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Development of a unified railway track stability management tool to enhance track safety

Shah Sanjar Ahmad^{1,2,3}, Nirmal K Mandal^{1,2,3}, Gopinath Chattopadhyay^{1,2,3} and John Powell⁴

¹Central Queensland University; ²Centre for Railway Engineering; ³CRC for Rail Innovation, Australia; ⁴Queensland Rail, Australia

Abstract: Track buckling is a serious problem for railways. High longitudinal rail stresses contribute to many problems such as track buckling, rail joint failure, rail breakage and failure of turnouts. The direct and indirect costs of track buckling problems are very high. The influences of rail temperature, SFT and lateral misalignment of track on track buckling need comprehensive investigation.

In this paper, an experimental design comprising strain gauges, thermocouples and rail stress sensors has been implemented on the QR heavy haul 60kg/m rail network. A new creep measurement technique using internal rail stress has been developed. The changes in rail neutral temperature due to the variation of actual rail temperature and the occurrence of rail creep in straight and curved track is quantified. Modes of differences of SFT in the two rails at a location, and of SFT in straight track and in curved track are discussed. The relationship of SFT to rail temperature is also presented. Daily variation in rail temperature due to ambient air temperature is presented.

Field trials showed that SFT can vary by 2-3⁰C during the day. Based on this finding and the derivation of an equation for change of SFT, an improvement in utilising rail creep measurements for assessing track condition has resulted. This finding suggests that it is possible to determine the SFT throughout a day rather than just a single SFT value.

This paper also presents a simple track stability management tool that is based on two major parameters, namely rail stress and track resistance. Each parameter in the tool has been given three levels of value to determine the required preventive measures. Overall, the tool decides the need for speed restriction during hot weather based on the quantified parameters from the field trials and rail standards.

Keywords: Rail creep, Rail stress, Track buckling, Stress free temperature, Track stability management tool

1. Introduction

Track stability is one of the serious problems with the use of continuous welded rail (CWR). The stability of CWR tracks is a balance between the environmentally induced temperature changes in rail and the counteracting resistive forces provided by the sleepers and ballast. The inability to always accommodate thermal expansion of the CWR track leads to a common mechanical failure known as buckling which can result in derailments (Figure 1).

Buckle occurrences can cause derailments, traffic delays, increased maintenance costs, reduced safety margins and negatively affect a customer's perception of rail safety [1]. The average cost of repair and replacement of damaged rolling stock per derailment in 1999 has been estimated as 178,000 AUD [2] in Australia; 50-60% of all train delays in South Africa are rail stress related [3]; a total of 3.3 million pounds revenue was lost due to heat related delays in a year in the south-east UK. In the USA, there were fifty track buckling related derailments with \$13 million reportable damage in 2006 and thirty-four derailments with \$14 million in 2007 [4].

As prevention of longitudinal thermal forces in CWR is an important track maintenance and safety issue, many studies in this field were undertaken to understand fully the critical factors of track buckling. These factors are: rail neutral temperature or stress free temperature (RNT or SFT) (the temperature at which rail longitudinal stress is zero), rail temperature and buckling temperature. The first critical parameter, SFT, is determined by many methods such as rail creep, strain gauges with thermocouples, rail stress monitors (RSMs), vertical rail stiffness test equipment (VERSE), rail cut and measure, D'stressen, SFTpro, Railscan, etc. In this paper, the first three methods are considered. The rail temperature, the second critical parameter, can be estimated either by empirical relations or measured by thermocouple and RSM and

weather station (air temperature close to the rail). The third critical parameter, the buckling temperature, depends on track lateral resistance, initial misalignment and recent maintenance and ballast stabilisation operations, and can be determined by methods such as the single-push-tie-test (STPT) and CWR-SAFE software analysis [5, 6].

With a view to a unification of track buckling management practices in Australia and overseas, the CRC for Rail Innovation undertook a track stability management project. That study revealed that the area of track stability research in Australia needs more development as the fundamental researches in this field were performed in the USA [7-9] or UK [10-12] and their research outcomes are not readily transferable to Australian conditions as there are discrepancies in the weather conditions experienced and the applicable track standards. Australian research into track stability has been hampered due to fragmentation of the railway industry and lack of a centralised knowledge base regarding the track stability area. Studies into track stability have not been revised nor progressed from the 1980s [13, 14]. The maintenance practices, stability assessment tools and safety criteria used by the various rail companies in Australia, such as Queensland Rail (QR), Australian Rail Track Corporation (ARTC) and Rail Corporation New South Wales (RailCorp), differ from organisation to organisation.

Inspection and assessment of track stability is usually carried out to identify any potential risk of reduced track stability. Speed restrictions are imposed as a precautionary step to reduce the dynamic loading due to passing vehicles whenever the thermal load is expected to be higher due to high air temperature. Therefore, prevention of track buckling by routine maintenance and inspection is desirable for the cost effective management of track stability as the costs related to derailments and delays in traffic are greater than that of regular maintenance and inspection. In the past, rail workforces could

provide human inspection, local knowledge, local temperature information and on-site communications to locate the potential track buckling risk sites. This was effective in that there were much larger numbers of fettling, bridge and maintenance staff located at frequent intervals along track routes. However, the situations and threats can no longer be managed in this way because of costs and the greatly reduced workforce in rail operations. This encourages research to provide a management and decision support tool for use during severe heat events with the view to preventing derailments. This paper focuses on existing practices to estimate SFT by monitoring rail creep [15]; uses strain gauges, thermocouples and RSMs to quantify rail creep; and finally proposes a simple track stability management tool to help deciding the need for speed restriction during hot weather based on the quantified parameters from the field trials and rail standards.

