

# Improved wheel-rail system of Sweden's iron ore line

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**ABSTRACT:** The Swedish Iron Ore Line (IOL) is the only heavy haul line in Europe. The northern part of the line is located above the Arctic Circle, a very harsh climate. Because of the introduction of new vehicles with a 30-tonnes axle load, the track were gradually replaced between 2006 and 2009 with heavier rails, mostly with a steel grade of R350LHT. Just after the first replacement of track in 2006, the project presented herein was established with the primary goal of improving the life length of the rail, and monitoring activities started. This project now has a unique database of rail degradation data. So far, the information has been used to improve the performance of the wheel-rail system and thus extend the life length of the rail, as well as to improve our knowledge of heavy haul operations in a cold climate. The paper discusses the project progress in general and gives some examples of improvements that have been successfully implemented, such as new rail profiles and a higher grinding frequency. Finally, it discusses the challenges of future capacity improvements, such as an increase in the axle load, and how these can be addressed.

## 1 INTRODUCTION

This paper deals with the Nordic iron ore line (IOL), Malmbanan in Swedish, and the heavy haul traffic operating on it. In operation since 1903, the IOL is a 473 km single standard gauge track section located in northern Sweden and northern Norway. The line is above the Arctic Circle, a harsh and cold climate. The axle load for heavy haul trains is 30 tonnes. Trains are 750 m long and consist of 68 wagons with one pulling units – two IORE locomotives. Their gross weight is about 8500 tonnes. The trains operate loaded at 60 km/h. In the rolling stock fleet of 17 trains, there are more than 1100 wagons, with about 80 approved for a 32.5-tonnes axle load.

The information and data in the paper come from 2007 to 2015 and were collected mainly by the project members.

The wheel and rail are interacting systems and, thus, should not be treated separately. In fact, the wheel-rail interface plays a significant role in the performance of the entire railway system. To reach a high quality of service, especially with the demanding conditions imposed by high axle loads, the wheel-rail interface needs to be managed particularly well. This paper deals with this important system and shows how it has been improved during the last ten years.

## 2 THE NORDIC IRON ORE LINE AND THE MONITORED SECTIONS

The IOL is the only heavy haul line in Europe. This investigation looks at the northern-most part. The IOL and the monitored areas, sections 4-6, are shown

in Figure 1. The middle of the figure shows Northern Sweden; there is a harbour in the south (Luleå) and another in the north (Narvik). Situated between the harbours are two mines, one in Kiruna and the other in Malmbanan. The IOL links the mines with the har-



Figure 1. Northern Sweden with the geographic situation of the IOL and monitored sections 4-6

bours. Material from the northern mine (Kiruna) generally flows to the northern harbour, and material from the southern mine (Malmbanan) goes to the southern harbour. These are called the northern and the southern loop, respectively.

The accumulated yearly tonnage on the northern loop is about 34 MGT and on the southern loop about 20 MGT. The traffic between the mines is about 6 MGT. For the northern loop, the increase in tonnage

from 2008, when the project started and a new track was in operation, to 2016 is about 43%.

The climate is characterized by dry periods in summer and extremely cold winters (under  $-40\text{C}^{\circ}$ ), interrupted by wet weather conditions in spring and autumn.

The track is electrified and contains mixed traffic, but the main traffic is heavy haul trains, with about 12 loaded trains per day on the northern loop and four loaded trains on the southern loop; a further two trains are test trains with heavier axle load of 32.5 tonnes.

From 2006 to 2009, a new track was laid from Kiruna to Riksgränsen (the border between Sweden and Norway). It was equipped with 60E1 head-hardened rails of grade R350LHT (CEN, 2011), concrete sleepers, and elastic fastenings.

The IOL has about 20 wayside monitoring systems of different types and applications. The wheel profile is monitored by a wayside wheel profile measurement system (WPMS) located on the southern loop close to Luleå. The WPMS has been in operation since 2011 and delivers information on wheel profiles to the rolling stock owner (Asplund et al., 2014), where two methods have been suggested to improve the data quality (Asplund & Lin 2016; Asplund et al., 2016). The WPMS has also been used to develop a new rail profile adapted for actual worn wheels in service; this rail profile is called MB5 (Malmbanan profile 5).

In the northern loop, track sections have been carefully monitored by manual profile measurements since the renewal of the track in 2006. The monitoring sections (3-6) are divided into curve segments, (A to E) and tangent track (T). There are 43 curves and sections of tangent track, as shown in Table 1. The total number of rail profile measurements for the sections is about 465.

