Maintainability in Extreme Seasonal Weather Conditions

M. Palo[1], H. Schunnesson[1], P.-O. Larsson-Kråik[2],
[1]Luleå University of Technology, Luleå, Sweden; [2] Trafikverket, Luleå, Sweden

Abstract

In Sweden, the winter of 2009-10 was especially severe, with cold and snowy conditions. Regardless of the weather, train operators must ensure the maximum availability of their vehicles with a minimum of risk and downtime. To this end, important tasks are to maintain high wheel quality, reduce wheel wear and ensure a steady supply of new wheels. This paper studies the problems created by severe weather, with a focus on wheel damage. It found an increase in wheel damage and wheel maintenance which put a great deal of strain on the workshops responsible for wheel turning and supplying fresh wheels. The study confirms a relationship between temperature and wheel wear and suggests the influence of the train brake system on wheel damage in cold weather.

1. Introduction

One of the most important elements in the dynamics of a railway vehicle is the interaction between the wheel and the rail [1]. The wheel profile determines the stability of a vehicle, while the rate of wheel surface wear [2] determines the life length of a wheel [3]. Increasing emphasis on maintenance and life cycle costs for both rolling stock and infrastructure have drawn attention to the need to predict wheel and rail wear [4] in order to optimize maintenance decisions and estimate remaining useful life.

Some studies of the relationship between wheel wear and climate have already been done. In a simulation, Sandström and Ekberg [5] find that temperature has a major influence on crack growth; similarly, Nielsen and Johansson [6] report that the risk of wheel fracture increases at low temperatures. A study by Kalousek et al. [7] reports a two- to five-fold increase in winter wheel removals due to high wheel flanges.

In another study performed in 2009-10 in Sweden, the wheel wear of two iron ore wagons with a three-piece AMSTED bogie and a 30 ton axle-load was monitored during 15 months of operation [8]. The cars were used to transport iron ore from LKAB's mine in Malmberget to the harbor in Luleå, passing through the Arctic Circle. To evaluate the wheel wear, eight identical wheel sets were regularly measured with a MiniProf™ [9]. In Fig. (1), the measured wheel wear is plotted against the average temperature between two profile measurements. Data are from both the leading and trailing axle. The results confirm the findings by ref. [5] and [6] of the influence of low temperatures on wheel wear and indicate a significant higher wear rate below -10°C.

In Scandinavia, the winter of 2009-10 was colder than normal, and this affected the wheel wear on operating trains. In this paper, we look into the reported increase of wheel wear and wheel damage during that cold winter to see if their extent can be estimated, as such estimations would be invaluable to rail companies seeking to optimize their maintenance decisions. Daily average temperatures along the lines are provided by Swedish Meteorological and Hydrological Institute. The number of re-profiled wheel sets is used as a measure of wheel wear. The study also notes the increasing workload that this wheel wear puts on maintenance workshops and suggests how it can be controlled. Finally, it finds an interesting correlation between brake type, cold weather and wheel wear.