2. SFT measurement principles

2.1 Rail creep method

In Mechanics, creep refers to the continued expansion or compression of material under load. However, in railway companies, rail creep is defined as the gradual longitudinal movement of rails in track caused by the action of traffic and thermal load on the rail line. In this paper the definition of railway companies is used to facilitate easy transferring of theory to the existent railway practices.

Rail creep happens when thermal and train dynamic forces exceed the longitudinal resistance of the track. Train braking, acceleration and temperature gradients along the rail can cause rail longitudinal movement [16]. Creep can occur in critical locations such as near fixed structures (level crossings, turnouts and fixed top bridges), in sags at the bottom of gradients or at any track segment with a history of buckles.

Due to creep, a portion of rail is **bunched** near a point where compressive stress increases and that portion of track can buckle at an unexpectedly low ambient temperature. The movement of traffic can also cause rail elongation due to plastic deformation in the top layers of the rail head [17].

When the rail is loaded axially for long periods of time, some materials develop additional strains that cause creep [18]. A detail study relating to rail creep was reported in an International Heavy Haul Association conference in Canada [15]. A new rail creep measurement method was proposed. The following section details briefly the rail creep models.

The rail is laid at the desired rail stress free temperature which is considered as the initial unstressed rail section or design neutral temperature (DNT). When rail temperature increases or decreases from this initial rail laying or DNT, rail expansion or contraction occurs as per Equation (1).

$$\Delta L = L\alpha(T_{N0} - T_N) \quad (1)$$

where ΔL = expansion or contraction in rail (mm), L = length of rail section (mm), α = thermal expansion coefficient ($^{\circ}\text{C}$), T_{N0} = initial rail laying temperature ($^{\circ}\text{C}$), and T_N = current stress free temperature ($^{\circ}\text{C}$). For a difference of 1°C in the stress free temperature within a 100m section of rail, the net creep required is 1.15mm. In other words, 1mm creep into or out of a 100m section of rail can change the SFT by 0.87°C . Equation 1 is the basis for determining the change of SFT due to rail movement in plain railway track [19].

Considering equivalent strain and allowing for the accuracy of instrumentation (δ), the general expression for the change of SFT can be obtained by using Equation 2 [15].

$$\Delta T_{\text{SFT}} = \frac{1}{\alpha} \left\{ \frac{\Delta L_3 \pm \delta}{L} + \frac{1}{2} \left(\frac{\Delta L_2 \pm \delta}{L} \right)^2 - \frac{\sigma_3}{E} \right\} \quad (2)$$

where ΔT_{SFT} = Change of SFT $^{\circ}\text{C}$, δ = accuracy of the instrument which needs to be

adjusted based on the distance of the measuring unit from the target point, ΔL_3 = longitudinal movement of rail over length L (mm) and ΔL_2 = vertical movement of rail over length L (mm), E = Modulus of elasticity of rail (207GPa).

2.2 Rail stress monitor (RSM) method

In the RSM, the longitudinal and vertical strain gauges are configured in the full bridge circuit such that longitudinal and vertical strains cause positive reinforcement of the bridge output voltage and compensates for temperature induced elongations in both directions [20]. The resultant longitudinal strain from the bridge circuit gives the longitudinal stress on the rail. The detail principles of operation of RSM sensors can be found in [20]. The RSM also uses an integrated circuit temperature sensor to measure rail temperature. Based on the longitudinal stress and rail temperature, the SFT is calculated by using Equations 3 and 4.

$$\varepsilon_3 = \frac{\sigma_3}{E} + \alpha(T_r - T_N) \quad (3)$$

$$T_{N0} + \frac{\varepsilon_3}{\alpha} = T_N = \frac{\sigma_3}{E\alpha} + T_r \quad (4)$$

where ε_3 = longitudinal strain, σ_3 = longitudinal stress (MPa), T_r = design neutral temperature ($^{\circ}\text{C}$), T_N = current SFT ($^{\circ}\text{C}$), T_{N0} = initial SFT ($^{\circ}\text{C}$), E = Modulus of elasticity (207 GPa for rail steel), α = coefficient of thermal expansion ($11.7 \times 10^{-6}/^{\circ}\text{C}$).

2.4 Longitudinal stress method

Since SFT can change due to both longitudinal and vertical movement of rail, it is important to measure both longitudinal and vertical strain while measuring the SFT. The longitudinal stress considers strains in both longitudinal and vertical directions. The longitudinal stress due to strains can be calculated by using Equation 5 [18]. The longitudinal stress can then be used to determine the SFT using Equation 6 which is simply a reorientation of

the basic equation for thermal stress (Equation 1).

$$\sigma_3 = \frac{E}{1-\nu^2}(\varepsilon_3 + \nu\varepsilon_2) \quad (5)$$

$$\sigma_3 = E\alpha(T_N - T_r) \quad (6)$$

where σ_3 = normal stress component in longitudinal direction, ε_3 , ε_2 = normal strain components in longitudinal and vertical directions respectively, E = Modulus of elasticity (207 GPa for rail steel), ν = Poisson's ratio (= 0.3 for rail steel), α = coefficient of thermal expansion ($11.7 \times 10^{-6}/^{\circ}\text{C}$), T_N = SFT ($^{\circ}\text{C}$), T_r = design neutral temperature ($^{\circ}\text{C}$).

