temperature, which is constantly increasing due to global warming. The Romanian railway regulations and instructions that are dealing with construction and maintenance works on CWR, define the neutral temperature range between 17 and 27 degrees Celsius for the entire railway network of the country. However, we must bear in mind that Romania, likewise several countries in the EU, has both a quite divers climate and geographical relief. In this condition, the temperature variations can generate excessive thermally induced axial forces, leading in most cases to destabilization or tensile fracture of the CWR track. One of the main concerns of Railway Administrations is to determine the buckling temperature of the CWR in different sections of the railway network. This is not an easy task, due to the several parameters which are affecting the buckling temperature such as: rail's neutral temperature, misalignment of the rails and ballast resistance. This paper introduces a comprehensive framework for predictive analytics by presenting a model of probabilistic buckling analysis for CWR tracks based on rail temperature predictions using different wayside monitoring equipment. By adopting these models, rail operators will be able to proactively address issues before they escalate, optimize their maintenance schedules, reduce downtimes, and minimize the risk of accidents.

*Keywords: continuously welded rail (CWR), rail temperature, neutral temperature, lateral buckling, buckling prediction, track parameters, linear asset management (LAM)*

## 1 Introduction

The modernization of rail infrastructure demands innovative approaches to ensure optimal performance and safety. Currently, the continuosly welded track (CWR) is increasingly used in the construction of new lines and in the rehabilitation works of railways, as it has a number of advantages, namely: increased comfort conditions, increased traffic speed, increased axle loading, lower noise pollution and reduced vibrations transmitted to constructions and installations located in the vicinity of the track.

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For optimum performance and, above all, safety in traffic, the CWR must be designed, constructed and maintained in such a way as to ensure its stability. Track stability means its ability not to deform due to the stresses to which it is subjected, especially due to axial forces in the rails that develop as a result of temperature increase.

Numerous factors affect track buckling, but the rail temperature and the stress-free (neutral) temperature of the CWR are two of the most important factors [1]. Rail temperatures are closely related to air temperature, which is constantly increasing due to global warming. For this reason, it is a primary requirement to choose the correct neutral temperature and comply with it in the installation process, as this significantly influences the maximum compressive efforts that can develop in the CWR at extreme temperatures. In essence, the study of CWR stability involves determining the maximum axial forces that can develop in rails without the CWR deforming known also by buckling. This phenomenon of stability loss will occur, both horizontally and vertically, in the most stressed area of the CWR, which is the central area.

This paper introduces a comprehensive framework for predictive analytics by presenting a model of probabilistic buckling analysis for CWR tracks based on rail temperature predictions using different wayside monitoring equipment. The 2nd section will address issues related to critical factors affecting CWR stability, stability calculation methods and a proposed predictive model to optimize maintenance processes. Section 3 will deal with the proposed prediction model for CWR stability assessment. The summary of the insights, key findings, and contributions of the study with emphasis on the significance of predictive analytics in enhancing CWR integrity will be mentioned in the last chapter of this paper.

# 2 Methodology

## 2.1 Critical safety factors affecting CWR stability.

The increase in axial compressive force combined with the action of forces given by moving vehicles may at some point lead to track deformation, when the temperature difference from the neutral temperature reaches large values, even if the ballast prism and fastenings are well maintained [2].

The Romanian railway regulations and guides for construction and maintenance works on CWR, define the neutral temperature range between 17 and 27 degrees Celsius for the entire railway network of the country [2]. However, we must acknowledge that Romania, likewise several countries in the EU, has both a quite divers climate and geographical relief. In this condition, the temperature variations can generate excessive thermally induced axial forces, leading in most cases to destabilization or tensile fracture of the CWR track.

One of the main concerns of Railway Administrations is to determine the buckling temperature of the CWR in different sections of the railway network. This is not an easy task, due to the several parameters which are affecting the buckling temperature such as: rail properties, track's neutral temperature, misalignment of the rails, curvature of the track, ballast lateral resistance, vehicle parameters [3].

## 2.2 Data sources

Looking to the future, we can glimpse a process of maintenance of railway lines with many innovative changes driven by advances in the development of various monitoring technologies – data collection, data analysis, automation and even sustainability initiatives.

The solution presented in this paper is based on a new concept of railway line maintenance, namely predictive maintenance based on predictive analysis algorithms. The purpose of the solution is to forecast the occurrence of CWR buckling and to provide the possibility to intervene before this phenomenon occurs.

The data used by such a model are varied and for the best accuracy of the results, it is necessary to implement a Linear Asset Management (LAM) Sub-System for the railway track superstructure assets, with a clearly defined objective of ensuring the stability of the CWR. This sub-system, based even on a Digital Twin (DT) technology must be continuously updated with data provided by various sensors mounted along the track, by Track Recording Vehicles (TRV), by maintenance teams intervening on certain areas of the CWR, thus facilitating a faithful rendering of the real condition of the railway track [4].