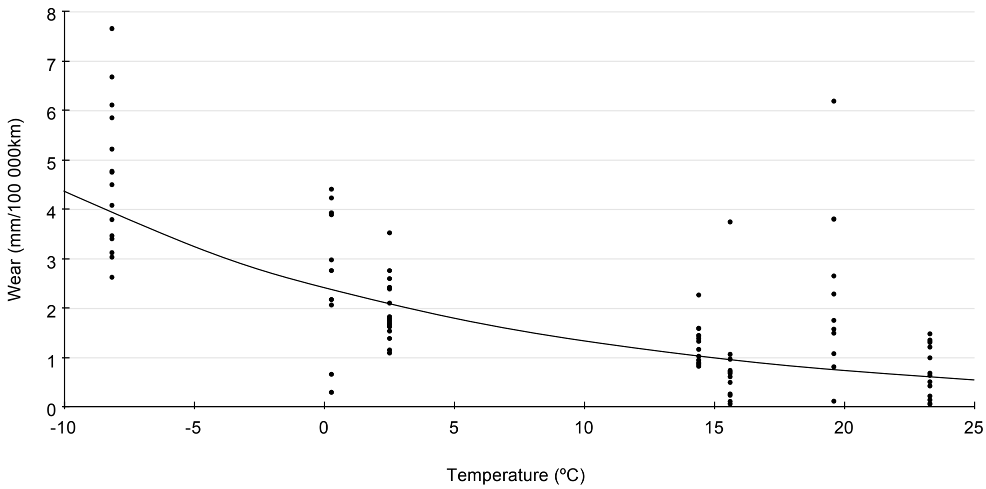

Figure 1. Wear at running circle in mm/100 000 km *versus* temperature

2. Wheel wear

2.1 Wheel deterioration

The interaction between wheel and rail resulting in material deterioration is a complicated process, involving vehicle-track dynamics, contact mechanics, friction wear and lubrication [1]. The course of events called wear is similarly complicated, involving several modes of material deterioration and contact surface alteration [10]. Two important deterioration mechanisms are wear and rolling contact fatigue (RCF). Friction heating occurs when train cars reduce speed by using their pads against the running surface of the wheels (i.e., braking). When the wheel surface layer is frictionally heated, and this is followed by the rapid cooling of the body of the wheel itself, there is an increased risk of forming martensite [7]. As martensite is much harder and more brittle than the surrounding material, it can break and initiate cracks. As for RCF, according to Stone et al. [11] freight car wheels in service may develop tread irregularities in the form of slid-flats, shells or spalls. Any of these irregularities can cause high wheel impact, but the first is the most common [12]. Another cause of high impact leading to RCF is a major defect in the tread surface; this has a higher probability of leading to catastrophic failure.

Railway wheel flats or slid-flats are a well known problem in railway engineering [13]. Wheel flats are formed when a wheel set is locked and skids along the rail. The friction between wheel and rail causes the surface of the wheel to become flat instead of round [12]. Wheel flats have mechanical singularities that frequently serve as sites for the formation of additional flats and resulting shells [14]. A martensitic layer several millimeters deep can be formed as well [7]. Thin martensitic layers may crack and wear off harmlessly; thicker ones inevitably spall or shell the wheel [7].

Shelling is a term normally used for all types of subsurface induced cracks [6]. Wheel shelling is defined as the loss of relative large (greater than 5 mm) pieces of metal from the wheel tread as the result of contact fatigue [15]. Typically, shelling cracks grow at an acute angle to the surface. Impact load can affect shelling in both crack initiation and crack propagation modes [14].

Spalling is the term used for the RCF phenomenon occurring when surface cracks of thermal origin meet, resulting in part of the wheel coming away from the tread [6]. It is associated with cracking induced by high transformation stress caused by surface martensite formation [15]. Cracks from spalling form both perpendicular and parallel to the wheel tread surface.

2.2 Inspection and non-contact condition monitoring

An important goal of predictive monitoring is to allow early, reliable and cost-effective detection of faults in rolling stock [16], including the discovery of early cracks [17]. Inspection techniques traditionally used in the railroad industry, such as drive-by inspections, are not as accurate or reliable as more rigorous and quantitative inspection methods [12]. For example, condition monitoring uses some level of knowledge of the system of interest to establish its current condition [1]. To this end, the railway industry uses wayside detection [2], a technique of detecting specific faults on rolling stock through the use of interrogating sensors placed along the sides of the track, usually at a wayside monitoring station. This non-contact method of monitoring can be used on trains travelling at track speed; it provides direct feedback to track owners and operators of the condition of vehicles passing the monitoring station. A survey mentioned by Stone et al. [11] notes that impact load detectors are effective tools for monitoring high impact load producing wheels, with an impact force of 400 kN or greater [12].