3. Experimental design and field testing

3.1 Laboratory tests

In this paper an experimental design is developed to measure the variations of SFT using rail creep, strain gauges and RSMs and rail temperatures of both rails. Strain gauges and rail stress monitors (RSMs) were installed on two 60kg/m rails of length 4m and 6m in the Heavy Testing Laboratory of the Centre for Railway Engineering at CQUniversity, and tested by applying a vertical load of 5 tons using a hydraulic actuator (Figure 2) and calibrated by finite element analysis (Figure 3) before putting it into a site (Figure 4).

The observed strains were compared with the results from a three dimensional finite element model developed in the ABAQUS software package (Figure 3). The vertical load of 5 tons was transferred to a surface area of $20 \times 50 \text{ mm}^2$ over rail head that constituted a pressure load of 50 MPa in the finite element model. A 3 metre long three dimensional (3D) finite element rail model has been developed with 4 fixed supports corresponding to the concrete sleeper track design, and an applied pressure load of 50MPa at the middle of the rail section. The strains in the longitudinal (ε_3), vertical (ε_2) and lateral (ε_1) directions have been obtained

from the model. In this finite element analysis (FEA), strains at the neutral axis of the rail (at 79.3mm above the bottom of the 60kg/m rail) have been obtained to compare with the strains in longitudinal direction (ϵ_3), obtained from the laboratory tests. The longitudinal strains obtained from the FEA analysis show a maximum variation of 2.5% from the strains measured in the load tests in the laboratory, which has been considered adequate to confirm the validity of test data given the expected variation between real world results and theory (Table 1).

3.2 Field instrumentation and techniques

The two instrumented rail pieces were installed on straight track at the 82.806km point on the QR Blackwater heavy haul export coal system of the QR National network at Edungalba (Figures 4 and 5). All sensors were zeroed when the rails were free before welding into the existing operational track. Additionally, an RSM was installed on each rail of the 400m radius curved track at 82.500km approximately (Figure 4). The weather station and wayside monitoring system (which wirelessly collects RSM data) were installed nearby on a pole outside the rail corridor (Figure 6).

Table 2 summarises the measuring parameters and techniques used in this paper. The SFT was measured by both RSM (section 2.2) and longitudinal stress methods (section 2.4).

Rail temperature has been measured by using both thermocouples and RSMs. The T type (copper constantan) thermocouple with accuracy of $\pm 0.5^\circ\text{C}$ over -250 to $+300^\circ\text{C}$ has been selected for the experiment. The manufacturer of the RSM claims the accuracy of the integrated temperature sensor used in their RSMs is $\pm 1^\circ\text{C}$ from -20 to $+60^\circ\text{C}$. The temperature of the curved track was measured by using the RSMs only, while temperature on the straight track was measured by both thermocouples and RSMs. The National

Instruments CompactRIO computing hardware and Data Acquisition (DAQ) card have been used to collect the data from the strain gauges and thermocouples. Initially, 60 samples were collected at the 60th minute of every hour and stored in memory disks which were collected periodically from the track site. Air temperature has been obtained from the weather station and collected periodically from the DAQ installed on the site.

The wayside monitoring system collects data (strain and rail temperature) from the RSMs every ten minutes by radio technology (IEEE802.15.4) and sends it via the wayside network to the Stress-Net database [21]. The data from the RSMs have then been collected remotely from the Stress-Net web based database.

Rail creep measurement setup and technique are shown in Figures 7 and 8. The creep in this section has been quantified in terms of rail strain and rail stress with respect to the rail temperature using Total Station Survey equipment (Figure 8d). Detailed formulation of the new method and analysis was presented elsewhere [15].

3.3 Steps of field testing

There are three different set of instrumentation on the site- instrumented rail piece, weather station and creep measurement. Data collection was performed both remotely and locally. The key steps of installing the instrumented rail piece have been described below

1. Installation and zeroing of all sensors on rail pieces in the laboratory
2. Cut rail on the test site, install instrumented rail piece by welding
3. Zeroing of all sensors installed on the rail instrumented rail pieces welded on actual track by the Compact Rio computing hardware
4. Start recording data from the RSMs, strain gauges, thermocouples and collect periodically from the site

5. Installation of wayside monitoring system to collect the data from the RSMs remotely
6. Installation of the weather station
7. Marking the rail for creep measurement (Figure 8)
8. Periodical measurement of rail creep using total station survey equipment

Table 3 shows that comparison of the measured change in SFT by the proposed creep measurement method (Equation 2) [15], conventional SFT measurement by creep method as shown in a GHD report [22] and RSMs reveals that these values of SFT were well correlated. Hence the results presented in section 4 can be trusted. This also establishes the proposed rail creep method as a more accurate method than the conventional measurement technique.

4. Field testing data results and discussion

Three surveys were carried out at the same sites. It is evident that both rails moved in the Down direction (+) at site 1 (km 82.804-82.820) and moved in the Up direction (-) at site 2 (km 82.890- 82.900) (see Up direction arrow in Figure 4). Results show that the change in SFTs determined by RSMs are 1°C and 4°C higher than those obtained by longitudinal creep measurement on the right and left rails respectively [15]. Figure 9 demonstrates a change of SFT with respect to rail creep and rail temperature within a 100m track section at a DNT of 38°C, and shows that SFT increases with the increase of rail temperature and decrease of rail creep.

