Use of electro-dynamic braking on locomotives and its effect on rolling contact fatigue

T. Nordmark & S.A. Khan
Luleå University of Technology, Luleå, Sweden

C. Domay
LKAB, Kiruna, Sweden

ABSTRACT: The mining company LKAB uses IORE locomotives to haul iron ore trains. When evaluated using life cycle cost (LCC) analysis for reliability, availability, maintainability and safety (RAMS), wheel life is found to be 930,000 km. The IORE locomotives are equipped with electro-dynamic (ED) brakes, but because of the inability of the contact grid to handle the full regenerative energy from the locomotives, the use of the ED-brake was restricted until the contact grid was upgraded in 2010. From around 2011, the wheel life started to decrease because of increased rolling contact fatigue (RCF), dropping to around 350,000 km. LKAB suspected the use of the ED-brake was contributing to the RCF problem. A field test compared one locomotive with ED-braking reduced to a minimum level to a locomotive with full ED-braking capacity. The wheels of the two locomotives were visually inspected at intervals of about 13,000 km. The results showed no difference in RCF performance between the locomotives.

1 INTRODUCTION

This paper looks at the effect of electro-dynamic (ED) braking on the generation of rolling contact fatigue (RCF) on the wheels of IORE locomotives used by the Swedish mining company LKAB to haul iron ore trains. The basic concept of ED-braking is to use electric traction motors as a brake. A moving train possesses a large amount of kinetic energy. Instead of expending this energy as heat, the traction motors are operated as generators providing braking effort. The generated energy can be used within the operation of the locomotive itself or for other trains on the same line; it can even be transferred back to the national grid, if there is a surplus.

A significant amount of energy can be saved with the ED-brake; for LKAB, savings represent about 25%. However, use of the ED-brake could generate indirect cost/damages in the form of RCF and other wear. For LKAB's freight trains, RCF is a major problem; in fact, it is the number one reason for removal of wheels for both locomotives and wagons.

2 IORE LOCOMOTIVE AND MALMBANAN

The IORE locomotive is a class of 34 electric locomotive sections built by Bombardier Transportation for LKAB between 2001 and 2014. The locomotives were procured under a LCC contract with performances according to RAMS. Evaluation from 2001 to 2005 showed that the wheel life would reach 930.000 km.

A complete locomotive consists of two sections with a Co-Co wheel arrangement each. The continuous power rating is 10,800 kW (14,400 hp), and the tractive effort is 1,200 kN with the possibility of boosting the function to 1,400 kN. The ED-brake is variable up to the limit of 750 kN. The current axle load of the locomotive and the ore cars is 30 tonnes. A train consists of 68 wagons attached to the front-end locomotive, resulting in a train length of 750 m and reaching a gross weight of 8,500 tonnes. Maximum speed is 80 km/h. Loaded trains are operated at 60 km/h. The 17 locomotive units haul about 40 MGT annually.

Figure 1. Iron ore (IORE) locomotive no. 101.

Malmbanan, the Iron Ore Line (IOL), is a standard gauge, 473 km section of electrified single track in northern Sweden and northern Norway, with most of the track above the Arctic Circle. The line consists of two parts; the northern part connects the mines in Kiruna to the port in Narvik; the southern part connects the mines in Kiruna and Malmberget to the port in Luleå. The former has been in operation since 1903; the latter has been in operation since 1888.

The climate in northern Sweden is harsh, characterized by cold winters, large quantities of snow and snowstorms; in some places, the snow depth can exceed 1 m. However, the summer can be quite warm. This means the temperature can vary greatly for a single stretch of track; for example, for the stretch from Boden to Gällivare, the temperature can vary by almost 70°C in a year.

The IOL has predominantly head-hardened rail with a hardness of 350 HB and a tensile strength of 1,200 MPa. Sleepers are concrete, and the fastening system is from Pandrol.

3 LOCOMOTIVE WHEELS

The locomotives were equipped with wheels from Lucchini when they were delivered to LKAB. The carbon content is between 0.64–0.75 percent, with hardness of 320 HB. The wheel diameter is 1,250 mm, with a condemned diameter of 1150 mm

At the start, the wheel profile was a standard P8 profile; this was later changed to WPL9 (LKAB profile; Wheel Profile Loco no.9). This profile matches the ore wagon's profile and the worn in profile of the rail and was installed from 2009 to 2010.

