Automated, Real Time, Longitudinal Stress Management to Improve Safety of Heavy Haul Operations

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ABSTRACT: Rail thermal stresses monitoring in coal heavy-haul of South Africa is carried-out traditionally through A-frame manual measurements, and secondly, through continuous welded rail monitoring system (CWRM) that provides measurements in real-time. The management of compressive stresses in particular is achieved through the use of continuous welded rail (CWR) buckling management model. The CWR model essentially deduces the safety factor called buckling margin of safety (BMS) through integrating thermal stresses and track properties i.e. curvature, and ballast integrity. The model is limited to evaluating the health status of the track towards track buckling manually, from manual measurements. Secondly, although the BMS made provision for uncertainties substantially, other critical parameters such as recent track maintenance activities and track buckling "hot spots" are inadequately accounted for. The maintainer is therefore required to consider fragmented systems and other fundamental parameters in order to effectively assess and manage rail longitudinal stresses. The objective of this study is to form an inclusive automated system that is self-sufficient in determining the risks towards track buckling, through integration and automating CWRM with the fundamentals of the CWR model so the track buckling health status is determined in real-time. This is achieved through building and programming an algorithm that is inclusive of thermal and other principal parameters to demonstrate a real-time BMS. The preliminary outputs of the new system presented the BMS and safety range in real time enabling the maintenance to make informed decisions.

1 INTRODUCTION

When the longitudinal compressive stresses exceed the lateral strength of the track, the track buckles explosively, predominantly under the train. The three principal causes of track buckling are 1) high thermal forces 2) poor track conditions, 3) heavy axle load and dynamics (Kish, 2017). The thermal stresses are governed by the rail neutral temperature (RNT), which is the temperature at which the longitudinal rail is stress free. Theoretically, RNT is the rail temperature at which the Continuous Welded Rail (CWR) was fastened. RNT, also called stress free temperature (SFT), varies with time typically due to the fastening loosing grip, the curve moving inwards during tamping, and during plugging of rail piece in cold season or day. Because of this uncertainty driven by this variability, it is essential to measure SFT regularly to establish the new SFT. In South Africa, the SFT is measured traditionally with the lifting frame at certain intervals. However in the coal heavy haul a real-time continuous welded rail monitoring system (CWRM) has been installed monitoring the CWR forces, rail temperature, and deducing the SFT. Regularly this system is calibrated remotely to account for the variability of SFT.

Concurrent with the CWRM system, for buckling prevention, the maintainer also utilises the Buckling management model (the fundaments are discusses in details in chapter 3) manually to plan for buckling prevention through determining the risk factor, called buckling margin of safety (BMS). Therefore the maintainer is required to manage compressive stresses with traditional methods, real time monitoring system, and the model independently. This study initiated when the track maintainer realized this gap, consulted technology management department and CWRM OEM (Original Equipment Manufacturer) to explore, and exploit this opportunity. The primary focus of this study is to simplify and integrate the fragmented systems to one harmonic system that take into consideration, the fundamental parameters over and above what is already catered in the existing buckling model. The Integrated system does not only display in real-time, the SFT, rail temperature, and force, but most importantly the buckling margin of safety BMS. Therefore, the track maintainer is to completely utilise one integrated system for CWR longitudinal stress management, particularly for buckling prevention. Furthermore, this system is to be utilised for auditing, compliance review, and investigation but not limited to these.

2. FUNDAMENTAL OF REAL TIME CONTINUOUS WELDED RAIL MONITOR (CWRM) AND CHALLENGES

The Continuous Welded Rail Monitor (CWRM) was developed by On-Track Technology against a Specification from Transnet Freight Rail (TFR) Technology Management. Using modern strain gauge and microprocessor technology, the system monitors longitudinal forces and temperature in the rail. Measurement nodes are typically installed at a frequency of one per kilometre and at critical areas such as entrances to tunnels or bridges (See figure 1 CWRM-Instrumented Site).

Figure 1: CWRM-Instrumented Site

The rail longitudinal force, F_L relationship is as defined:

$$F_{L}= \alpha\ AE\ (T_R - T_{SFT}) \tag{1}$$

Where α is the rail coefficient of thermal expansion, A, is the rail cross sectional area, E, is the young modulus, T_R, is the current rail temperature, and T_{SFT} is the stress free temperature.

