HEAVY HAUL RAIL PERFORMANCE AT TRANSNET

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SUMMARY

Infrastructure reliability and availability are key factors influencing Transnet's ability to achieve the Market Demand Strategy (MDS) and grow in highly-competitive global markets. For the Sishen-Saldanha Heavy Haul Line (ORELINE), the track structure is in many respects the backbone of the operation and the integrity of the rails requires ongoing and specific attention to ensure safe and affordable railway operations. A review of derailments and assessments of rail failures afford detailed insights into the respective challenges and trends. The root causes have been critically assessed, leading to a wide range of solutions that are being implemented. These include improved condition monitoring and weld management, in addition to addressing training requirements. Furthermore, benchmarking has been done with Transnet's COALLINE and international heavy haul operations.

1 INTRODUCTION

The operation of long trains and high axle loads places considerable strain on the ORELINE system, particularly the rail infrastructure. A high-level review of the rail performance has therefore been performed. This includes thorough analyses of derailments and rail breaks, assessments of welding performance, and benchmarking in order to better understand the situation, identify the most important maintenance issues and prioritise the areas that require improvement. It is important to ensure safe and reliable railway infrastructure in light of the influence of rail breaks on derailments and Transnet's planned MDS volume increases for the ORELINE.

2 DERAILMENTS

The ORELINE derailment history since FY2006/7 is shown in Figure 1. This reveals a strong upward trend in all derailments up to FY2010/11 and then a dramatic improvement since. Almost 60% of all derailments over the past 9 years have been due to Rail Network failure. The overwhelming majority of derailments due to Rail Network failure are due to rail breaks and thus the contribution of rail breaks to all derailments is 54%.

This contrasts vastly with the COALLINE where only 20% of all derailments since 2009 have been due to Rail Network failure. Furthermore, on the COALLINE there is a greater spread in the root causes of Rail Network caused derailments and therefore the contribution of rail breaks to all derailments is very low at only 6%. Furthermore, when benchmarked with the North American Class 1 Railroads (2010 to 2014) [1, 2], the ORELINE shows a significantly higher contribution of derailments due to rail breaks. *[Benchmarking information is unfortunately not available for heavy haul systems operating 30 tonne axle load on 60 kg/m rail at maximum speed of 60 km/h, i.e. MTAB (Sweden) and ARTC Hunter Valley (Australia).]*

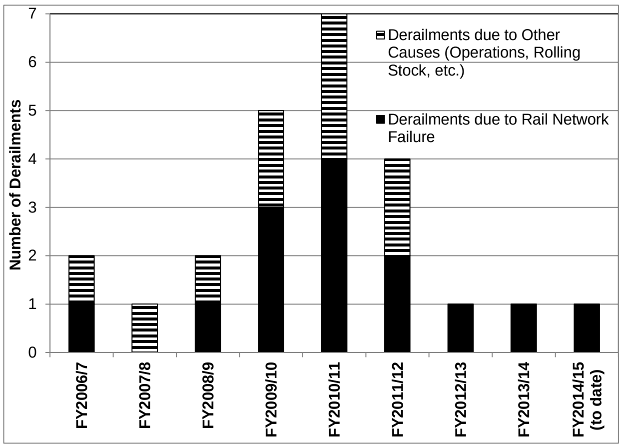

Figure 1. Derailment History

An assessment of the derailments due to Rail Network failure per section reveals a significantly higher derailment density for the sections north of Halfweg (see Figure 2). The density of derailments for the entire line is 0.026 Derailments due to Rail Breaks per Billion Gross tonne km, contrasting starkly with the COALLINE experience over the past 6 years of only 0.006. Furthermore, when benchmarked with the Class 1 railways, the ORELINE is at a considerably higher rail break caused derailment density.