Table 1. Description of the curve types.

Type	Layout	Radius (m)	Number of curves
A	Curve	<550	9
B	Curves	550-650	17
C	Curves	650-750	3
D	Curves	750-850	2
E	Curves	850-1500	6
T	Tangent		6

### 3 THE RAIL

As mentioned above, after the track change on the northern loop, the rail is now 60E1 head-hardened rail of grade R350LHT. It has been regularly ground since the track change in 2006. The actual status of the rail is generally good in tangent track and in the high rail of curved track. The low rail of curves has some problems with spalling, however, especially in narrow curves.

On a test section, it is performed trials with rail grades of R370CrHT and R400HT (CEN, 2011). The results were good for the R400HT rail because there was less wear and material flow compared to the R350 LHT. This trial will be discussed later in the article.

One significant failure mode on rails, especially on heavy haul lines, is crack propagation caused by rolling contact fatigue (RCF) on the rail head. Good knowledge of the crack behaviour is important to plan grinding. Crack propagation and wear compete with other, as grinding and milling, artificial wear actions, are done to remove cracks. The crack growth should not be much larger than the wear, but in natural conditions, the crack growth rate is greater than the wear rate. The crack growth rate also has a different speed in different phases.

Figure 2 shows the surface of an IOL rail. The grade of this rail is R260 (CEN, 2011); it was removed from service because of RCF. At the top of the rail, it can be seen a white layer (likely a martensite layer) with a thickness of about  $50\ \mu\text{m}$ . This white layer can be produced in hard steel by adhesive slid-

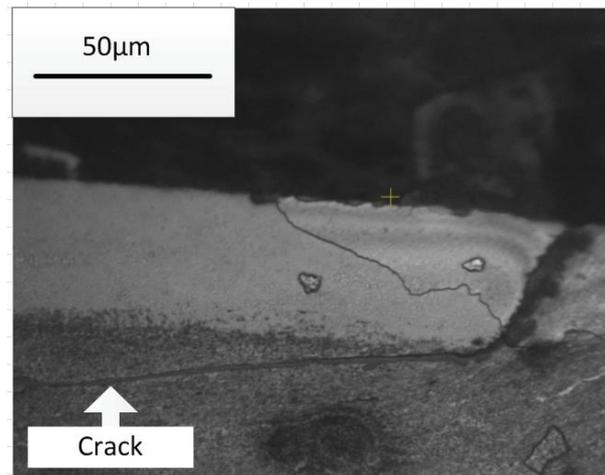


Figure 2. Crack propagation on the surface of an IOL rail. ing wear without lubrication (Siposet. al., 2008) of the rails. The crack angle changes direction dramatically after passing the white layer, most likely influenced by both material properties and pressure distribution.

The hardness of the rail varies; close to the surface, it is about 445 BHN. The hardness decreases as a function of the distance from the surface. At 0.5 mm from the surface, it is 339 BHN, and at 3 mm, it is about 300 BHN. The standard for R260 rail requires hardness between 260 to 300 BHN, and this is limit reached at 3 mm under the surface (CEN, 2011). Table 2 shows the hardness distribution for the rail head starting from the surface, in HV (Vickers) and BHN (Brinell).

Table 2. Hardness distribution as a function of distance from the surface.

From surface [mm]	HV	BHN
0.05	468	445
0.25	410	390
0.38	408	388
0.5	357	339
0.75	351	334
1	362	344
2	330	314
3	317	301
4	309	294
5	313	297
7.5	304	290
10	278	267
15	293	275

The crack is branching inside the rail during the load cycles of passing wheels, Figure 3 shows how a typical crack branches in a rail. This particular crack reaches almost 2 mm into the material at an angle of about 30° from the surface. In the end phase, the crack angle (bottom right of Figure 3) is about 70°.

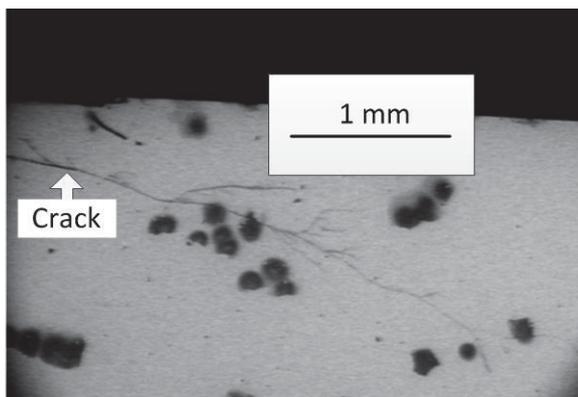


Figure 3. Crack branching inside the rail.