## 2.3 CWR Stability Calculation Method

Determining the stability condition of CRW involves a complex calculation due to the numerous parameters that must be taken into account. The parameters shall be chosen according to the plane in which the loss of stability occurs, horizontally or vertically. Loss of stability in the horizontal plane has a higher frequency of occurrence in CWR. The main parameters that are conditioning the stability of the CWR in the horizontal plane are as follows [5]:

- CWR stress-free / neutral temperature
- Rigidity of the rail in the horizontal plane
- Rigidity of rail-sleeper frame in horizontal plane due to fastenings
- The resistance of the ballast to lateral displacement of the rail-sleeper frame
- Dynamic loads from rolling stock
- Horizontal track geometry (tangent track / curves)
- Missalignments of the track
- Maintenance work quality on CWR.

Several calculation methods can be used to calculate CWR stability:

- Differential equations of equilibrum method
- Energy method
- Stability in elastic medium method

The purpose of this paper is not to present in detail a particular calculation method, but rather to integrate these calculations into an algorithm for predictive analysis of CWR loss of stability. However, in the following will be exemplified a calculation based on the method of differential equations of equilibrium developed by Dr. Nemesdy E. [6], in order to establish the relationships that assess the degree of safety of CWR stability and to determine the temperature in the rail at which loss of stability may occur.

Basically, the study of the CWR stability consist of determining the maximum axial compresion force ($P_{max}$) that can occur in the rails without CWR being deformed. The primary condition for the CWR not to lose stability is that the maximum compressive force generated by increasing temperature in the rails relative to neutral temperature is below the minimum critical loss of stability force ($P_{cr}^{min}$). This condition is expressed by eqn (1):

$$c \cdot P_{max}^{+} \le P_{cr}^{min} \tag{1}$$

where:

$P_{max}^{+}$ – the maximum compressive force in the CWR generated by the temperature rise
$P_{cr}^{min}$ – minimum critical force for stability loss
c – safety coefficient (c = 1,3, ..., 1,5)

The maximum axial compressive force generated by the increase in rail temperature is calculated with eqn (2):

$$P_{max}^{+} = \alpha \cdot E \cdot A \cdot \left(t_r - t_n\right) \tag{2}$$

where:
$\alpha$ – coefficient of thermal expansion [2], $\alpha = 11{,}5 \cdot 10^{-6}$ [1/°C]
E – modulus of elasticity of steel $E = 2{,}15 \cdot 10^{6}$ [daN/cm$^2$]
A – cross-sectional area of rails $A = 2 \cdot A_r$ [cm$^2$]
$t_r$ – rail temperature [°C]
$t_n$ – stress-free / neutral temperature [1/°C]. In Romania $t_n = 17 \ldots 27$ [°C]

In the assessment of the critical force of stability loss, three parameters were taken into account: the own rigidity of the rails relative to the vertical axis ($2EI_y$), the rigidity of the rail-sleeper frame, the resistance to lateral displacement of the track (q). Parameters were taken into account for the most common types of misalignment defects (A, B and E) exemplified in Fig. 1. At the limit, the critical force of stability loss of the CWR will be balanced by the resistance forces determined by the rails' own rigidity ($P_r$), frame stiffness ($P_c$) and ballast prism reaction ($P_q$).

$$P_{cr} = P_r + P_c + P_q \tag{3}$$

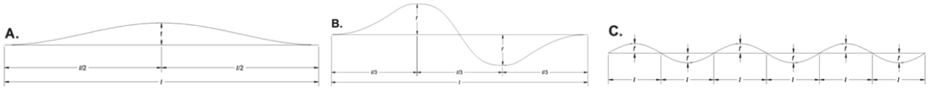

**Figure 1** A, B and C types of misalignment defects

Without going into detail about the calculation of each resistance force in eqn (3), the calculation relationships for the critical force of stability loss both in tangent track and in curved track will be presented below, considering the most common misalignment defects (A, B and E) [7]. For alignment, the critical CWR stability loss forces are as follows:

$$P_{cr}^{A} = 40 \cdot \frac{E \cdot I}{l^2} + \frac{2 \cdot r}{a} + \frac{l^2}{10 \cdot f} \cdot q \tag{4}$$

$$P_{cr}^{B} = 80 \cdot \frac{E \cdot I}{l^2} + \frac{2 \cdot r}{a} + \frac{l^2}{39 \cdot f} \cdot q \tag{5}$$

$$P_{cr}^{E} = 10 \cdot \frac{E \cdot I}{l^2} + \frac{2 \cdot r}{a} + \frac{l^2}{8 \cdot f} \cdot q \tag{6}$$

$$I = 2 \cdot I_y \tag{7}$$

where:
$I_y$ – rail moment of inertia about the y-y axis [cm$^4$]
l – misalignment length [cm]
r – fastening characteristic of rail-sleeper frame [daN · cm]
a – distance between sleepers [cm]
f – misalignment value [cm]
q – resistance of ballast to transverse displacement of track sleepers