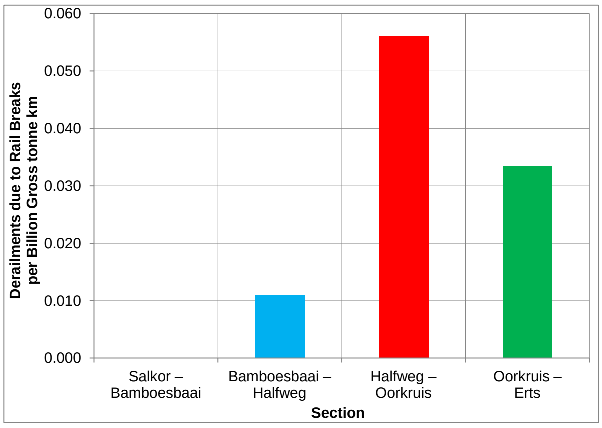

Figure 2. Density of Derailments due to Rail Break per Section

An assessment of the number of derailments due to rail breaks and the rail breaks during the same period indicates that the proportion of rail breaks that result in derailment is 5.8%. This is the Probability of Derailment due to Rail Break as a function of total number of rail breaks and infers that – *on average* – there is a derailment due to a rail break for every 17 rail breaks. As a comparison, the COALLINE has since 2009 experienced a Probability of Derailment due to Rail Break of only 0.8% and the only available Class 1 benchmark, i.e. BNSF for the period 2000-2003, shows a similarly low probability of only 0.6%. Therefore, if there is a rail break on the ORELINE, then the probability of this resulting in a derailment is in fact astonishingly high. The following factors are affecting this derailment behaviour:

- Train length. The operating of 342 wagon trains significantly increases the risk posed by an undetected rail break compared to that of shorter trains, as the number of axles passing over the point of failure is much higher and there is therefore an extended period of rail damage and track deterioration under a single train; and
- Axle load. Operating at 30 tonne axle loads significantly increases the amount of track deterioration, rail deflection and material destruction suffered should there be a rail break, compared to a lower axle load.

Furthermore, the line is not equipped with track circuitry, as the train authorisation system makes uses of axle counters, and therefore the benefit of rail break detection by means of the signalling system is not available. In light of the fact that derailments on the ORELINE are a very direct function of the incidence of rail breaks and since it is highly unlikely that the operation will return to shorter trains and the original axle load of 26 tonnes, the focus must be placed on the reduction of the incidence of rail breaks plus the intelligent detection of rail breaks. The installation of the Ultrasonic Broken Rail Detector (UBRD) has therefore made significant strides in improving the safety of the operation.

A deeper analysis of the position of rail breaks leading to derailments on the ORELINE reveals that over two-thirds of rail break related derailments are due to failure of aluminothermic “Thermit” welds, shown in Figure 3. The distribution differs somewhat with that of rail breaks, with the contribution of aluminothermic welds to derailments being greater than the contribution of aluminothermic welds to rail breaks, indicating that aluminothermic welds have a greater propensity for derailment (compared to flash-butt welds and parent rail). Furthermore, ultrasonic detectability of defects in aluminothermic welds is very low. Therefore, particular effort is required to improve the management of aluminothermic welds, as this is the most significant derailment risk.

Two flash-butt weld related derailments have been a feature since February 2013 and both have been related to transverse fatigue defects in the rail foot. The flash-butt welds were 6 and 9 years old respectively. These defects are typically undetectable by the routine ultrasonic testing techniques currently deployed. This places a focus on the manufacturing quality of flash-butt welds (specifically the alignment and shearing processes), as the fatigue defect originates at a discontinuity on the surface of the foot.

Furthermore, attention to rail support in terms of track roughness, sleeper/ pad, ballast and formation condition is paramount to ensure that flexural stresses are contained in light of the 30 tonne axle load conditions. The sections requiring critical attention are north of Halfweg, in which both flash-butt weld related derailments occurred, and the track quality of the Oorkruis – Erts section in particular is lying at a higher TQI_{50} of 4.5, with the remainder of the line performing much better at TQI_{50} of between 3.5 and 4.0 [14]. Should rail support conditions and rail longitudinal stress management not improve, the incidence of flash-butt weld related derailments is likely to increase.

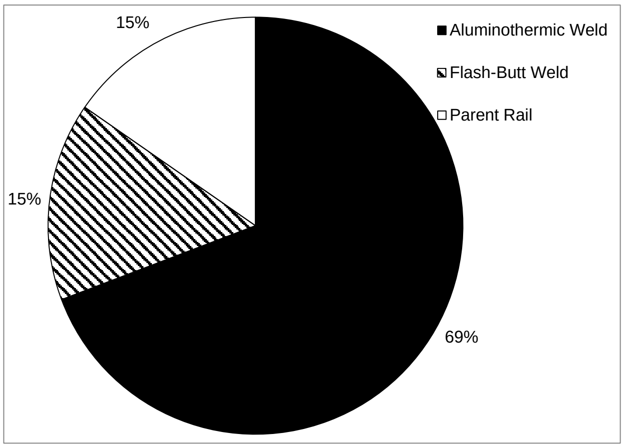

Figure 3. Distribution of Position of Rail Breaks causing Derailments

A significant 85% of derailments due to rail breaks occur in the winter period from April to August (see Figure 4), not surprising since this is the period of higher incidence of rail breaks. The "cold snap" months of April and May are the first high season period for derailments due to rail breaks, accounting for 55%. August is the next high season due to very low temperatures, accounting for almost a quarter of derailments due to rail breaks. Two derailments have occurred in summer (both on welds), demonstrating that if the vertical load (and therefore bending stress) is sufficiently high and the rail foot defect is large enough, the combined effect can be catastrophic even in the absence of tensile longitudinal stress. This further demonstrates the need to tightly control rail longitudinal stresses.