Another significant degradation mode is the wear of the rail. The natural wear in the wheel-rail interface is the loss of metal caused by sliding in the presence of an abrasive third body. Wear is directly related to the load, the type of stress and the configuration of the contact (Zarembski, 2005). The main wear mechanisms in wheel-rail sliding or rolling contacts are adhesive, abrasive, fatigue driven, thermal and oxidative wear processes (Lewis & Olofsson, 2009).

The average annual wear rate of the rail area monitored for 2009 to 2013 is shown in Table 3, separated out by curved and tangent track. Recall that curve types A-E are described in Table 1. An interesting observation is that after the introduction of larger axle loads of 30 tonnes in 2011, the natural wear of the rail increased but stabilised again after a couple of years.

 Table 3. Natural wear in mm<sup>2</sup>/MGT for different curve types during 2009 to 2013.

Year	A	B	C	D	E	Tangent
2009	0.36	0.26	0.11	0.03	0.05	0.09
2010	0.33	0.22	0.09	0.09	0.06	0.13
2011	0.58	0.39	0.27	0.20	0.17	0.10
2012	0.63	0.36	0.29	0.16	0.13	0.05
2013	0.05	0.29	0.29	0.28	0.06	0.09

Investigations of the IOL have shown that the natural wear rate is about two to five times higher in sharp curves than in mild curves or tangent track, and the natural wear rate is influenced by the annual tonnage on the track. Furthermore, more material is removed by grinding than by natural wear, and different track segments have different wear behaviour (Famurewa et al., 2015).

#### 4 THE WHEEL

WPL9 became the wheel profile for IORE locomotives after 2009, but the recently developed locomotive wheel profile WPL5V2 was implemented in the fleet in 2016. This profile should extend the life length of the wheel by reducing rolling contact fatigue (RCF) on the wheel tread (Asplund et al., 2017).

Reliability investigations of locomotive wheels show that the wheel position in the bogie has an impact on the wear rate. Studies also indicate that the most frequent failure mode is RCF on the wheel tread (Lin et al., 2013; Lin et al., 2015). Figure 4 shows the fatigued surface of such a locomotive wheel.

Work is under way to fine-tune the wheel profiles and to find methods to reduce RCF. The wheel profile impacts on the rail, e.g. small contact patches and high stresses, while the track status impacts on the wheel, e.g. track gauge and unfavourable contact conditions. The contact area on the wheel can be divided into zones, each with its own RCF pattern (Deuce, 2007). One of the zones is more exposed to straight lines, one is exposed to the curves on the high rail, and one is exposed to the curves on the low rail. The different RCF zones (RCF 1 - 4) and the connections between the track and the zones are explained in Figure 4. In the figure, the RCF1 zone shows the connection to the low rail field side in curves; the RCF2 zone shows the connection to the gauge corner of the high rail; the RCF 3-4 zones are related to tangent track and mild curves. The circles indicate different RCF types (UIC, 2004). The RCF of locomotive wheels is well described in Ekberg et al. (2014).

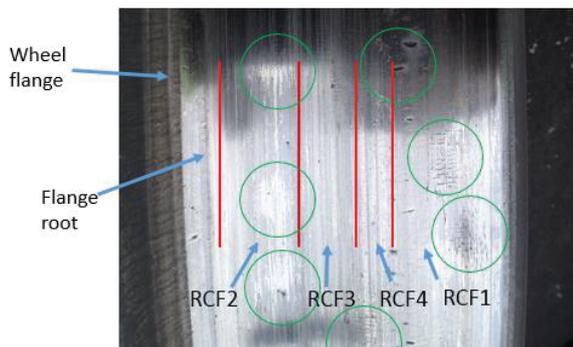


Figure 4. Surface fatigue on a locomotive wheel with locations of different patterns.

## 5 THE WHEEL-RAIL SYSTEM

There are four main rail profiles on the main track of the IOL: 60E1, MB1, MB4 and MB5. The MB4 rail profile is used for switches and crossings and is the standard profile for tangent track. Narrow curves have MB1 on the high rail and 60E1 and MB5 on the low rail. Figure 6 shows profiles 60E1, MB1 and MB4. MB5 is a recent profile, developed for worn wheels in curves <650 m where gauge widening has taken place.