As discussed in [1], due to its variability, T_{SFT} is monitored in real time. Therefore in equation 1, the cross sectional area and the young modulus are the tow constants. In the Coal heavy haul line, although not fully utilised, the CWRM stations are currently installed every 2km on strategically selected locations. The inherent challenges hindering the availability and reliability of the system is the physical equipment damage during maintenance, predominantly during tamping. The lack of timeous calibration of the SFT is also a contributing factor. TFR expected this system to be utilised optimally, however because other key and influencing parameters are not incorporated. The track maintainer did not recognise the importance of the system.

3. THE FUNDAMENTAL OF BUCKLING PREVENTION MODEL

Since track buckling is a dynamic event, it complex to computationally determine all the parameters in the buckling regime with certainty. However within the regime, there are two key parameters, the upper maximum and lower minimum buckling temperature. The focus in this study is around the minimum buckling temperature, which are the bear minimum longitudinal stresses that the overall track is required to resist.

3.1. Buckling Margin of Safety

For buckling prevention the maintenance and safety model is formulated on the basis of defining the relationship between the buckling margin of safety (BMS), overall buckling strength, T_{BS}, and the operating temperature, T_{OP}, (Kish, 2017). The relationship is as simplified:

$$BMS = T_{BS} - T_{OP} \tag{2}$$

T_{BS} is fusion of three key parameters, the SFT, the Critical temperature, T_{CT}, which generally defines the ability of track properties and integrity in resisting buckling. Particularly the ballast lateral strength. The third parameter is the increased risk, T_{IN}, which generally accommodate the increase risk of weakened track from the latest maintenance activities. From the existing model T_{IN} catered only tamping, sleepers replacement, and sections with formation problems.

$$T_{BS}= T_{CT} + T_{SFT} - T_{IN} \tag{3}$$

T_{OP}, being the operating temperature, for manual computation, it is the maximum probable temperature locally, that the strength against buckling should be able to resist. This however is the maximum rail temperature inclusive of the rail temperature due to the sun intensity and also train dynamics.

3.2. Fundamental of Critical Temperature

The force required to trigger buckling in a tangential and curve track varies according to theory of buckling. For a curved track it is marginal compared to a tangential one. Therefore the ability of the track to resist buckling should be computed separately. T_{CT} relationship for tangential and curve track is as defined in equation 4 and 5 respectively:

$$T_{cr} = 8.96 * \left(\frac{J_y * Q_{eq\ lateral}}{A^2 \Delta_l}\right)^{0.5} \tag{4}$$

$$Tcr = \left(\frac{\left(\frac{4\,J_y * Q_{eq\ lateral}}{E\propto^2 A^2 \Delta_l} + \left(\frac{4J_y}{A\propto\Delta_l R_c}\right)^2\right)^{0.5}}{\left(\frac{4J_y}{A\propto\Delta_l R_c}\right)}\right) - \left(\frac{4J_y}{A\propto\Delta_l R_c}\right) \tag{5}$$

Where $Q_{eq\ lateral}$ = lateral track resistance for an ideal track, A= rail cross sectional area, Δ_{L} = allowable deflection, E= Rail young's Modulus number, R_c= Radius of the curve, α= rail thermal coefficient, and

$$I_y = (2{*}I_{Y-Y} * K)/10^{\wedge}6 \tag{6}$$

Where I_{Y-Y} = second moment of area, K= measure of clamping ability number.

33. Risk Categories of buckling margin of safety

The overall purpose of defining BMS is to produce sound guideline for managing compressive stresses. The BMS ranges therefore require specific recommendations for actions to be taken for stress variations. According to Kish, 2017, this range differs for different countries. In South Africa 0-3 °C, 4-6°C, 7-10 °C are the stipulated BMS ranges. The actions required vary from stopping the trains, imposing speed restrictions, topping up the ballast, and Rail destressing.

When T_{CT} is marginal, it is therefore crucial to further scrutinise the underlying factors. It could be because of insufficient ballast, therefore the action would simply be toping up ballast. Or the ballast is degraded lowering the ballast replacement ratio, therefore in this case ballast cleaning would be an appropriate action.