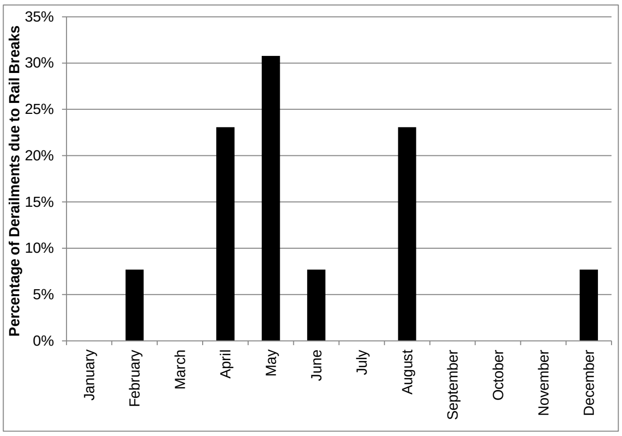

Figure 4. Seasonal Variations in Derailments due to Rail Breaks

3 RAIL BREAKS

Since April 2006, a total of 222 rail breaks have been reported for the mainline. Rail breaks can be divided into those attributable to rail quality and fatigue of parent rail, and those related to the welding of rails [6], shown in Figure 5. There has been a sudden increase in rail breaks towards FY2009/10, and a dramatic plunge in FY2012/13 (see Figure 6) – largely due to a significant reduction in aluminothermic weld failures. The trend mirrors to a large extent the trend in derailments over the same period and points to rail longitudinal stress being a key driver in the occurrence of rail breaks. Rail breaks related to welds account for 70% of all rail breaks. This value is higher than the experience of the COALLINE for the past 5 years of 59%, but considerably lower than the BHPBilliton Iron Ore Railway (BHPBIO) experience for the period 2001-2004 of 85% [7, 8]. Nonetheless, this highlights the importance of satisfactory welding being performed on an ongoing basis, specifically aluminothermic welding. The earlier flash-butt weld failures due to the spheroidite zone dipping and related "upward bending & grinding" project previously completed are presently not a feature, as the original Grade 1100 rails installed during construction presently account for only 134 Rail km.

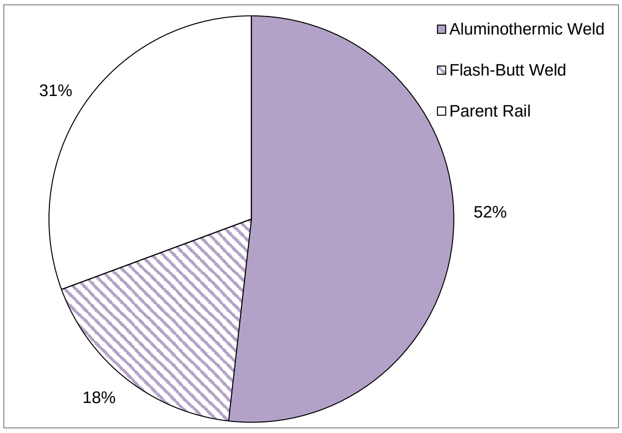

Figure 5. Rail Breaks by Position

The contribution of welds to rail breaks varies somewhat across the line and there is a step change in weld performance for the interior sections, to some extent mirroring the density of derailments due to rail break per section. The improved management of welds and welding quality for these sections is therefore critical. Furthermore, rail longitudinal stress significantly influences rail breaks in welds because of their reduced fracture toughness [7].

On average, there has been a reasonably even split between breaks reported by train drivers and breaks detected by routine inspections done by the daily patrol trolleys or Track Inspector trolleys. Of significance is the contribution of the UBRD system which has successfully reported 4 breaks, i.e. almost a third of all breaks in FY2014/15 to date. It is therefore safety-critical to complete the roll-out of the program and ensure full availability of the system. The current availability of the system has been impacted by theft of solar panels, batteries and charging regulators.