3. Case background

Northern Sweden has harsh climatic conditions, with cold snowy winters and extreme temperatures ranging from -40˚C to +30˚C [18]. An example of the extra stresses that ice and snow put on wheels can be seen in Fig. (2). In Sweden, train operators need to carefully plan their maintenance to take environment and weather conditions into account.

During the warm season, from May to September, wayside wheel/rail curve lubricators are used on the railway lines in northern Sweden. The driver can use sand if the friction gets too low.

Figure 2. Train wheel covered in snow

In the investigated area in northern Sweden, as shown in Fig. (3), both the steel shuttle train and the iron ore train operate with high axle loads. The latter transports iron ore pellets from LKAB's mines in Kiruna and Malmberget to the harbors in Narvik and Luleå. The former transports steel slabs (plates) from Luleå to Borlänge in the center of Sweden. Table (1) compares the axle load and the top speed (when loaded).

Table 1. Comparison of iron ore and steel shuttle wagons

	Iron ore	Steel shuttle
Axle load	30 t	22.5 t
Top speed	60 km/h	100 km/h

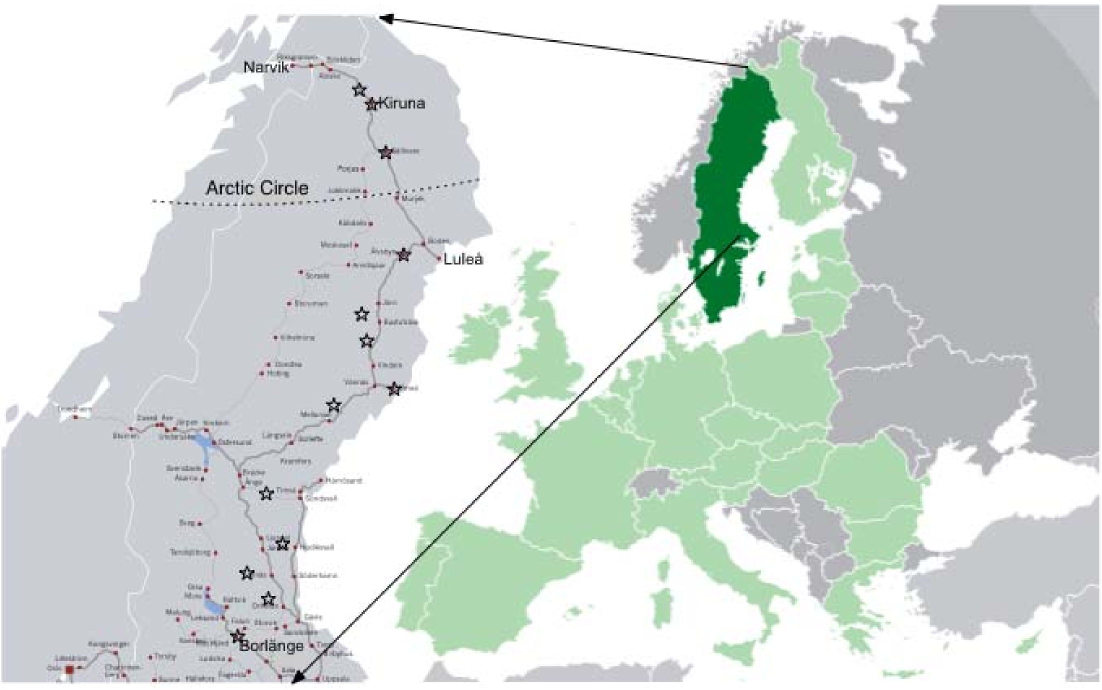

Figure 3. Map of the investigated area, showing the Swedish railroad network with weather stations marked by a star

Table (2) depicts the shipped volume of iron ore pellets and production volume of steel plates for the last 6 years. The table shows a slow, steady increase in production from 2004 to 2007. Due to the global recession, the production of both iron ore pellets and steel plates stopped almost completely during Autumn 2008. During the second half of 2009, both companies returned to normal production, but the annual production rate remained low for 2009.