Generally, the rule of thumb is to avoid or control a scenario where the rail temperature rises above 60 degrees. In South Africa, particularly in coal heavy haul line, immediately the rail temperature reaches 60 degrees the train speed is reduced until the rail temperature drops below 55. This is following the observation that the rail temperature rises by a magnitude of 5 degrees during passage of long heavy trains pertaining to frictions during wheel rail interaction. Therefore it crucial to control additional increase in rail temperature.

4. INTERGRATION OF BUCKLING MODEL WITH CWRM

The integration of the already existing buckling prevention model and the CWRM into one inclusive system is to magnify the value and significance of the system to the track maintainer. Respectively, the maintainer is to willingly safeguard the CWRM stations against damage during maintenance, particularly ballast tamping.

Since CWRM deduces the SFT and rail temperature in real time the BMS is also then incorporated and determined in real time. However, contrary to the buckling model where BMS is computed on the basis of expected maximum rail temperature, the proposed system is to be determined in real time.

Therefore, it is also possible to then establish the variation of Tr and T_{BT} with time. Although the critical temperature is expected to be uniform until the track is disturbed or altered, it is imperative to integrate the variation of these parameters in real time. Ideally an alarm is to appear to the maintainer where BMS beyond safe range and appropriate actions are taken. I.e. introduction of temporary speed restriction to mitigate elevation of rail thermal stress from train dynamics. Stopping of trains with the expectation of track buckling under the train.

The buckling influencing parameter (as defined by T_{in}) were also considered and incorporated to the program to accommodate the history of maintenance and rehabilitation and, buckling hotspot, and community unrest. These influencing parameters that increase the risk of bucking were recorded for a period of three year under the coal-line; namely: re-railing, re-sleepering, tamping, ballast screening, formation rehabilitation, and community unrest. The latter is a risk that arose recently in the coal-line whereby unrest community members burn tyres on the tracks inducing thermal stresses in the process. Later on, during track destressing, it was observed that the respective sections buckles explosively. Bridges, tunnels, and turnouts approach also form part of the add-ins of increasing risk factors as parameters. In the coal-lines of south track buckling records are predominant in these regions, particularly due the higher density across the network.

There is a fine line between the buckling strength and the buckling temperature during buckling dynamic event. Consequently, it is imperative to clarify the ranges of BMS through 1) displaying in colour codes the riskiness and safeness of the range, 2) recommend/ or instruct on appropriate actions to be taken by maintainer or responsible personnel. For 0-3 °C, 4-6°C, 7-10 °C are the defined ranges of BMS, with recommend actions to stop the trains, imposed speed restriction, offload ballast, respectively.

5. INTERGRATED CONTINUOUS WELDED RAIL MONITOR SYSTEM RESULTS

In this chapter the preliminary results from the integrated CWRM system are presented. Figure 2 illustrates the variation of all key parameters for buckling; namely, Buckling strength/temperature, Rail temperature, and SFT.

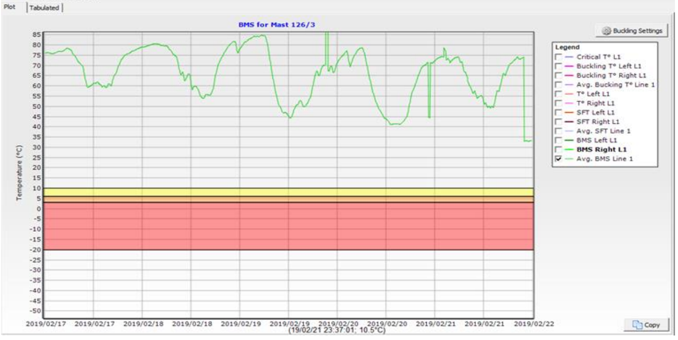
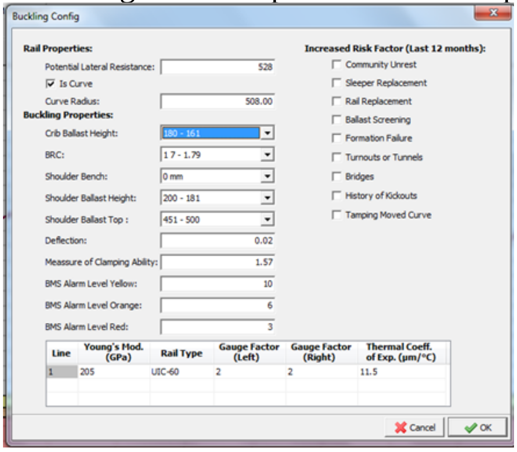