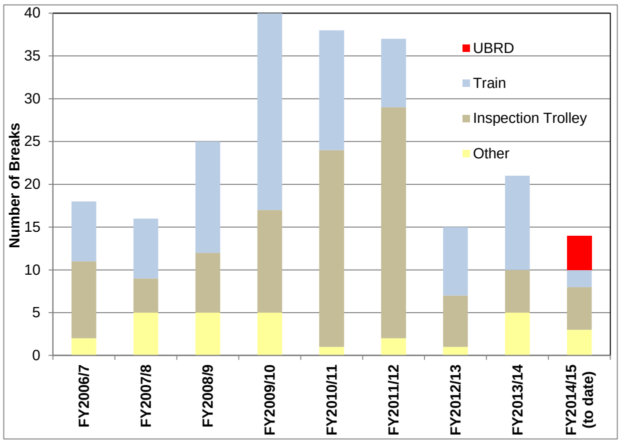

Figure 6. Rail Break Trends by Detection

An assessment of the incidence of rail breaks through the year shows that the months of May to July jointly contribute to almost half of all annual rail breaks (see Figure 7). The peak month is May, at the onset of the winter period, when daily minimum temperatures plummet significantly. The annual temperature fluctuation is considerably deeper for the interior, compared to the coastal areas. This naturally results in the need for a tighter destressing range (A-range) for the interior sections, compared to the Saldanha – Bamboesbaai section.

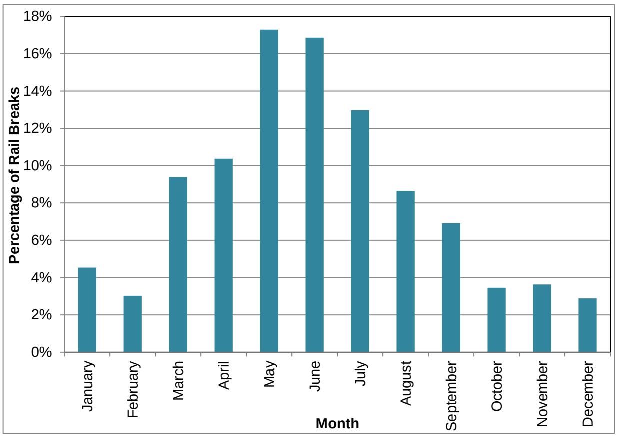

Figure 7. Seasonal Variations in Rail Breaks

The time of day that rail breaks occur naturally varies considerably through the day as a function of rail temperature (see Figure 8). The incidence of breaks increases steadily from mid-night, peaks during the prime time hours of 07:00 to 08:00, and thereafter drops rapidly towards noon and is then reasonably stable until mid-night. 75% of breaks occur from 02:00 to 11:00. During the danger period from April to August (i.e. when the probability of rail breaks and the probability of derailments due to rail breaks are both significantly high), the coldest time of the day is at around 08:00 and rail temperatures rise rapidly from this point onwards.

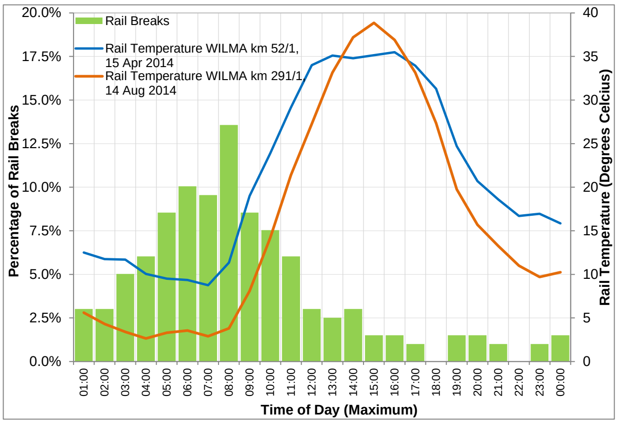

Figure 8. Daily Variations in Rail Breaks

The average density of breaks occurring per year, normalised by line length, is 0.015 Annual Breaks per Rail km. This is an internationally recognised metric [9] and the ORELINE performance is commensurate with the recent experience since 2009 on the COALLINE and the only available Class 1 benchmark, BNSF (2000-2003) [10, 11]. Furthermore, the ORELINE performance is significantly better than the performance of BHPBIO for the period 2001-2004. See Figure 9. The higher break densities for the interior sections (demonstrated in Figure 10) are not surprising, *~inter alia~* due to the following:

- Higher failure rate of welds, particularly in the Halfweg – Oorkruis section;
- Higher rail tensile longitudinal stresses due to deeper temperature fluctuation below the destressing range;
- A higher proportion of steeper gradients in the interior sections, i.e. gradients 1 in 250 and steeper. Traction loading, braking forces and related rail movement increases rail longitudinal stress. Furthermore, rail surface damage influences rail internal defect formation. Altitude of the line is shown in Figure 11; and
- A higher proportion of track of 1500m radius and sharper curvature in the interior sections. These areas are subject to more eccentric loading, higher lateral loads and increased Rolling-Contact Fatigue (RCF).