Table 2. Shipping volume for iron ore and production volume for steel plates, in Mton

	Iron ore	Steel plate
2004	22.8	4.54
2005	23.2	4.50
2006	23.3	4.68
2007	25.1	4.78
2008	22.7	4.46
2009	18.7	2.80

In Sweden, only two workshops do wheel maintenance, one in Gothenburg and the other in Luleå. In this paper, only data from the northern workshop in Luleå are used (Fig. 3). The majority of wheel maintenance at the workshop in Luleå is done on iron ore wagons and steel shuttle wagons; there is also a wheel pool to service trains transporting goods and passenger trains.

3.1 Weather information

In the investigated area (Fig. 3), there are large differences in climate and temperature. In the northern part of the region, the cold normally arrives earlier and stays longer. The study uses average values for daily temperature and humidity, tracking data from 13 different weather stations along the track, see Fig. (3) and Table (3).

Table 3. Weather stations used.

1 – Borlänge	4 – Delsbo	7 – Petisträsk	10 – Älvsbyn	13 – Rensjön
2 – Åmot	5 – Torpshammar	8 – Umeå	11 – Gällivare	
3 – Delsbo	6 – Hemling	9 – Norsjö	12 – Kiruna	

The steel train from Borlänge passes weather stations 1 through 10; the iron ore train passes stations 11 to 13 (Fig. 3 and Table 1).

The following formula is used to calculate an annual temperature factor for each year;

$$\text{Temperature factor} = \sum_{\text{1 October}}^{\text{30 April}} (Temp - Temp_{lim}) \quad (\text{for all } (Temp \leq Temp_{lim})) \qquad \text{(Eq. 1)}$$

Where:

$Temp$ = daily temperature average

$Temp_{lim}$ = temperature limit

The temperature limit is set to -10°C. The temperature factor is the number of days over the time period when the average temperature is lower than the temperature limit times the number of degrees Celsius. A larger negative value indicates a colder winter than a smaller value.

Fig. (4) presents results from three weather stations for 10 consecutive years. The stations are Åmot (2) located in the south close to Borlänge, Hemling (6) and Älvsbyn (10) located close to Luleå. The figure shows a significant difference between the southern and the northern part of the track, as the temperature factor for Älvsbyn is, on average, five times higher than the factor for Åmot. In Åmot, the temperature factor is normally between 0 and 150, indicating very few days with temperatures below -10°C, while Älvsbyn has temperatures under the limit several months of the year. The normal climatic conditions mean that the steel train moves from the colder northern temperatures towards the warmer temperatures in the south, while the iron ore train operates continuously in a cold climate with only minor differences.