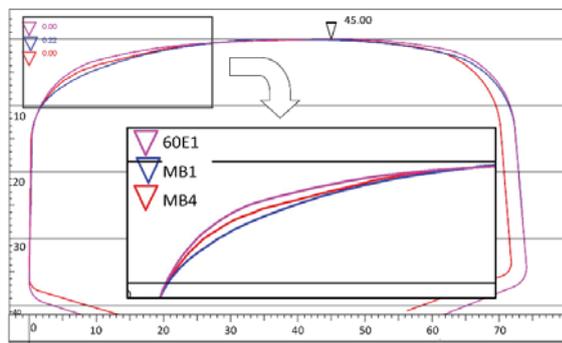


Figure 6. Three profiles used on the iron ore line.

The MB5 profile is close to the 60E1 profile, but is 0.4 mm higher on the field side and 0.1 mm higher on the gauge side. This gives a wider running surface to solve the emerging RCF problem on the low rail. Figure 7 shows the MB5 profile on the low rail; after one pass of the train with a 30-tonnes axle load, the contact band width is 30 mm.

The track gauge widening needs to be managed as well, as this parameter changes the wheel-rail contact conditions. Simply stated, it leads to an accelerated formation of RCF (Asplund et al., 2017). Investigation of the IOL in test sections A to E shows that the gauge widening is about 1.6 to 0.6 mm each year, depending on the radius of the curve. In general, a smaller radius leads to faster gauge widening, and the main cause of gauge widening is worn and broken fastenings.

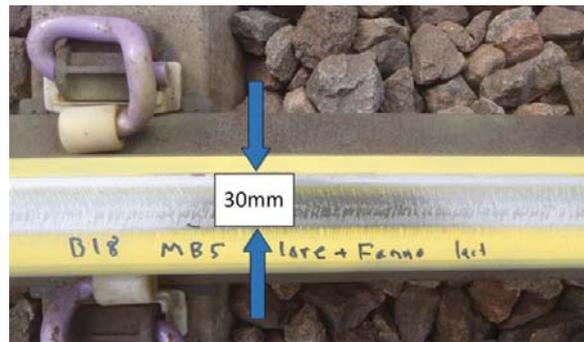
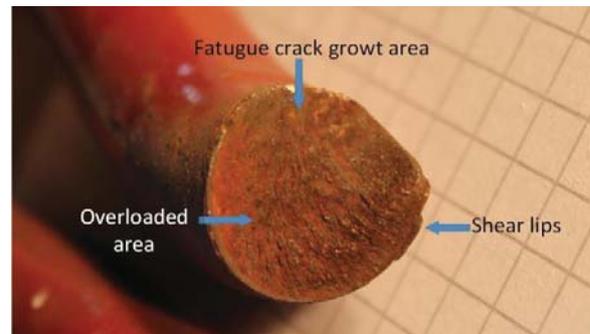


Figure 7. MB5 profile on the low rail where gauge widening take place.

It is discovered that a certain section had a large number of broken fastenings. This was surprising, as the curve in question does not have a specifically small radius; its radius is 765 m (D-curve; see Table 1). The accumulated tonnage for this curve is 240 MGT. The broken fastenings were investigated by the manufacturer who determined that fatigue cracking caused the failure. There were too many or too large force cycles in the vertical direction.

The manufacturer's recommendation was to use another type of fastening, change to a stiffer pad to reduce the deflection, and change the isolators to keep



a better gauge in narrow curves. Figure 5 shows the typical failure mode and the fractured face of a fastening clip.

Figure 5. Fractured face of a fastening clip.

A new type of fastener with heavier clamping force was introduced in 2012, but the results so far are not revolutionary, Figure 7 shows the new type of fastening. With these fastenings, the degradation rate in curves < 550 m in radii went from 0.0603 mm/MGT to 0.0564 mm/MGT. For curves between 550 to 650 m the track gauge widening actually increased with the new fastenings; in addition, the standard deviation (STD) was larger for these curves. However, more traffic is needed before a final conclusion can be drawn. Table 4 shows the track gauge degradation rate mm/MGT for old and new fastenings.



Table 4. Track gauge degradation rate mm/MGT, new and old types of fastenings.