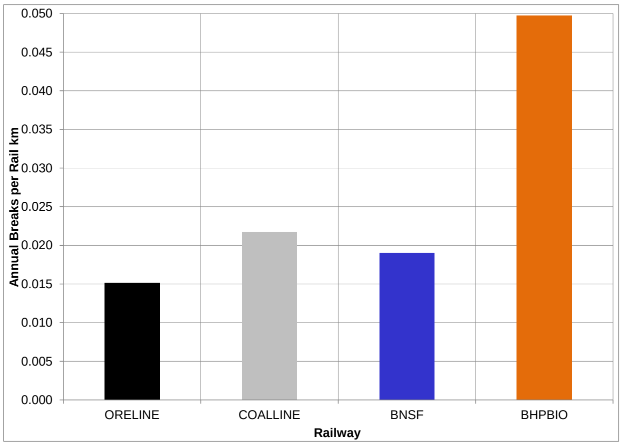

Figure 9. Annual Breaks per Rail km and Benchmarks

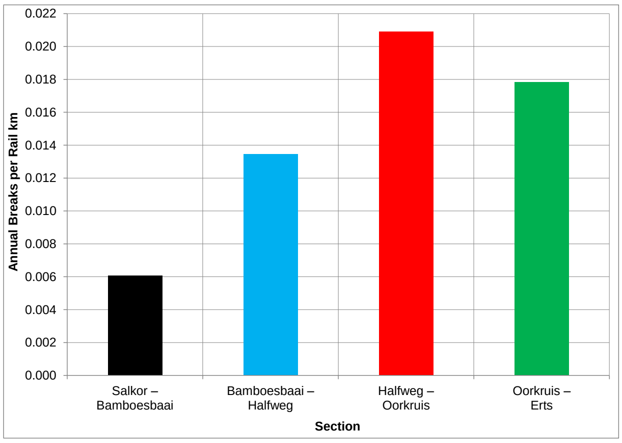

Figure 10. Annual Breaks per Rail km by Section

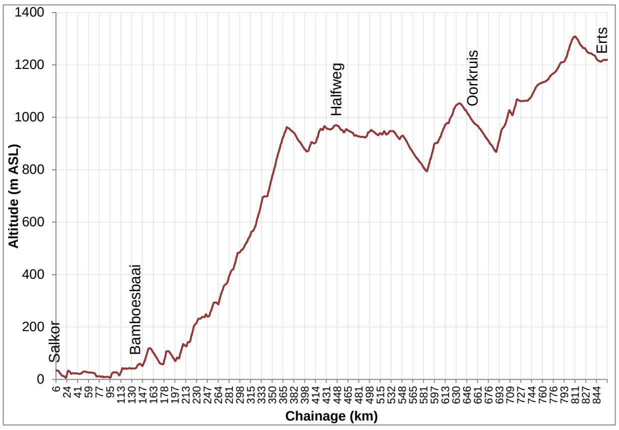

Figure 11. Altitude of the Line

4 MANAGEMENT OF RAIL BREAKS

A total of 2253 classifiable Ultrasonic Measuring Car (UMC) rail defects were detected since April 2006. The distribution of rail defects according to position reveals a significant problem (see Figure 12): The distribution contrasts starkly with what is experienced for rail breaks and proves that ultrasonic detectability of defects in aluminothermic welds is significantly lower than that of flash-butt welds.