Current practice to determine the length over which to measure rail creep does not consider the resistance of the track. If the thermal and vehicle loading is fully restricted by the track resistance there would be no rail creep. At low resistance, the longitudinal load would be distributed over a longer section of track. If

two measurement points are not within a minimum length on any track structure over which the longitudinal load is distributed, the net change in SFT on that section cannot be reliably determined. The longitudinal resistance is determined on as per unit length basis, while thermal and vehicle loads do not depend on length. In order to minimise the load developed on a track section, the total track resistance (F_R) over a length needs to be equal and in the opposite direction to the longitudinal force developed by heat and vehicle action. Based on the empirical fraction of 25% of the axle loadings [12] acting along the longitudinal direction by braking, and using the conventional thermal load relationship, the following condition can be developed to determine the required length of any track structure based on track resistance:

$$0.25F_V + F - F_R L = 0 \quad (7)$$

where F_V = vertical axle load (N), F = thermal load (N) = $AE\alpha(T_R - T_N)$, F_R = longitudinal resistance per metre of track (N/m), L = length of track (m), T_R = rail temperature.

Equation 7 can be used to determine the maximum length required for different track resistances, thermal and axle loads. For a track resistance of 8kN/m, an axle load of 26 tonnes and an expected temperature deviation from the SFT of 20°C, in Figure 10 was generated which shows that the longitudinal force (thermal and braking) becomes equal to the track longitudinal resistance over a length of 55m. This length can be considered as the maximum allowable distance (L_{max}) between two creep measuring monuments. The significance of this L_{max} is that, beyond this length, the longitudinal resistance is adequate to suppress the longitudinal movement by loads and hence, no creep can be found beyond this length.

Table 4 shows typical allowable maximum distances between creep measuring monuments based on track resistance of a

track subject to maximum rail stress corresponding to a rail temperature 20°C above SFT and an axle load of 26 tonnes. The difference (F_c) between the longitudinal force and resistance is the cause of the longitudinal movement. The force, F_c , in Figure 10 is responsible for any longitudinal movement of track at any length of track. It is obvious that, after $L_{\max}$, the F_c becomes negative, i.e., no longitudinal movement is possible at any length beyond $L_{\max}$.

Of the four RSMs installed at the test site (Figure 4), two RSM modules show large irregular variations in SFT (Figure 11). Later, two additional modules were installed and observed that those two modules were malfunctioning. In the current analysis, data obtained from the suspect modules are taken up to the date that they were in good agreement with the desired stable change in SFT (Figure 12). Analysis has been made restricted to data that showed regular trends only (Table 5). It has been observed that one RSM on each straight and tangent track showed a desired range of SFT. However, the other two RSMs did not match well with the theoretically acceptable range of SFT over a long period of time.

Figure 13 represents the SFTs obtained by longitudinal strain, longitudinal stress and the RSM methods. It was observed that RSMs showed higher SFTs than those obtained by the longitudinal strain method, but lower/similar SFTs than those obtained by the longitudinal stress method. The RSMs are expected to give more accurate data than those obtained by theoretical longitudinal strain and stress methods since the residual force component is taken care of in RSMs. Figure 14 shows variations of SFT due to rail temperature. It has been observed that SFT tends to increase with rail temperature on a day with high rail temperature. Strain gauge and thermocouple based calculations (Figure 15(a) and 15(b)) showed a decreasing trend of SFT at the high rail temperature, but RSM

showed an increasing trend of SFT at the high rail temperature (Figure 15(c)). The circuit design in RSM measures rail force and then converts it to stress and SFT by using Equations 3 and 4 that continually refer to the previous SFT, and hence a cumulative reading is achieved. On the other hand, strain gauges and thermocouples were zeroed to initial zero stress condition and do not consider the change in zero stress condition.

SFT on the curved track showed a decreasing trend over the period of the data acquisition, but SFT on the straight track did not show any change trend (Figure 16). SFT of the straight track was found to be $3\text{--}5^{\circ}\text{C}$ higher than that of the curved track within the time interval observed (Figure 17). The inside rail on the curve experienced a higher rate of change of SFT than the outside rail (Figure 18). It is noted that the variation between inside and outside rails on the curve is significant only during the heat of the day, and can be due to the difference in rail temperature between left and right rails at the peak of the day (Figure 18). In stable conditions, RSMs showed a difference in SFTs between the two rails of about 5°C (Figure 19) on straight track and of about 12°C on curved track. SFT has been found to change within an entire daily cycle (Figure 20). Considering the negligible rail movement in any direction within a day on a stable track, the reason behind the variation in SFT is the internal stress developed in the rail due to change in rail temperature related stress. Though SFT doesn't really show any trend at low rail temperature, it was observed that, at high rail temperature, SFT can increase by $2\text{--}3^{\circ}\text{C}$. The increase in SFT means reduced risk of track buckling.

Results from the weather station and the thermocouples on the rails (Figure 21) showed that rail temperature increased by about 20°C over air temperature when air temperature started to increase over 20°C . At low air temperature, the rail temperature is nearly the same as that of air. A typical daily curve

(Figure 22) shows rail temperature increased rapidly by about 17°C from 9am to 12pm when air temperature increased by 5°C. The peak rail temperature was observed between 12pm and 3pm. Rail temperatures tended to decrease after 3pm even though there was an increase in air temperatures. This observation reveals that rail temperature cannot be approximated based on air temperature only.

The rail oriented in E-W and N-W/S-E directions experience direct solar irradiation at the time of highest air temperature which increases the maximum rail temperature compared to that of other rail orientations [23]. A typical daily curve shows a variation in rail temperature of about 4-5°C at the peak rail temperature due to change in orientation of the rail (Figures 23 and 24). At the instrumented site, the curved track oriented in the N-S direction exhibited higher rail temperatures than that of the straight track oriented in an approximate E-W direction. The rail temperature reached its peak in the late afternoon for track in a N-S direction, while this occurred in the late afternoon for track with an approximately E-W direction. This observation can be useful to justify the reduction of the duration of speed restriction on any particular geographic area where a significant portion of rail is oriented to a particular direction.