Figure 2: BMS for km 126/3 station

For this station only the BMS has been selected. It was then observed that the BMS was fluctuating safely above the BMS critical ranges (less than 3, 3-6, and 6-10 degree Celsius) as denoted by colour codes. This is because all fundamental parameters influencing the BMS, including the safe average SFT of 35 degree Celsius were also within the safe limits. Figure 3 then presents the track properties.


Buckling Config

Rail Properties:
Potential Lateral Resistance: 528
☑ Is Curve
Curve Radius: 508.00

Buckling Properties:
Crib Ballast Height: 180 - 161
BRC: 1.7 - 1.79
Shoulder Bench: 0 mm
Shoulder Ballast Height: 200 - 181
Shoulder Ballast Top : 451 - 500
Deflection: 0.02
Meassure of Clamping Ability: 1.57
BMS Alarm Level Yellow: 10
BMS Alarm Level Orange: 6
BMS Alarm Level Red: 3

Increased Risk Factor (Last 12 months):
☐ Community Unrest
☐ Sleeper Replacement
☐ Rail Replacement
☐ Ballast Screening
☐ Formation Failure
☐ Turnouts or Tunnels
☐ Bridges
☐ History of Kickouts
☐ Tamping Moved Curve

Line	Young's Mod. (GPa)	Rail Type	Gauge Factor (Left)	Gauge Factor (Right)	Thermal Coeff. of Exp. (µm/°C)
1	205	UIC-60	2	2	11.5

Figure 3: properties of bucking temperature

The track properties were approximated/ assumed to be a representative of a 500m track segment from either side of the station, depending if the station is installed in an open track or adjacent the fixed structure. The variable from the inputs to the buckling systems were recorded from the weakest point within the 1km segment. The foundation of the assumption is that if buckling was to occur, it is going to occur around the weakest link. Within the 1km it was observed that the track had sufficient lateral strength from sufficient ballast; crib ballast, shoulder ballast, and also the ballast degradation was insignificant as denoted by ballast replacement ratio (BRC). Furthermore, the increasing risk factors are also presented. Please note these factors are customised for a particular location or region. Therefore, it was visible that around this station there were no major maintenance activities that were carried out that could have elevated the risk of track buckling. Additionally, this station was not installed adjacent or within fixed structures influencing the stress build ups therefore increasing the risk.

Figure 4 then illustrates results of a contrary scenario recorded from a different station in line 1, at km 206/04 where the SFT is significantly lower than the regional prescribed SFT range (20 to 45 degrees). Please note however that the displayed SFT was not the actual onsite. The station was noticed during the study that it was last calibrated in 2016 hence the inaccuracies in the SFT. This error was however exploited for the purpose of explaining the typical expected results for a station that is under significant risk of track buckling.

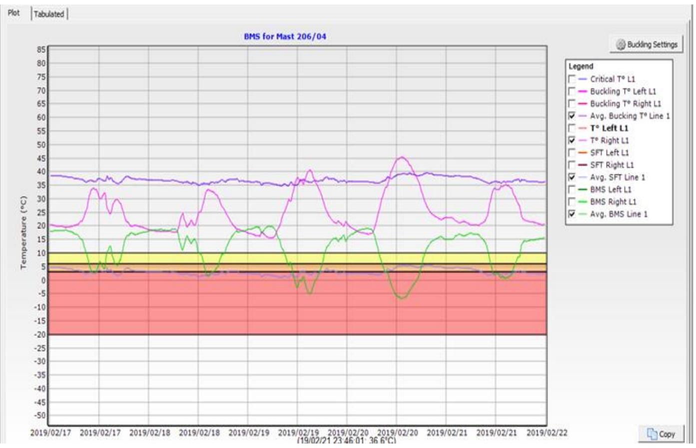


Figure 4: BMS at 206/04 station

In this scenario the BMS was also observed to be fluctuation within the danger zone, implying that the represented track segment was under significant risk of track buckling. Successively, it was then noticed that the significant contributor of the unsafe BMS was the low SFT fluctuating below safe limits (see the blue line) and the curvature ahead of other parameters. This observation was also supported by 1) nonexistence of recent historical maintenance activities that could have increased the risk 2) the rail temperature was fluctuating to an ideal maximum rail temperature of 48 degrees .The details of the buckling temperature are presented in figure 5.