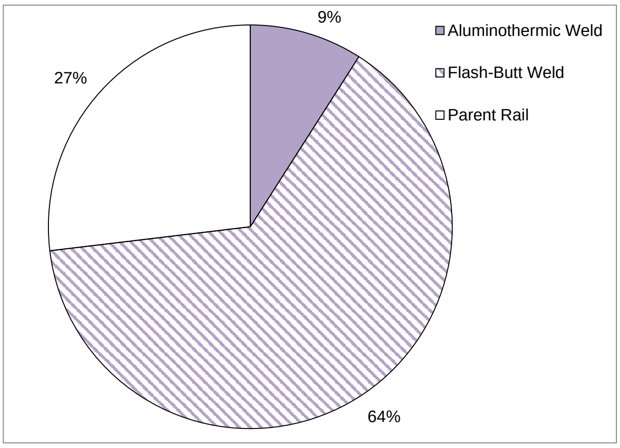

Figure 12. UMC Rail Defects by Position

Now, it is imperative to sufficiently detect failures whilst these are still only in the form of defects, prior to maturing into breaks. The successful management of rail breaks includes frequent rail testing in order to detect defects prior to ultimate failure and it is important to ensure acceptable levels of safety, whilst avoiding overly conservative rail replacements [12]. The Break / Defect Ratio is an internationally recognised metric [9] to assess the effectiveness rail management strategies. It infers that a sufficient base of prior-detected defects is in fact necessary to enable the effective control of rail breaks. One requires a reasonably-shaped "incident pyramid", with the breaks being an acceptable fraction of the defects. The Break / Defect Ratio of 10% for the ORELINE is commensurate with the BNSF (2000-2003) and BHPBIO (2001-2004) benchmarks. The COALLINE shows significantly poorer performance compared to all railways. See Figure 13.

As demonstrated in Figure 14, the interior (the Oorkruis – Erts section in particular) is performing considerably poorer that the remaining lines. The possible factors contributing to the higher Break / Defect Ratio on this section could include *~inter alia~* :

- An inadequate base of prior-detected UMC defects to cover the breaks, either due to: A significant proportion of defects in the foot of the rail avoid the scope of conventional ultrasonic rail testing. *(It has been proven above that ultrasonic detectability of defects in aluminothermic welds is particularly low compared to that of flash-butt welds and the interior has a higher density of weld failures.);* Poor rail surface condition is contributing to defects "hiding" from ultrasonic detection; Speed of ultrasonic testing is too high;
- Increased rail flexural stresses due to poor rail support, particularly at aluminothermic welds (i.e. track geometry and condition of sleepers, ballast and formation); and
- Increased rail longitudinal stresses due to inadequate measurement/ destressing.

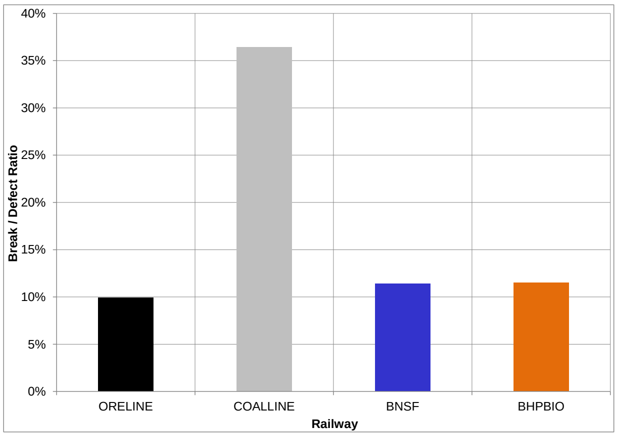

Figure 13. Break / Defect Ratio and Benchmarks

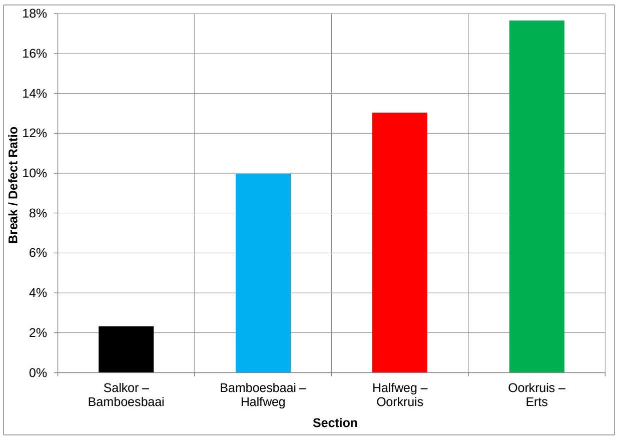

Figure 14. Break / Defect Ratio by Section

The WILMA (Wayside Intelligent Longstress Management) program has been rolled out over approximately 44% of the mainline. There are therefore 372 WILMA sites currently installed at 1 km intervals. Not all sites are fully-functional, typically due to problems with communications and/ or connections.

5 ALUMINOTHERMIC WELDING

Analysis of radiographic ("X-ray") reports for 713 welds tested since March 2014 shows that the overall percentage of welds failed (i.e. Class 2 plus Class 3 failures) is high at 9%. Significant improvements in quality control and improved supervision are necessary, as the targeted failure rate is less than 5% (this is certainly possible, as proved by certain Welders). Urgent extreme attention is necessary to address the performance of Welders showing high failure rates,

Since radiographic inspection is proven to be highly effective in identifying weld defects not identifiable by ultrasonic testing [6], a proper documentation system is necessary to properly manage all new welds and assess Welder performance on an ongoing basis.