5. Development of a track stability management tool

Different procedures and tools are currently used in different railway companies to determine the need for maintenance to reduce the risk of track buckling. The tools are mostly based on empirical relationships between track resistance and SFT. In some of the tools, the setting of priority levels for rail restressing is included. However, the imposition of train

speed restrictions has been kept separate from all the assessment tools of track stability and is solely decided based on forecast or measured air temperature, and in some cases on measured rail temperature variation above the SFT. So far the requirement for inspection and implementation of a preventive maintenance action plan has not been included in the existing tools. The segmentation of different activities affecting track stability has made the decision making process regarding maintaining track stability complex and time consuming.

A unified track stability management (TSM) tool has been developed to determine the requirements for predictive rail adjustment and improved hot weather speed restriction policy. The TSM tool combines stability considerations and rail stress, and also suggests criteria for the priority rating for rail adjustment. The TSM tool is based on a margin of safety (MS) concept which is regarded as the difference in track strength (TB) and rail stress ($TR - TN$) of any particular track structure. TB is the temperature above SFT at which buckling is likely to occur; TR is the maximum expected approximate rail temperature including rail temperature factor and TN is DNT with stress free temperature factor. Details of these factors are discussed in [24].

The track strength (TB) has been quantified in terms of buckling temperature (Figure 25). Buckling temperature is the estimated temperature rise above stress free temperature that is likely to buckle a track considering the track resistance; the effects of various recent maintenance activities and/ or measures undertaken to improve track stability; and localised track structure weaknesses. Rail stress has been defined as the difference in approximate rail temperature (TR) and approximate stress free temperature (TN). Difference between track strength (buckling temperature) and rail stress at any particular site and time would determine the MS for that

site at that time (Figure 26). The developed TSM tool combines the recent theory on track buckling, the expected variation in SFT and the uncertainty in predicting rail temperature based on maximum air temperature to decide on the need for preventive maintenance and operational precautions on track. The approximation of buckling temperature, modified SFT and modified rail temperature help to identify the cause of loss in the margin of safety, and hence it is possible to determine the inspection requirement and preventative maintenance action plan.

Recent data based on tests on American railroads has been included in CWR-SAFE software. Considering the strength of modern Australian track structures, these data can be used until track lateral resistance data for Australian conditions are available. In this study, the industry version of CWR-SAFE software used in the web based Stress-Net application has been used to quantify the buckling temperature. In the software, buckling margin of safety has been determined by non-linear buckling response characteristics and safety criteria as discussed in [24]. Based on the relationship used for buckling margin of safety, buckling temperature has been calculated by using Equation 8:

$$TB = BMS + (TR_{max} - TN) \quad (8)$$

where, TB = Buckling temperature ($^{\circ}C$), BMS = buckling margin of safety ($^{\circ}C$), TR_{max} = expected maximum rail temperature on the desired section of the track ($^{\circ}C$) and TN = SFT of the track ($^{\circ}C$).

Buckling temperature increases with the increase of track lateral resistance and decrease of misalignment which is supported by other studies of Bartlett, Schramm and Kish discussed in [25] (Figure 27).

5.1 Priority rating for rail restressing

Priority rating for restressing has been determined based on both the margin of safety

and the consequence of buckling on a specific track section. The parameters of severity of track buckling have been derived from the standard of Network Rail [26]. However, in this analysis the score has been modified to coincide with the concept that low margin of safety means high risk. High priority (low number) has been given to those conditions with high consequences if there is a buckle incident (Table 6).

The overall priority score is the product of the different priority numbers of different consequences. The overall priority of rail adjustment needs to be decided based on Equation 9. Here, the product of margin of safety and the priority score has been deducted from the maximum expected value of 3780 ($MS(70) \times \text{priority score}(54)$) in order to set a high priority level corresponding to track with low margin of safety and high level of priority.

$$\text{Priority of adjustment} = (3780 - (\text{margin of safety} * \text{overall priority score}))/37.8 \quad (9)$$

As an example, a track with conditions of a MS of 50, an operating speed >130kph, a traffic task >15 MGT, and >2 tracks at grade should have a priority of adjustment of $(3780 - 50 * 1 * 1 * 2 * 1)/37.8 = 97.4$. A track with similar conditions but with a lesser operating speed of 80-130kph would have a lower priority of adjustment level of $(3780 - 50 * 2 * 1 * 2 * 1)/37.8 = 94.7$. Similarly, track with high MS would have a low level of priority considering the comparatively high resistance against track buckling.

5.2 Track stability management tool

The track stability management tool can be used to determine the need for preventive inspection and maintenance of rail (Figure 28). Margin of safety (MS) has been separated into three segments. At the worst case the track needs to be shut down; at an intermediate MS,

a speed restriction can be imposed during the heat of the day; and at a satisfactory MS there should be no alteration from regular train speed. A low MS does not always mean restressing the rail is a good option to ensure safety. Low buckling temperature resulting from low lateral resistance can also reduce the MS. It is necessary to determine the cause of the low MS to decide whether rail restressing or improving lateral resistance is a better option.