Curve size	Status	Mean*	STD
R<550 m	Old	0.0603	0.0174
R<550 m	New	0.0564	0.0161
550<R<650	Old	0.0304	0.0161
550<R<650	New	0.0750	0.1608

\* Mean degradation rate in mm/MGT

## 6 FRICTION MANAGEMENT

### 6.1 Lubrication in general

To reduce shear forces between the rubbing surfaces, the introduction of a third body, generally lubricant, is recommended. For optimum rail operation, the friction between the gauge face and the wheel flange should be minimized as much as possible, but the friction between the top of the rail and the running surface of the wheel should be 0.3–0.4.

In railways, the application of an additive third body in the wheel–rail interference has been in practice for many years. It was initially limited to the gauge face (Stock et al., 2016). Gauge face lubrication in curves was widely introduced in Sweden during the 1970s (Waara, 2006). In the last two decades, an additive third body, known as top of rail (TOR) lubricants, has evolved to control the friction between the top of the rail and the wheel running surface. TOR lubricants can be applied separately or in combination with the gauge face lubricating system. Research across the globe has shown tremendous benefits of using TOR lubricants, including reductions in noise (Asplund et al., 2016, Eadie & Santoro, 2006), wear (Lu et al., 2012), energy consumption (VanderMarel, 2014), rolling contact fatigue (RCF) (Eadie et al., 2008, Khan, 2016, Stock et al., 2011) and short pitch corrugation (Eadie et al., 2008). TOR lubricants are generally classified according to their solvent and can be divided into three sub-classes:

- TOR oil (oil-based TOR fluid)
- TOR grease
- TOR–friction modifier, TOR–FM (water-based fluid)

### 6.2 TOR FM tests on the IOL

RCF is a major problem, especially on curves in the IOL, mostly because of the high haul trains. Therefore, Swedish Transport Administration (Trafikverket) is considering implementing the wayside TOR lubrication system on curves. An ongoing project is assessing the technical and economic efficiency of applying TOR–FM to the IOL's wayside equipment. In its initial phase, multi-body simulations (MBS) were performed after taking parameters of the IOL. The simulations focused on the

effect of friction control on the generation of RCF. The MBS used basic theory such as shakedown and energy dissipation methods to predict the generation of RCF. A sample result from the MBS is a fatigue index (Ekberg & Kabo, 2005), based on shakedown theory, for a curve of 200 m radius. This is shown in Figure 8 and Figure 9. The fatigue index reports only the initiation of RCF. If the index is positive (>0), RCF will initiate; otherwise, there will be no RCF. The fatigue index value represents the proportion of the pressure which has overshoot the limit for shakedown.

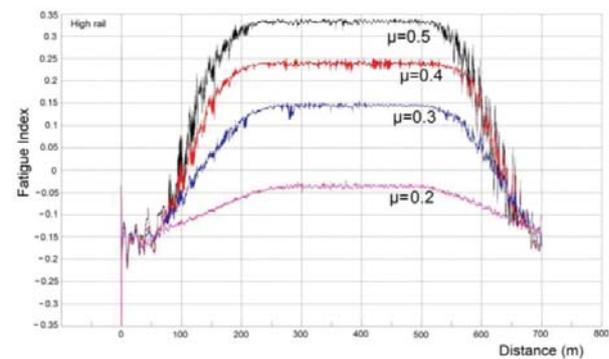


Figure 8. Fatigue index for a curve of 200 m radius and 700 m length at different friction values with respect to the distance in the curve of the high rail (Khan et al. 2016).

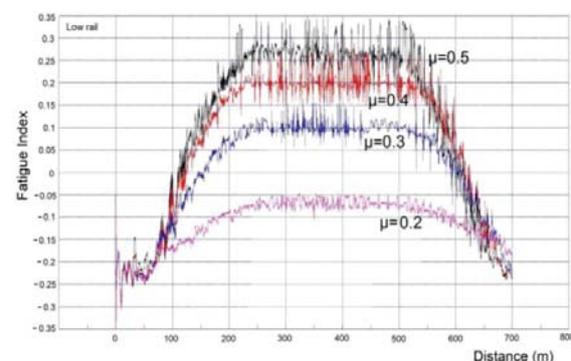


Figure 9. Fatigue index for a curve of 200 m radius and 700 m length at different friction values with respect to the distance in the curve of the low rail (Khan et al. 2016).