The predominant failure modes according to the previous assessments of radiographic results are wormholing and inclusions [14]. The high incidence of wormholing is typical for the Transnet environment, with other heavy-haul railways typically experiencing higher incidences of inclusions and significantly less wormholing [8,12]. The predominant location of defects reported by the radiographic examinations are situated in the foot of the rail, which is typical for a heavy-haul railway [13]. Problems with cleanliness and/or moisture in the mold or crucible is a key problem and the incidence of wormholing has been proven to reduce with the use of the single-use crucible for the SkV-M welding process. Furthermore, wormholing and inclusions are also affected by various combinations of the following operator-dependant issues [8]:

- Cleanliness of the rail ends;
- Rails/ molds not aligned;
- Sand not applied properly to seal the molds;
- Insufficient preheat
- Incorrect gap resulting in metal flow; and
- The intrusion of sand/ mold particles in the weld metal.

Furthermore, poorly manufactured welds likely to fail the radiographic examination in terms of internal defects will most probably have additional and/ or related defects such as dipped vertical profile and/ or breakouts of the rail crown. These conditions influence impact loads on the rail and place the weld under severe dynamic stress and further increase the risk of weld failure.

In light of the facts that more than half of all rail breaks relate to aluminothermic welds and that aluminothermic welds are the most significant single contributor to derailments, there is a significant impact of improvement to Welder performance on overall rail performance. The following are therefore paramount:

- Training of Welders;
- Equipment condition;
- Rail support at the weld (condition of ballast, sleepers and track geometry); and
- Welding according to the standards, specifications and processes. Precision and consistency is imperative [9], particularly: Matching of rail wear; Square cutting of rail ends and correct gap; Rail setup and alignment; Mold cleaning, adjustment and fitment/ sealing; Control of pre-heat; and Stripping, shearing and grinding.

6 RAIL WEAR

The remaining original construction rails are exclusively situated south of Halfweg. These rails have to date sustained approximately 1400 MGt.

An assessment of Remaining Rail Life (RRL), as per the measurements from the most recent IM2000 campaign of February 2014, indicates that all sections show healthy, satisfactory rail wear condition and there is no rail at this stage that is beyond the legal wear limit (i.e. RRL < 0 mm).

Detailed assessments of rail wear rates and annual rail requirements according to rail wear have been performed. Combined wear values) for sample curves (high leg and low leg individually), were plotted against tonnage since installation. A reasonably conservative slope has been determined for each curvature category, yielding combined wear rates ranging from a minimum of under 0.008 mm/MGt for tangent track and up to more than double this value for the sharpest curves. Based on the average realistically useable combined wear of 14mm (i.e. around 80% of the total theoretical available rail head wear of 17mm to account for variability of rail wear through curves and the need to replace both legs simultaneously when rerailing), the realistic wear life expectation is at a maximum of over 1800 MGt for tangent track and down to less than half this for the sharpest curves. Weighted average realistic wear life is thus over 1700 MGt. Based on the forecast tonnage of 72 MNt for FY2020/21, i.e. the final year of the MDS, the Annual Equilibrium Replacement Requirement is calculated to be in the order of 109 Rail km per Year and this is confirmed by the calculations previously performed in 2013-2014, where two methods made use of individual rail wear algorithms to intelligently predict the date of replacement of each curve [14].

7 RECOMMENDATIONS [15]

7.1 Railway Operations

Certain operational measures are safety-critical in light of the high risks on the operation due to the train length, axle load and the absence of track circuitry. These are necessary during the five months from 1 April to 31 August in order to mitigate against derailments that will otherwise be highly probable during this period:

- Track inspection trolleys run daily, and are to be given movement priority over all trains. Trolleys run in the loaded direction and are scheduled so that their journey is completed at ~08:00.
- A 50 km/h speed restriction is imposed daily from 02:00 to 11:00 for all loaded trains in the Bamboesbaai (inclusive) – Erts section. The speed restriction is closely monitored by means of CS90 and/or telemeter reports and strictly enforced.