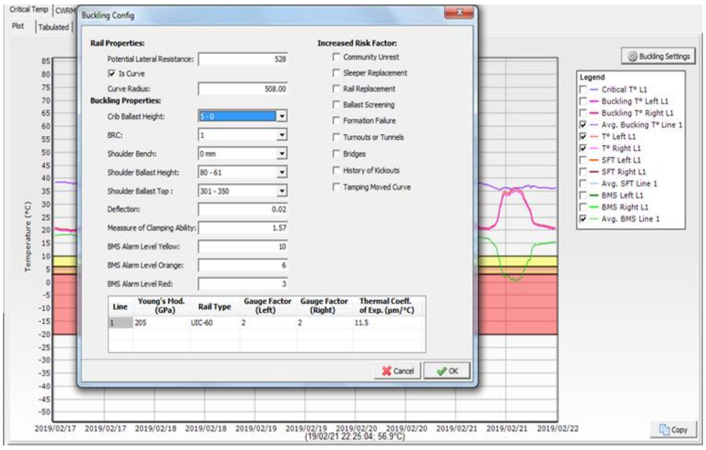

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Figure 5: buckling temperature properties

6. DISCUSSION OF RESULTS AND CONCLUSIONS

This chapter presents the discussion of the results as summarised:

- The principal causes of track buckling; weakened track strength, thermal stresses, and train dynamic that elevates the rail temperature were adequately accommodated for in the integrated CWRM system.
- The factors that influences the increase the risk of track buckling from literate review, coal-line track buckling history, and other practical obser-

vations were also adequately accommodated in the integrated CWRM, however the study is still ongoing to ascertain the scientific contribution to the risk elevation.

- The SFT is fundamental however not the only significant parameter in addition to ballast quantity for compressive stress management as perceived by the senior management. Integrating and automating the deliverable of the model, real time measurement, and other local influencing parameters in one system is to provide a better stress management system to the maintainer.
- The output of the integrated CWRM system is not only the average BMS however the rail leg individual BMS were also represent to accommodate the differential stresses that would paint a wrong picture of track strength if totally ignored.
- The current installed system is to yield value to stress management in addition to monitoring, consequently the maintainer is to safeguard against damage during ballast tamping.
- Furthermore, currently the system is not fully utilised to evaluate the variability in SFT pertaining poor condition of fasteners. The reliability and availability of the new CWRM system will positively influence this function.
- The integration is to also standardise the prioritisation when maintenance planning is carried out. Currently, for those maintainers not equipped with stress management skills and knowledge, only the SFT gets to be consider when planning destressing. However this new is simply the planning and prioritization.
- The study is still ongoing with the objective of configuring, integrated, and automated the alarm with train control officer and maintenance team with recommendations of appropriate action required.

7. RECOMMENDATIONS

The recommendations from the investigation are as detailed:

- It is recommend that BMS be the primary parameter to deduce the risk of the track buckling.
- The integrated CWRM system once piloted and yielding results is to be configured in the system to advise the TCO to, stop train, and implement speed. To the maintenance team it is to recommend offloading of ballast if insufficient, or replacement pertaining to low BRC.
- It is recommended that funds be made available to the maintainer to install further stations to cover the rest of critical areas in the coal-line to have a good coverage.
- It is also recommended that a further improvement in the system be carried out to automate the capturing of maintenance and update in the system, as currently this is function of the maintainer.
- It also recommend that the calibration rights be shifted to the maintainer but reviewed centrally as currently the information get to be sent to technology management department not calibrated.

8. ACKNOWLEDGEMENTS

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