In curves, when calculating the reaction of the ballast prism, a reduced transverse resistance $q_r = q - q'$ shall be taken into account, where:

$$q' = \frac{2 \cdot P_{max}^{+} \cdot \sin\frac{\beta}{2}}{R \cdot \beta} \tag{8}$$

where:
R – curved track radius [m]
β – angle at the centre of the circular curve [rad]

Analyzing the above formulas, it can be seen that the critical force at which the loss of stability occurs depends on five constants characterizing the construction of the track (E, $I_y$, r, a, q) and two variable parameters characterizing the size and length of the misalignment of the track (l, f). The critical force of loss of stability shall be determined by setting limit values for the two variables characterising the track misalignment defect.
In Fig. 2 it can be observed the representation of the critical force of loss of stability depending on the length of the track misalignment (2 m to 20 m) for several values of type A defect (f) in the range of 1.4 mm to 14 mm. A CWR with wear-free rails of type 54E1, concrete sleepers placed at a distance of 60 cm, a ballast resistance to transverse displacement of the sleepers q = 7daN/cm and a neutral CWR temperature of 20 °C were considered.

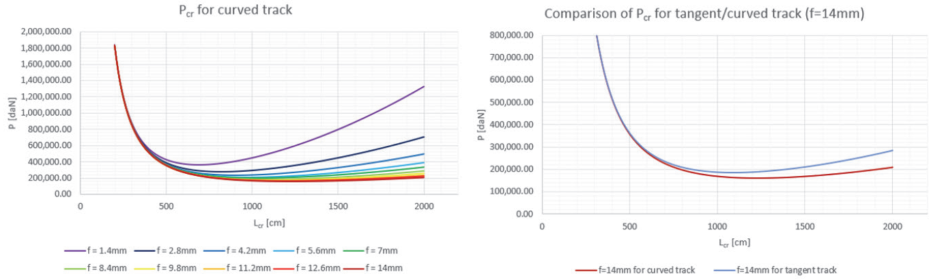

**Figure 2** a) $P_{cr}$ for curved track; b) $P_{cr}$ comparison for tangent/curved track

From the analysis of the graph above, it can be seen that for each value of the track misalignment, the $P_{cr}$(l) function presents a minimum value ($P_{cr}^{min}$) corresponding to a critical length ($l_{cr}$) which can be determined from the relation:

$$\frac{dP_{cr}}{dl} = 0 \Rightarrow l_{cr} \tag{9}$$

$$P_{cr}^{min} = P_{cr}\left(l_{cr}\right) \tag{10}$$

The value of the rail temperature at which the loss of stability of the CWR occurs for an A type of misalignment, can be determined using eqn (1, 2 and 3) for tangent track by eqn (11) and curved track by eqn (12) as follows:

$$t_r = t_n + \frac{P_{cr}^{min}}{c \cdot \alpha \cdot E \cdot A} \tag{11}$$

$$t_r = t_n + \frac{P_r\left(l_{cr}\right) + P_c + P_q\left(l_{cr}\right)}{\alpha \cdot E \cdot A \cdot \left(c + \frac{2 \cdot l_{cr}^2 \cdot \sin\frac{\beta}{2}}{10 \cdot f \cdot R \cdot \beta}\right)} \tag{12}$$

It can be seen from the above relationship that using a safety coefficient c = 1.3….1.5, will determine in the calculations a loss of stability temperature lower than the real one, as seen in Fig. 3. For this reason, in order to determine as accurately as possible the temperature at which CWR loses its stability, it is recommended to use a safety coefficient c = 1.