7.2 Condition Monitoring

- Ultrasonic measurement is restricted to a maximum testing speed of 25km/h, strictly monitored on the machine by the Technical Officer.
- The rail longitudinal stress measurement regime is being improved, particularly in the interior sections. Measurements on the ORELINE are planned to be completed every kilometre, twice per year (includes calibration of WILMA sites) and the target measurement periods are by the end of March and by the end of September. Measurement reports are generated on a daily basis and destressing action plans compiled in order to pro-actively identify work locations and enable rail at high stress free temperature to be prioritised for emergency destressing occupations to be completed by the end of March.
- The full roll-out of the WILMA program for the remaining areas to be completed as a matter of urgency. Evaluation of other Rail Longitudinal Stress Monitoring System products to be done as part of the CSIR Track Research Programme.
- The UBRD program is viewed as mission-critical and availability of the system is being improved: Upgraded equipment cabinet to be installed in theft hotspot areas
- The UBRD upgrade project is being expedited via the CSIR Track Research Programme and includes: Improved detection of defects in the rail foot; Improved accuracy of location/ distance of defects in rail head and rail foot; and Installation of upgraded device/s at trial sites: Baboonspoint Tunnel, Olifants River Bridge and other priority locations.
- IM2000 Vertical Acceleration Reading (VFR) data is being used to identify dipped welds, rail break-outs/ spalling and faulty/ damaged turnout components, etc… VFR accelerations exceeding 30g are prioritised, followed by site inspections and action plans to eliminate the defects.
- A thorough review of alarm levels/ hierarches and respective action criteria for all ASW and WIM-WIM equipment is planned. This will include detailed audits of equipment availability/ calibration, and audits of alarm monitoring at the CTC.

7.3 Weld Management

- Compliance with the stipulated radiographic testing regime is being enforced: X-Rays to be done within 7 days of manufacture; Reports presented within 14 days of manufacture; Failed welds to be removed *(Class 3: Cut out with an emergency occupation. Class 2: removed within 30 days of manufacture)*; and Welds to be clamped from the date of manufacture, until cleared. All clamps inspected weekly and tightened/ adjusted if necessary.
- Visual inspection and geometric measurement (especially vertical profile) of all new welds to be done within 7 days of manufacture.
- Rail height difference shall not exceed 6 mm and the correct step mold kits shall be used if rail height difference is 3 – 6 mm. Where rail height difference exceeds 6 mm, an appropriate closure to be used. Discipline to be initiated for any transgressors.
- Ensure that the single-use crucible is used exclusively.
- Improve preheat integrity with the use of foot insulation pads for all aluminothermic welds.
- All welds to be tamped 7 days from manufacture to ensure satisfactory rail support.
- A thorough review to be done of the flash-butt welding acceptance testing regime in place at the Beaconsfield Flash-Butt Welding Plant. This will include detailed audits of equipment condition, and an audit of weld quality for randomly selected samples.
- Rail samples for all rail breaks are sent within 7 days of occurrence to the Track Technology Laboratory for evaluation and metallurgical analysis.

7.4 Training

- A certification system to be established whereby routine formal training and practical assessment of Welders is done every two years by School of Rail. Certification of each Welder accordingly is a mandatory safety-critical requirement and no Welder may operate should he/ she not have been passed.

- Welders showing high failure rates (as per routine assessments of Welder performance) are immediately stopped. These are to be re-assessed/ re-certified by School of Rail or independent training authority. Task observations are done and the Welder's working conditions and equipment assessed.
- A one day on-site workshop/ presentation is conducted by the approved Welding equipment/ consumables supplier, ideally every three months. Failure rates, types of defects and related causes and remedies discussed.
- Formal recognition and rewarding of Welders is done regularly according to low radiographic failure rates. "Annual Award for Welding Excellence" is given to Welder/s who prove consistently low failure rates.
- Formalised training is conducted for management of rail longitudinal stress, i.e.: The University of Pretoria Course "Management of Continuously-Welded Rail (CWR)" to be completed by all Engineers and Technicians; and CWR Training (conducted by School of Rail) for all Track and Welding personnel

8 CONCLUSION

Whilst the occurrence of rail breaks on the ORELINE is low, the incidence of rail related derailments is ironically high. It is a case of rail breaks being of a low probability, but delivering a very high consequence. Therefore, in order to mitigate against derailments on the ORELINE, improvements to weld management, condition monitoring and training are absolutely safety-critical. Numerous soft issues also need to be addressed. The interior sections require the most immediate and focused attention due the higher probability of rail breaks and derailments. Furthermore, in light of the high risks on the operation due to the train length, axle load and the absence of track circuitry, some additional measures and restrictions are mandatory during the winter months.

9 ACKNOWLEDGEMENTS

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