Despite the positive theoretical results, the presently installed wayside equipment (see Figure 10) does not seem a promising solution for the application of TOR–FM. The equipment is battery powered and is recharged using wind and solar energy; it is a challenge to keep the battery alive during winter, but installation of a direct power supply is costly and therefore is not possible in this project. In addition, to keep the equipment running, regular refill and maintenance are required. In an initial field test (Asplund & Nordmark, 2015) before the start of the current project, the similar wayside equipment is used, but observed no benefit. It was thought the benefits were negligible

because of good wheel and rail maintenance practices. However, more recent experiments show that the carry distance of TOR-FM when using wayside equipment is extremely short. With an application of 1 litre/1,000 axles, four times the recommended amount, it was observed a carry distance of 20 m when using the product from one supplier and 225 m when using the product from another. Possibly different solvents are used in the products, and this may explain the difference, but this is speculative, as the contents of the FMs are unknown. The carry distance of TOR-FM on wheels was also followed; it is observed a dried FM layer on the wheel surface for up to 1 km, but there was no FM in the contact band where it is actually needed.

The simulation results and various research results around the world suggest friction control is beneficial for both rail and wheels; however, wayside equipment does not seem to be a good candidate because of the short carry distance. An on-board system might overcome the issue. That being said, the reliability, maintenance cost and technical efficiency of on-board systems are not known in Nordic conditions. It is known how much on-board equipment is required per train in the case of freight trains from LKAB.

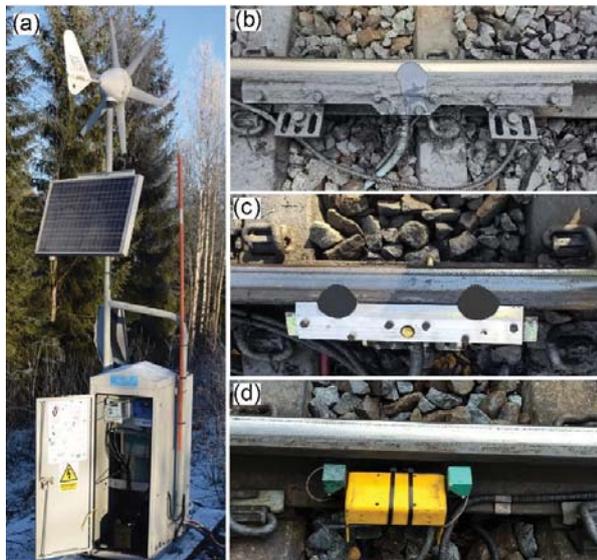


Figure 11. The wayside TOR equipment installed at Gullträsk, Sweden (a) Main unit (b) Distributing bars used for FM-A (c) Distributing bars used for FM-B (d) Wheel detecting sensor

## 7 MAINTENANCE

### 7.1 Rail

Machining is the main maintenance action for rails. Machining can be divided into milling and grinding. Milling is a cutting process, while grinding is an abrasive wear process to remove surface material. This

paper only deals with grinding, as this is the practice used on the IOL.

Grinding is a “process of material removal from the top surface of the rail head through the use of abrasive girding materials, specially girding stones or wheels” (Zarembski, 2005). It is an established maintenance action to increase the life of rail and to improve its life cycle. For curves < 650 m radii, the IOL rail is ground every 15 MGT, and for other track, every 30-90 MGT. By introducing two grinding campaigns, the grinding depth of rails could be reduced from 0.7 mm to 0.4 mm each year.

Regular grinding has been implemented since 2006 with the installation of the new track. The use of a continuous grinding strategy has resulted in good rail condition. Although the rail in tangent tracks and on curves is good, the low rail on curves with a small radius needs more investigation. Figure 10 shows the low rail and its failure mode, line spalling.



Figure 10. Low rail with spalling on the running surface.

### 7.2 Wheel

The wheels on the heavy haul trains are regular re-profiled. The wagon wheels perform very well and are usually re-profiled after approximately 180,000 – 200,000 km. Their failure modes are 55% RCF and 45% wheel wear.

In contrast, the locomotive wheels are never re-profiled because of irregular profile or wear). Instead, the reason for turning locomotive wheels is surface damage like RCF (Ekberg et al., 2014). The wear rate differs between wheels, the natural wear rate is smaller than the artificial wear with a ratio of about two in averaged (Lin, Nordmark & Asplund, 2013). In general, the re-profiling intervals for locomotive wheels vary from 25,000 to 110,000 km. Therefore, in this project, the plan is to test wheel profile modifications and change in braking regimes, as well as wheel lubrication in different combinations, with selected locomotives.

## 8 ONGOING TRIALS

### 8.1 *The ReRail*

The ReRail is a totally new concept of how a rail is built up. The ReRail is a replaceable rail head made of hardened steel (martensitic micro structure) with a thickness of 10–12 mm. The concept of a replaceable rail head is shown in Figure 12.