Lateral resistance can be improved by increasing crib and/or shoulder ballast, and by mechanical ballast stabilisation, etc. SFT can be improved by carrying out rail adjustment operations. If there is no evidence of reduced lateral resistance or SFT, it is necessary to observe the maximum rail temperature. If maximum rail temperature is above a certain limit on a specific section, care should be taken to reduce the rail temperature. Painting of rail and/or creating shade by planting trees near the track can help to reduce maximum rail temperature. In a case of failure to identify the cause of low MS, a direct measurement of SFT on the specific track is suggested. The measured SFT should replace the modified *TN* in the stability management tool.

The characteristic values of parameters a, b, c, d, e and f in Figure 28 need to be selected based on the track and weather conditions of a specific section. A guideline has been developed in the following section to determine the characteristic parameters. Parameters d, e and f depend on buckling temperature, SFT and rail temperature, while parameters a, b and c are related to margin of safety.

It has been determined from Stress-Net that, for a concrete sleepered track with 60kg/m rail, half crib ballast, 200mm ballast shoulder and a 50mm misalignment over a 10m track length, the buckling temperature can be as low as 40°C. Buckling temperature can be improved to as high as 54°C on the same track if lateral resistance is improved. Here, any value of *TB*

less than 45°C (parameter d) has been considered as needing to be improved.

The allowable decrease in SFT has been considered with respect to a reduction from the Design Stress Free Temperature (DSFT) as provided by the QR standard for the instrumented site in the Blackwater system, i.e. 31°C (DSFT – 7°C) for concrete sleepered track (parameter e). Based on historical data and an empirical relationship between air and rail temperature, it is expected that the maximum rail temperature for the Blackwater system should be less than 60°C (parameter f).

At the limiting condition of parameters d, e and f, the MS becomes $(d - (f - e)) = 16$ which is close to the margin of safety of 18 as determined based on track conditions. Characteristic parameters a and b have also been determined based on the analysis of speed restriction discussed in the following Section 5.3. Typical values of characteristic parameters a to f have been presented in Table 7.

In the track stability management tool, three situations, namely safety (stage1), track condition (stage2) and priority of stressing (stage3) have been used to identify the required action corresponding to a value of any parameter (Figure 29). Margin of safety has been considered as the primary parameter for making a decision. If the MS is below a critical value, careful investigation of track strength and rail stress is required. Three levels of buckling temperature, rail temperature and stress free temperature have been proposed based on track conditions (Figure 29). For example, if MS falls below 15 (S3) it is necessary to impose a Level 1 speed restriction (Figure 29, Stage 1), and an investigation into track strength and rail stress needs to be carried out as per the method described in Figure 29. If any parameter is found to be in the T3 zone (Figure 29, Stage 2), it is necessary to take action to improve that parameter and then carry out the assessment of track stability again (Figure 28). If the SFT has

been suspected to be at a low level, it is necessary to determine the priority level of that site for rail adjustment (Figure 29, Stage 3).

As an example, two track sections have been investigated using this tool (Figure 30). Both track sections showed adequate MS, however modified rail temperature shows a high value. If the rail temperature shows a high value for a significant period of time, it is necessary to set an inspection plan to measure the rail temperature of that section and take action to reduce the rail temperature. Reduction of rail temperature can be achieved by painting or increasing shadow near the track. The SFT on the curved section (82.5km) is at the yellow band that suggests inspecting track for rail creep, pull in or any other reason that might affect the SFT.

Considering good track condition and small creep and curve pull in, it was observed that only heat patrol is necessary at air temperatures of 47°C and 42°C (corresponding to MS of 18) on the two sections of track respectively. Level 1 speed restrictions need to be imposed only at air temperatures of 50°C and 45°C respectively on the straight and curved portion of track. Since the distance between the two sections is only 300m, it is not practical to apply different speeds within this small length. The maximum allowable air temperature to apply heat patrol and level of speed restrictions need to be decided on the lowest permissible air temperatures within a specific length of track section. For example, in the considered case, heat patrol needs to be applied at an air temperature of 42°C and a level 1 speed restriction needs to be applied at 45°C. These air temperature values (45°C for straight track, 42°C for curved track) are higher than both the QR standard and the increased threshold of air temperature recommended by GHD [22] in case of straight track.

The TSM tool also shows that the reason behind this low margin of safety is high rail

temperature which suggests reducing rail temperature can achieve a greater MS. Reduction of rail temperature can be achieved by painting or increasing shadow near the track. The SFT on the curved section (82.5km) is at the yellow band that suggests inspecting track for rail creep, pull in or any other reason that might affect the SFT.

5.3 Speed restriction

Speed restrictions are usually imposed due to hot weather or maintenance operations. A report by GHD [22] recently recommends increasing the temperature threshold for speed restriction on concrete sleepered track considering its high track resistance. However, this can prove to be misleading for a track with low SFT, when a relatively low rail temperature can induce high thermal stress. Here it is advised to use the MS of the relevant track structure to decide on the applicability of a speed restriction. Two levels of speed restriction have been proposed considering two limiting conditions of the MS (Figure 29). The consideration of SFT and reduced lateral resistance due to maintenance operations can make this TSM tool suitable for imposing a speed restriction due to maintenance work also.

Information on speed restrictions based on SFT and track disturbance used by Network Rail [26] has been used here to quantify the requirement of speed restriction (Table 8). For example, an undisturbed, fully ballasted and consolidated track would require heat patrol at rail temperature 32°C higher than the SFT of that track. In other words, this track can withstand a rail stress equivalent to 32°C. A weaker track is likely to withstand less stress and heat patrol is required at a low temperature for weak track structures. Based on the information on two levels of speed restrictions, the required margin of safety has been developed in Table 9. The required margin of safety to apply heat patrol reduces with the reduction in track strength.