The locomotive wheels are to 100 % re-profiled due to RCF from year 2012 (Ekberg et al., 2013). The span between the re-profiling intervals varies from 25,000 to 110,000 km. The estimated lifetime based on turning intervals of rolling 12 months (mean value per month for a year) is about 350,000 km, as shown in Figure 2.

Since 2010, LKAB has made more changes than simply adding the ED-brake. In 2010, the company scrapped the old ore cars and created a uniform wagon fleet. All trains now have 68 wagons, with a concomitant increased train length and train weight. Wheel and rail profiles (Nia et al., 2015a,b) have changed, as have maintenance strategies, like rail grinding and lubrication practices (Asplund et al., 2015) (Asplund & Schoech, 2015). The total traffic has also increased on the IOL; more freight operators use the line with different wagons and wheel profiles.

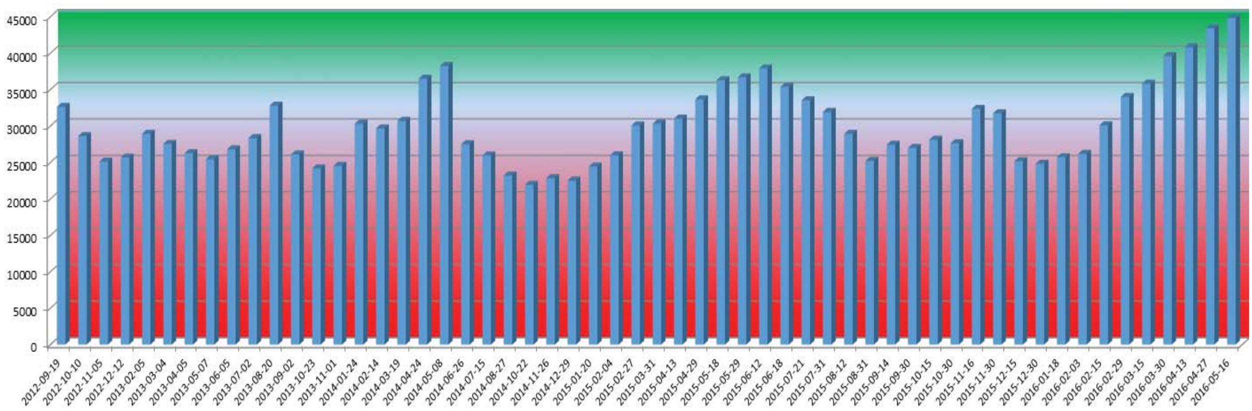

Figure 2. Estimated lifetime locomotive wheels based on turning interval rolling 12 months, September 2012 to May 2016.

4 THE USE OF ED-BRAKING

All LKAB locomotives are similar, hauling similar wagons on the same line, running under similar climatic conditions at the same speed and with the same loads. The only difference is that about 80 drivers drive these locomotives, and different drivers have different driving styles. That being said, however, the locomotive control system does not enable the locomotive to be run at the driver's whim. The greatest degree of freedom drivers have is how to brake the locomotive. They can use the train braking system (ED-brake together with mechanical brake on all wagons) or only the ED-brake. The use of ED-braking alone is intended to regulate the speed; since 2010, it has been used more often because it saves about 25% energy for LKAB. Not surprisingly, LKAB has begun to ask: What if there is a connection between the increased use of ED-braking and the rise in RCF?

The brake force of the ED-brake can provide ranges from 0 to -375 kN per locomotive section. That is, for a locomotive (composed of two sections), it can vary from 0 to-750 kN. The full force of ED-braking is rarely applied; when the use of the ED-brake is logged, the full force is applied approximately 5 % of the time, as shown in Figure 3.

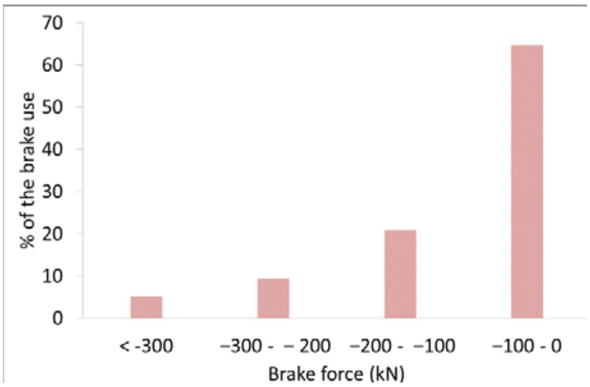

Figure 3. ED-brake force distribution for IORE locomotives.