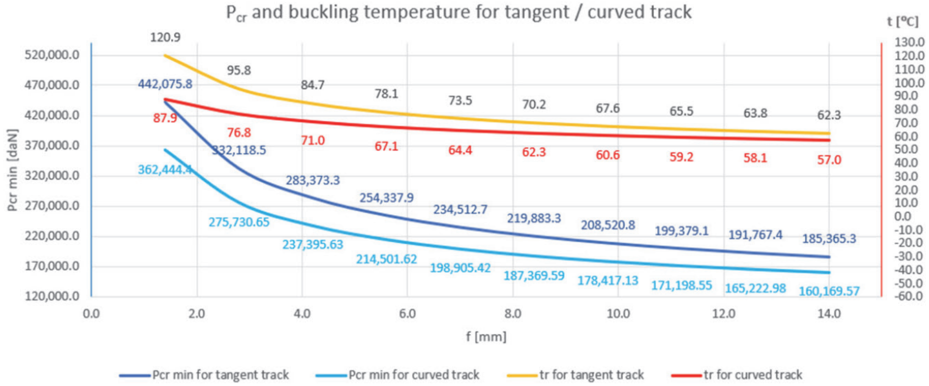

**Figure 3** Variation of minimum critical force and loss of stability temperature as a function of misalignment value (for c = 1,30)

In Fig. 3 it can be observed the variation of the minimum critical force of CWR stability loss and the temperature at which the phenomenon of stability loss occurs, taking into account a type A defect with different values. It is obvious that for a defect of a certain value located in a curve, the loss of stability occurs at a temperature lower than the stability loss temperature for the same defect located in tangent track. For this reason, additional measures are introduced in curves of small radii, e.g. modification of the shape of the track bed on the outer side of the curve.

## 3 Proposed prediction model for CWR stability assessment

The proposed prediction model is based on an architecture incorporating a continuously updated railway infrastructure linear asset management (LAM) sub-system by two railway track network data collection systems: one based on static measuring devices - sensors located at critical points of the CRW and the other, mobile, focused on measurements of track geometric parameters performed with track recording vehicles (TRV) or other devices dedicated to this purpose.

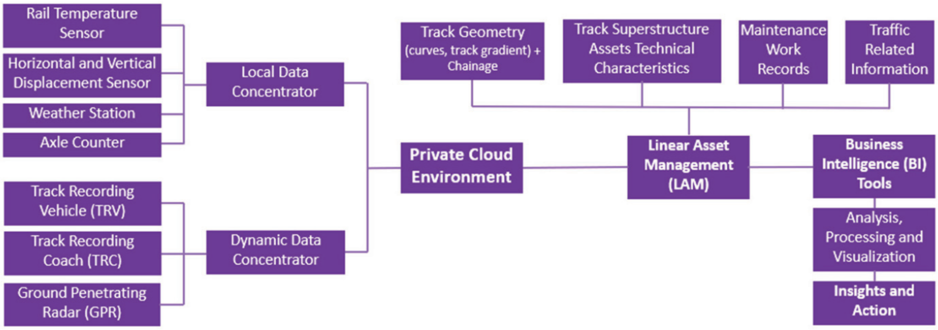

**Figure 4** Prediction Model Architecture for CWR Stability Assessment

The local sensors have the role of collecting data about the temperature in the rail, horizontal and vertical displacements, air temperature, weather conditions, number of axles. On each location a data concentrator collects and manages data from multiple sources. The data concentrator sends the data to cloud storage through various communication protocols and interfaces. The data is persisted and made available for further analysis, processing, or visualization by various Business Intelligent (BI) Tools, i.e. Power BI.

The track geometry parameters are measured by track recording vehicles and the condition of the ballast by Ground Penetrating Radar technology (GPR) which provides data on all relevant geotechnical parameters of the ballast bed. There can be differences in all track geometry parameter values, according to whether they are measured in loaded or unloaded, static or dynamic conditions. These differences should be considered when comparing measurements made under different conditions [8].

The LAM subsystem should contain all data on the constituent elements of the track superstructure as well as data on track geometry and traffic. This subsystem is the data source for a predictive analytics model in the cloud. Predictive analytcs algoritms has to consider as many parameters as possible which could influence the stability of the CWR. Predictive analytics algorithms can also analyze historical asset data to identify patterns and make predictions about future asset behavior, in this case stability loss or misalignment development.

Cloud-based BI tools can provide real-time monitoring and alerting capabilities for linear assets. Railway maintenance organizations can set up alerts based on predefined thresholds or conditions (rail/air temperature, misalignments, etc.), allowing them to proactively address issues and minimize downtime. Combining LAM with BI tools in the cloud enables organizations to unlock the full potential of their asset data, driving improvements in asset performance, reliability, and profitability.

## 4 Conclusion

Predictive analytics is an innovative concept through which the real-time monitoring of the technical condition of the CWR is possible, whether there is a robust, continuously updated database and a calculation model that takes into account all parameters influencing the stability of the CWR. Predictive analytic model can simulate possible consequences of an established defect and allows a predictive analysis of the development of a track buckling phenomenon at high temperatures. Thus, a track maintenance process that relied mostly on interventional operations over time can turn into a predictive maintenance process. By adopting these models, rail operators will be able to proactively address issues before they escalate, optimize their maintenance schedules, reduce downtimes, and minimize the risk of accidents.

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