It is obvious that strong and weak tracks show a regular trend in margin of safety requirement when considered heat patrol and speed restrictions. Allowable margin of safety decreases with the increase of track strength between medium and strong track. In order to simplify the relationships the greatest values of margin of safety in all cases has been used in the TSM tool to make it applicable for all track conditions. It may be noted here that applying all conditions of Table 9 can reduce the possibility for speed restrictions in some degree. The simplified quantified values of margin of safety for all track structure have been presented in the last row of Table 9.

Levels of speed restriction can be based on axle loadings on any specific track. Level 1 speed restrictions are usually 10-15km/h less than the operational speed. A 50% reduction in speed has been found in QR and Network Rail standard as a mean of level 2 speed restrictions. In case of major track disturbing work NR even recommend to obtain one-third of the normal speed. Based on this information the level 1 and 2 speed restrictions has been set as a reduction of 10% and 50% of normal speed.

6. Conclusions

A thorough investigation relating to track buckling was carried out considering a test site in a heavy haul coal line near Blackwater in Central Queensland. Different equipment such as a Total Station Survey setup for measuring rail creep, strain gauges, RSMs, thermocouples and weather station are used. Finally, a simple track stability management tool is developed. Its performance needs to be tested for its intended uses. The following conclusions are made:

1. Quantified information on rail stress and lateral resistance can help better manage the stability of continuously welded rail.
2. A theoretical maximum allowable distance between two creep

monitoring monuments has been established.

3. Depending on the orientation of rail and exposure to sun, the maximum rail temperature can be lower than the established relationships indicate; this can reduce the need for speed restrictions.
4. The combination of information on weather parameters, history of track maintenance and the statistical distribution of SFT in a single tool can help better manage the stability of track.
5. SFT tends to become 2-3⁰C higher at the maximum rail temperature than the SFT at the minimum rail temperature of the day.
6. The inclusion of rail temperature related internal stress components in the calculation of rail creep data to determine the SFT has led to the determination of a range of the expected SFT rather than a single SFT value within a day.
7. The best practice tool suggests reacting according to the requirements determined by the margin of safety theory that considers the rail SFT, rail temperature and track strength parameters to determine the need for inspection and maintenance.

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Figure 1: Track buckling

Figure 2: Test of strain gauges in lab

Figure 3: Finite element analysis to confirm the lab test results

Figure 4: Field test setup

Figure 5: Field instrumentation (82.806- 82.811km)

Figure 6: Wayside monitor, weather station and data acquisition system of weather station

Figure 7: Creep measurement: (a) mark on rail, (b) laser tool, (c) string line

Figure 8: Setup for rail creep measurement: (a) site 1, (b) site 2, (c) glued mark on rail, (d) total station survey equipment

Figure 9: SFT versus rail creep over a 100m track section for varying rail temperature

Figure 10: Longitudinal force and resistance along length of a track section

Figure 11: Uneven variation in SFTs on straight and curved track

Figure 12: SFT and temperature distribution on straight track (km 82.810)

Figure 13: Frequency distribution of SFT obtained by strain gauges, thermocouples and RSM on left straight rail

Figure 14: Change in SFT with rail temperature

Note: SFT4- SFT measured by longitudinal stress method using strain gauge 4 ($^{\circ}$ C), SFT4s- SFT measured by longitudinal strain method using strain gauge 4 ($^{\circ}$ C), SFT4srm-SFT measured by RSM ($^{\circ}$ C), TR- Rail temperature ($^{\circ}$ C).

Figure 15: Variation in SFT and rail temperature by strain gauge, thermocouple and RSM

Figure 16: Variation in SFTs on left rail between straight and curved track

Figure 17: Difference in SFTs ($^{\circ}\text{C}$) between straight and curved track

Figure 18: Variation in SFT on inside (module 799-R) and outside (module 796-L) rail of curve

Figure 19: Variation in SFT between left and right rail on straight track (1 June - 1 September, 2010)

Figure 20: A typical diurnal cycle of SFT on straight track (7-8 August, 2010)

Figure 21: Rail temperature and air temperature variation with date

Figure 22: Typical daily variation in rail temperature with air temperature (1 June, 2010)

Figure 23: Variation in rail temperature due to different orientation of rail on curved and straight sections

Figure 24: Variation in daily rail temperature due to change in orientation of rail

Figure 25: Buckling temperature and energy

Figure 26: Methodology to use Margin of Safety tool

Figure 27: Change of buckling temperature with respect to misalignment and track lateral resistance obtained by using StressNet

Figure 28: Implementation of the track stability management tool as a guide to determine the need for inspection, maintenance and preventive measures

Stage 1			
	Margin of Safety		
S1	$\geq$	18	Normal Operation
S2	$\geq$	15	Heat patrol
S3	$\geq$	13	Level 1 speed restriction
S4	$<$	13	Level 2 speed restriction

Stage 2				
	TB	TR	TN	
T1	≥ 50	< 55	$> \text{DNT}-7$	Normal Operation
T2	≥ 45	≥ 55	$> \text{DNT}-10$	Inspection
T3	< 45	≥ 65	$< \text{DNT}-10$	Preventive Action

Stage 3			
	Priority of Stressing		
P3	$<$	90	Normal Operation
P2	$\geq$	90	Inspection
P1	$\geq$	95	Preventive Action