5 FIELD TEST METHOD

To investigate whether a hard use of the ED-brake can affect the appearance of RCF, a test was proposed to limit the braking force to 125 kN. The test was applied to an IORE locomotive equipped with new wheels. This locomotive, no. 101, went into operation on 16 January 2015.

A month earlier, 10 December 2014, locomotive 118 had been put into operation; it too had new wheels, but had no limitations imposed on its use of ED-braking.

All LKAB locomotives have energy meters installed. These measure both the total energy consumed and the surplus energy generated to the catenary system. The energy fed back to the catenary system is a measurement of how much ED-braking has been used.

The test proposed monitoring and comparing locomotive no. 101 with locomotive no.118 until there was proof of a connection/no connection to RCF.

LKAB locomotives travel, on average, 10,000 km/month and come into the maintenance depot for inspection of the wheels and other worn parts after 13,000 km. The wheels are inspected visually at the workshop by experienced locomotive maintenance personnel. These workers also operate the under-floor lathe and do all the wheel turnings on the locomotives.

LKAB classifies RCF severity in three classes. The first is mild RCF: the locomotive can go back into operation. The second is developed RCF: the locomotive will be sent into operation but put into a plan for re-profiling within a month. In the third class, severe RCF, the locomotive cannot be scheduled for operation before re-profiling is performed. LKAB does the re-profiling in-house (Lin et al., 2015). An example of an RCF class 3 damaged wheel is shown in Figure 4.

Figure 4. RCF class 3, IORE locomotive no. 101.

6 RESULTS

The results can be divided into two phases. Phase one represents the time before the first turning for RCF; phase two is after the first turning.

In the first phase, locomotive no. 101 (limited ED-braking) travelled only 26,312 km, while no. 118 (unlimited ED-braking) travelled 50,073 kilometers. That is a difference of almost 100%, in the performance of the former. The proportion of regenerative energy to the total energy consumed was 19.7% for locomotive no. 101, while no. 118 fed back 24.7%. Table 1 shows these results.

Table 1. Energy consumption, regenerated energy for ED-brakes and mileage for locomotives 101 and 118 first phase.

Locomotive IORE no.101, 2015-01-16 to 2015-05-04		
Energy consumed	702,187 kWh	26,69 kWh/km
Regeneration by ED braking	138,223 kWh	5,25 kWh/km (19,7 %)
Net energy used	563,964 kWh	21,43 kWh/km
Mileage	26,312 km	

Locomotive IORE no.118, 2014-12-10 to 2015-06-10		
Energy consumed	1,277.784 kWh	25,18 kWh/km
Regeneration by ED braking	315,602 kWh	6,21 kWh/km (24,7 %)
Net energy used	962,182 kWh	18,96 kWh/km
Mileage	50,743 km	

The unexpectedly low mileage of locomotive no. 101 before RCF problems caused it to be re-profiled may have nothing to do with the imposed limitations on ED-braking. The time when it was put into service, the middle of January, could have influenced the rapid development of RCF; January and February are the coldest and most demanding months for the locomotives, with temperatures down to –40 C. Everything is under more stress; the track and locomotive suspension are stiff, the material properties of the steel wheels change, and experience says RCF and other damage increase during this period. Why locomotive no. 118 managed double mileage compared to no. 101 before it had to be re-profiled may have a simple explanation: its wheels had a "stress-less" start during December and the hardening of the wheels during this period allowed it to resist RCF longer.

In the second phase, i.e., after the re-profiling necessitated by RCF, locomotive no. 101 travelled 50,502 km, and locomotive no. 118 travelled 49,722 km, bringing them much closer. The difference in regenerative energy (use of ED-braking) was 20.3% and 28.0% for locomotive no. 101 and locomotive no. 118, respectively, as shown in Table 2.