Figure 12. ReRail is a replaceable rail head.

One advantage of ReRail is that there is less carbon emission in the rail production; another is that the material chosen can be harder than the regular rail.

A 6 m test rail is mounted as a high rail in a curve of 600 m radii on a section of the IOL. This has been in service since June 2016 and is loaded with about 10 MBT (until February 2017). This rail is carefully monitored in terms of wear, fatigue and conductivity. So far, the test shows positive results.

### 8.2 *R400HT*

The performance of new steel grades is also being tested. A curve (A6) has test rails with the steel grades R370CrHT and R400HT. While they show less wear than R350HT because of the greater hardness, the decreased RCF development is not sufficient to extend the grinding cycle from one year to two years. More investigation of the different steel grades will be done in the future; the findings will be the basis for changes to the steel grade.

### 8.3 *Trials with 32.5-tonnes axle loads*

In September 2015, LKAB and Trafikverket started a test in which they dispatched a dedicated test train with a 32.5-tonnes axle load once a day on the southern loop, from the Malmberget mine to the harbour in Luleå. The aim was to analyse the technical and economic effects on the railway system of upgrading the whole IOL to a 32.5-tonnes axle load.

In October 2016, the test was assessed and summarized. For Trafikverket's part, i.e., the infrastructure, including the rail system, and the subgrade, including bridges and culverts etc., the conclusion was that there was no sign of increased wear or downgrading of the infrastructure. For the train operator, LKAB, the result was also positive in the following aspects. The train load was increased by 8% but the

punctuality was the same as for other trains. The negative aspect was that the energy consumption increased by 1% and the wagon wheels had 14% higher occurrence of RCF.

They decided to continue the test for another year, but with two trains per day.

## 9 CONCLUSIONS AND FUTURE WORK

First, for crack propagation, the crack angle seems to get larger as it goes deeper into the rail head. At about 2 mm under the surface, the crack angle is about 70°. This can give a different crack propagation behaviour after grinding if the crack is not totally removed. This new knowledge needs to be taken into account in the planning of grinding.

Second, the latest developed rail profile MB5 shows good results with a wide contact band. However, it should only be applied where the track gauge is under 1450 mm because wheels with hollow wear can destroy the rail.

Third, new fastenings that may show a lower degradation rate need to be investigated before their value can be summarised.

Fourth, with respect to TOR-FM, there are some problems in the carry distance capabilities of wayside equipment; depending on the product used, this varies from 20 to 225 m, but in all cases, the distance can be considered short. Luleå University of Technology and LKAB are discussing the installation of one or two on-board systems and calculating the life cycle cost of the on-board system.

Fifth, the ReRail findings are promising. ReRail has been used on track with about 10 MGT with no abnormalities; the trial will continue until 2019.

Sixth, trials with larger axle loads (32.5 tonnes) indicate this increase will have an impact on the formation of RCF on wheels.

Finally, work on improving the wheel-rail system is ongoing.