Figure 29: Decision making by the application of track stability management tool

Km	Date	Maximum ambient temperature	Maximum rail temperature	Design stress free temperature	Safety				
					TB- (TR- TN)				Priority for stressing
					TB (from Stress-Net)	Modified TR	Modified TN	Margin of Safety	
82.8	04/03/2011	47	67	38	57	71	32	18	94
82.5	05/03/2011	42	61	38	53	66	31	18	94

Figure 30: Print screen view of analysed data on the TSM tool

Table1: Comparison of strain data

Strain gauge	Strain (mm/mm)		Error
	lab test	FEA	
4.2	0.0000373	0.0000383	2.5%
3	0.0001039	0.0001042	0.3%
6.2	0.0000411	0.0000416	1.3%
8	0.0001061	0.0001042	-1.8%

Table 2: Measuring Parameters and Techniques

Parameter	Measuring Technique	
	Option 1	Option 2
SFT	RSM	Strain Gauge and Thermocouple
Rail Temperature	Thermocouple	
Air Temperature	Weather Station	
Creep	Total Station Survey equipment	
Misalignment	Tape measure	Total Station Survey equipment

Table 3: Calculation of SFT from Rail Creep Data between Survey 2 (14.10.10) and Survey 3 (12.11.10)

Rail	Points	Distance (mm)	Creep (mm)	Change in SFT ($^{\circ}\text{C}$) due to Creep		Change of SFT by RSM ($^{\circ}\text{C}$)
	From-to			Theoretical	GHD (2005)	
Left Rail	4-10	83040	-1.31	-1.35	-1.39	-4.95
	4-11	83788	-0.79	-0.81	-0.83	
	5-10	82368	-1.7	-1.76	-1.81	
	5-11	83116	-1.18	-1.21	-1.25	
Right Rail	1-8	89100	-2.18	-2.09	-2.16	-1.88
	1-9	89907	-1.93	-1.83	-1.89	
	3-8	83020	-1.39	-1.43	-1.47	
	3-9	83813	-1.14	-1.16	-1.20	

Note: creep into a rail section is considered as negative (-), creep out of a section is considered positive (+)

Table 4: Maximum allowable distance ($L_{\max}$) between two creep monuments based on track resistance

Sleeper type	Track condition	Resistance (kN/m)	$L_{\max}$ (m)
Timber	Medium	3	83
Concrete	Weak	3	145
Concrete	Medium	8	55
Concrete	Strong	12	36

Note: Axle load = 26tonnes, $TR-TN = 20^{\circ}\text{C}$

Table 5: Period of regular data obtained by different RSMs

RSM no. - Left/ Right rail	Track condition	Data Start	Data End
794-L, 795-R	Straight	24 May, 2010	1 September, 2010
796-L, 799-R	Curved	24 May, 2010	21 July, 2010
795-R	Straight	24 May, 2010	1 March, 2011
796-L	Curved	24 May, 2010	1 March, 2011

Table 6: Priority rating to restress the rail

Number	Parameter of Consequences	Priority
1	Line speed	
	a) < 80 kph	3
	b) 80- 130 kph	2
	c) > 130 kph	1
2	Traffic	
	a) < 5 MGT	3
	b) 5-15 MGT	2
	c) > 15 MGT	1
3	Cutting or Embankment	
	a) At grade/ in cutting	2
	b) Embankment or structure	1
4	Number of tracks	
	a) 1	3
	b) 2	2
	c) >2	1
	Overall priority score	Product of priorities

Table 7: Typical values of characteristic parameters of track stability assessment tool for QR heavy haul Blackwater system

Parameter	Symbol	Critical Value (°C)		Action
Margin of Safety	MS	a	< 13	Level 2 speed restriction
	MS	b	< 13	Level 1 speed restriction
	MS	c	< 15	Heat patrol
	MS	c	> 18	Normal operation
Buckling Temperature	TB	d	< 45	Improve lateral resistance
Stress Free Temperature (modified)	TN	e	< 31	Improve SFT
Maximum Rail Temperature (modified)	TR	f	> 60	Reduce rail temperature

Table 8: Requirement of heat patrol based on track condition

Stress-Net results				Network Rail	
TB (°C)	Misalignment (mm)	Shoulder (cm)	Crib	Conditions	Heat patrol (SFT+)
>50	10	30-45	FC	Undisturbed, fully ballasted and consolidated	32
45-50	10-30	30-45	FC, 3FC/4	No ballast shoulder (no other disturbance or deficiency)	27
40-45	10-30	20-45	FC, FC/2	Tamped/ lined with slews/ lifts up to 25mm	22
35-40	30-50	20-45	FC/2	Measured shovel packed/ hand-held stoneblown	17
30-35	75	30	3FC/4	Ballast generally full between sleepers on shoulders, but not consolidated (less than 8 sleeper beds)	15
<30	75	20-30	FC/2	Severe shortage of ballast between sleepers and/or part sleeper ends exposed, extending 8 sleeper beds or more	10

Note: FC- Full Crib

Table 9: Required level of margin of safety to determine heat patrols and speed restrictions based on track strength (TB) and rail stress (TR- TN)

Track Strength	TB (°C)	TR- TN (°C)			Margin of Safety		
		Heat patrol	level 1 SR	level 2 SR	Heat patrol	level 1 SR	level 2 SR
Strong	>50	32	37	42	18	13	8
	45-50	27	32	35	18	13	10
Medium	40-45	22	26	29	18	14	11
	35-40	17	20	22	18	15	13
Weak	30-35	15	18	20	15	12	10
	<30	10	13	15	15	12	10
All tracks					18	15	13

Note: SR- Speed restriction