Table 2. Energy consumption, regenerated energy by ED braking and mileage for locomotives 101 and 118 second phase

Locomotive IORE no. 101, 2015-05-04 to 2015-11-20		
Energy consumed	1,322,937 kWh	26,20 kWh/km
Regeneration by ED braking	269,426 kWh	5,33 kWh/km (20,3 %)
Net energy used	1,053,511 kWh	20,86 kWh/km
Mileage	50,502 km	
Locomotive IORE no. 118, 2015-06-10 to 2015-12-10		
Energy consumed	1,278.929 kWh	25,72 kWh/km
Regeneration by ED braking	358,679 kWh	7,21 kWh/km (28,0 %)
Net energy used	920,250 kWh	18,51 kWh/km
Mileage	49,722 km	

The second phase of the test was more comparative in terms of climate conditions and stress state. Here, the result is unquestionable: even with the limited and reduced use of the ED-brake for locomotive no. 101, the wheels were removed for turning at approximately same mileage as for locomotive no. 118. This means the reduced use of the ED-brake does not contribute to a decreased RCF level.

The test was stopped after the second re-profiling of the wheels and about 100,000 km because LKAB saw no reason to continue. A graphical summary of the test can be seen in Figure 5.

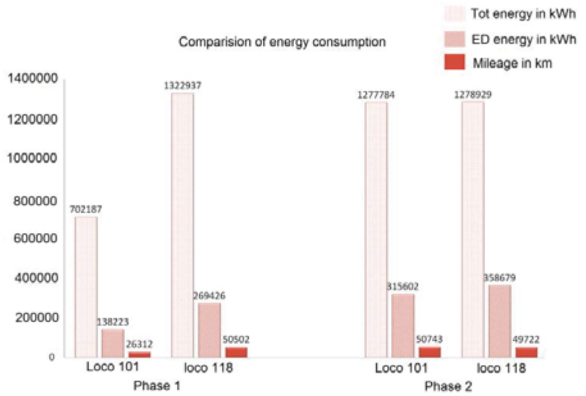

Figure 5. Comparison of energy consumption, regenerative energy and mileage between the re-profiling of locomotives no.101 & 118 during the period of 2014-12-10 to 2015-12-10.

7 CONCLUSIONS

After two wheel-turning intervals of two locomotive sections that went into service at basically the same time and experienced the same climate and line conditions over almost 100,000 km, it cannot be concluded that limiting the ED-braking force or lower use of the ED-brake has a positive impact on the development of RCF and thereby on increased wheel life.

8 FUTURE WORK

Work on increasing the life length of locomotive wheels continues at LKAB. New wheel materials, new wheel profiles and changes in the control system to allow more wheel slippage are measures that are all in progress with the aim of reducing RCF.

9 ACKNOWLEDGMENTS

The authors particularly acknowledge the work done by the other group members in the LKAB wheel-rail group to reduce RCF, notably Robert Pallari, Jan Olovsson and Per Gustafsson from LKAB, Matthias Asplund from Trafikverket, Björn Larsen from Jernbaneveket, Roger Deuce (Deuce, 2007) from Bombardier Transportation, Anders Ekberg from CHARMEC, Saeed Hosseian Nia KTH and Alexander Baltzewitsch from Speno.

10 REFERENCES

Asplund, M., Nordmark, T., Gustafsson, P., 2015. Comparison of TOR lubrication systems on the iron ore line, in: Proceeding of International Heavy Haul Association(IHHA). Perth, Australia.

Asplund, M., Schoech, W., 2015. Towards perfected rail maintenance – combining routine and long-term research activities, in: Proceeding of International Heavy Haul Association(IHHA). Perth, Australia.

Deuce, R., 2007. Wheel tread damage – An elementary guide. Netphen, Germany.

Ekberg, A., Kabo, E., Karttunen, K., Lindqvist, B., Lunden, R., Nordmark, T., Olovsson, J., Salomonsson, O., Vernersson, T., 2013. Identifying Root Causes of Heavy Haul Wheel Damage Phenomena, in: Proceeding of International Heavy Haul Association(IHHA). New Delhi, pp. 520–527.

Lin, J., Asplund, M., Nordmark, T., 2015. Data analysis of wheel-sets' running surface wear based on re-profiling measurement: a case study at Malmbanan, in: Proceeding of International Heavy Haul Association(IHHA).

Nia, S.H., Casanueva, C., Stichel, S., 2015a. Prediction of RCF and wear evolution of iron-ore locomotive wheels. Wear 338–339, 62–72. doi:10.1016/j.wear.2015.05.015

Nia, S.H., Stichel, S., Casanueva, C., Nordmark, T., 2015b. Study of the long term evolution of low-RCF wheel profile for LKAB iron ore wagons, in: Proceeding of International Heavy Haul Association(IHHA). Perth, Australia.