## 10 ACKNOWLEDGMENTS

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## REFERENCES

- Asplund, A., & Nordmark T. (2015). Comparison of TOR lubrication systems on the iron ore line, International Heavy Haul Association: The 11th International Heavy Haul Association Conference held 21-24 June 2015 in Perth.
- Asplund, M., Famurewa, S. M., & Shoech, W. (2017). A Nordic heavy haul experience and best practices [accepted for publication]. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*.
- Asplund, M., Gustafsson, P., Nordmark, T., Rantatalo, M., Palo, M., Famurewa, S. M., & Wandt, K. (2014). Reliability and measurement accuracy of a condition monitoring system in an extreme climate: A case study of automatic laser scanning of wheel profiles. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 228(6), 695-704.
- Asplund, M., Rantatalo, M., Johnsson, R., & Hiensch, M. (2016). Combating curve squeal noise. *World Congress of Railway Research: 29/05/2016-02/06/2016*.
- Asplund, M., & Lin, J. (2016). Evaluating the measurement capability of a wheel profile measurement system by using GR&R. *Journal of the International Measurement Confederation*, 92, 19-27.
- Asplund, M., Lin, J., & Rantatalo, M. (2016). Assessment of the data quality of wayside wheel profile measurements. *International Journal of C O M A D E M*, 1-7.
- CEN. (2011). *EN 13674-1:2011: Railway applications –Track –rail – part 1: Vignole railway rails 46 kg/m and above*. Brussels: European Committee for Standardization.
- Deuce, R. (2007). *Wheel tread damages –an elementary guide line, 100115000* (Deuce, Roger; ed.). Netphen, Germany: Bombardier Transportation GmbH.
- Eadie, D. T., Elvidge, D., Oldknow, K., Stock, R., Pointner, P., Kalousek, J., & Klauser, P. (2008). The effects of top of rail friction modifier on wear and rolling contact fatigue: Full-scale rail–wheel test rig evaluation, analysis and modelling. *Wear*, 265(9), 1222-1230.
- Eadie, D. T., Santoro, M., Oldknow, K., & Oka, Y. (2008). Field studies of the effect of friction modifiers on short pitch corrugation generation in curves. *Wear*, 265(9), 1212-1221.
- Eadie, D., & Santoro, M. (2006). Top-of-rail friction control for curve noise mitigation and corrugation rate reduction. *Journal of Sound and Vibration*, 293(3), 747-757.
- Ekberg, A., & Kabo, E. (2005). Fatigue of railway wheels and rails under rolling contact and thermal loading—an overview. *Wear*, 258(7), 1288-1300.
- Ekberg, A., Kabo, E., Karttunen, K., Lindqvist, B., Lunden, R., Nordmark, T., Olovsson, J., Salomonsson, O., Vernersson, T. (2014). Identifying the root causes of damage on the wheels of heavy haul locomotives and its mitigation. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 228(6), 663-672.
- Famurewa, S. M., Asplund, M., & Kumar, U. (2015). Evaluation of rail wear characteristics on heavy haul track section using measurement data. *International Heavy Haul Association: The 11th International Heavy Haul Association Conference held 21-24 June 2015 in Perth*.
- Khan, S. A., Persson, I., Lundberg, J., & Stenström, C. (2016). Prediction of the effects of friction control on top-of-rail cracks. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 0954409716674984.
- Lewis, R., & Olofsson, U. (2009). *Wheel-rail interface handbook*. Cambridge: Elsevier.
- Lin, J., Asplund, M., & Parida, A. (2013). Reliability analysis for degradation of locomotive wheels using parametric bayesian approach. *Quality and Reliability Engineering International*.
- Lin, J., Pulido, J., & Asplund, M. (2015). Reliability analysis for preventive maintenance based on classical and bayesian semi-parametric degradation approaches using locomotive wheel-sets as a case study. *Reliability Engineering & System Safety*, 134, 143-156.
- Lu, X., Makowsky, T. W., Eadie, D. T., Oldknow, K., Xue, J., Jia, J., Li, G., Meng, X., Xu, Y., Zhou, Y. (2012). Friction management on a chinese heavy haul coal line. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 226(6), 630-640.
- Lin, J., Nordmark, T. & Asplund, M. (2013). Data Analysis of Wheel-sets' Running Surface Wear Based on Re-Profiling Measurement: A Case Study at Malmbanan. *International Heavy Haul Association: The 11th International Heavy Haul Association Conference held 21-24 June 2015 in Perth*.
- Sipos, K., López, M., & Trucco, M. (2008). Surface martensite white layer produced by adhesive sliding wear friction in AISI 1065 steel. *Rev Latinoam Metal Mater*, 28(1), 46-50.
- Stock, R., Eadie, D. T., Elvidge, D., & Oldknow, K. (2011). Influencing rolling contact fatigue through top of rail friction modifier application—A full scale wheel–rail test rig study. *Wear*, 271(1), 134-142.
- Stock, R., Stanlake, L., Hardwick, C., Yu, M., Eadie, D., & Lewis, R. (2016). Material concepts for top of rail friction management—Classification, characterisation and application. *Wear*, 366, 225-232.
- UIC. (2004). *Atlas of wheel and rail defects*. [http://www.uic.org/etf/publication/publication-detail.php?code\\_pub=135](http://www.uic.org/etf/publication/publication-detail.php?code_pub=135): International Union of Railways.
- VanderMarel, J., Eadie, D. T., Oldknow, K. D., & Iwnicki, S. (2014). A predictive model of energy savings from top of rail friction control. *Wear*, 314(1), 155-161.
- Wara, P. (2006). Lubricants influence on wear in sharp rail curves. [Doctoral Thesis], Luleå University of Technology.
- Zarembski, A. M. (2005). *The art and science of rail grinding* Simmons-Boardman Books.