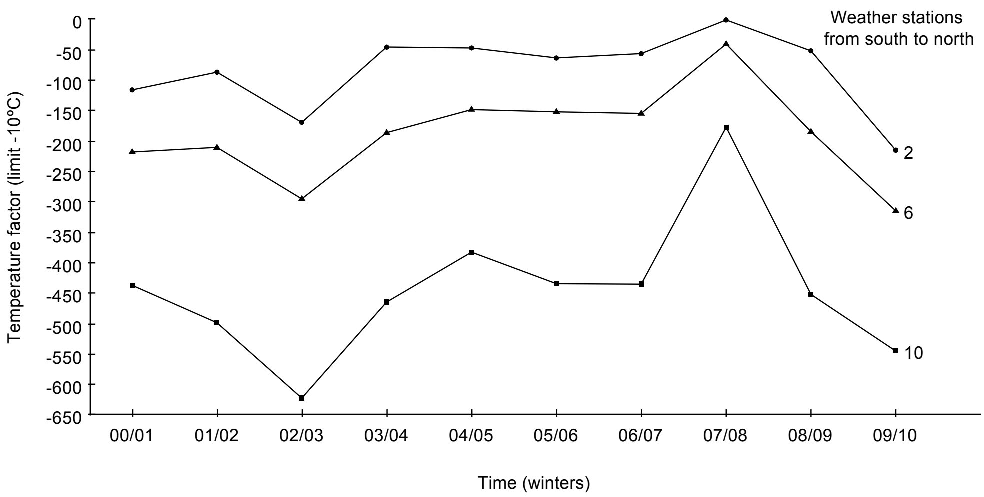

Figure 4. Differences for three weather stations going from the south to north

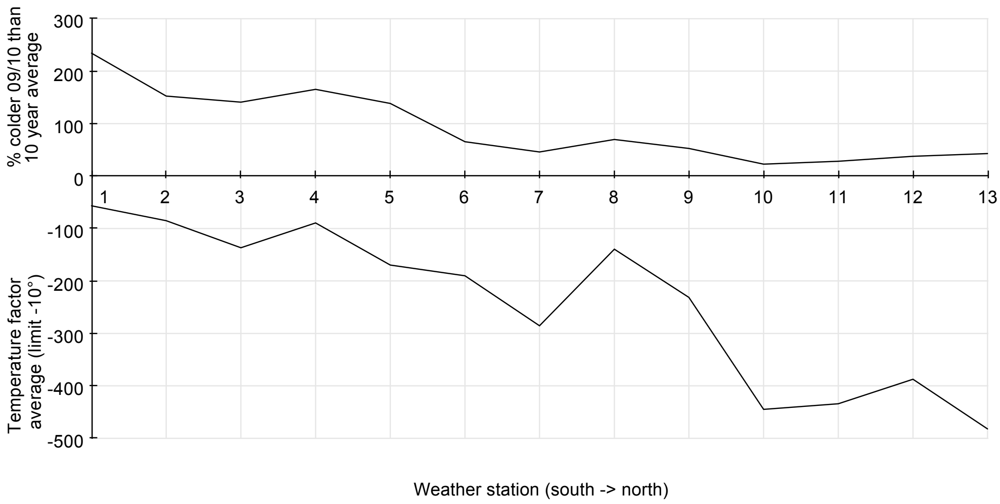

Figure 5. Temperature factor for 2009-10 at -10°C and difference to average

As noted, the winter of 2009-10 was generally cold in Scandinavia, but there were some variations in different parts of the studied railway line. Fig. (5) shows the average temperature factor for the 13 stations (south to north). The top graph shows the difference between 2009-10 temperatures and the average values. The temperature along the entire track was colder than normal. However, in the north where the iron ore train operates, it was only slightly colder than normal, while in parts of the south, it was over 200% colder than normal, as defined by the temperature factor. This large deviation from normal temperatures is likely to influence wheel maintenance and affect the number of wheels that require re-profiling.

4. Results

In this project, the indicator selected for wheel wear was the number of re-profiled wheels. From the Luleå workshop, the monthly average values were collected from 2006 to 2010. The number of re-profiled wheel sets as function of calendar time is presented in Fig. (6).

The graph shows a clear cyclic behavior with more wheels being re-profiled during the cold period of the year. This supports the hypothesis that there is a relationship between cold temperatures and wheel surface damage, such as wear and RCF initiated damages.

During the winter 2009-10, a number of wheels belonging to the steel shuttle were sent to a workshop in Germany for re-profiling. The extra 600 wheels are shown in the four columns at the bottom; the extra average line in the graph, thinner, is including these wheel sets. These extra wheel sets can also be seen in (Table 4) where the additional column for 2009-10 is marked with a star.

Table 4. Number of re-profiled wheel sets from October to September

Year	06/07	07/08	08/09	09/10	09/10*
Total	7460	7292	7469	8156	8756

To quantify the temperature influence on re-profiling, the number of re-profiled wheel sets is plotted against the total temperature factor at -10°C for the total track section; see Fig. (7).

As seen in the figure, there is a clear increase in the number of re-profiled wheel sets when the temperature drops. Over the 10-year period, there is a yearly re-profiling volume of about 7850 wheel sets. However, a peak of 9000 can occur during cold winters.

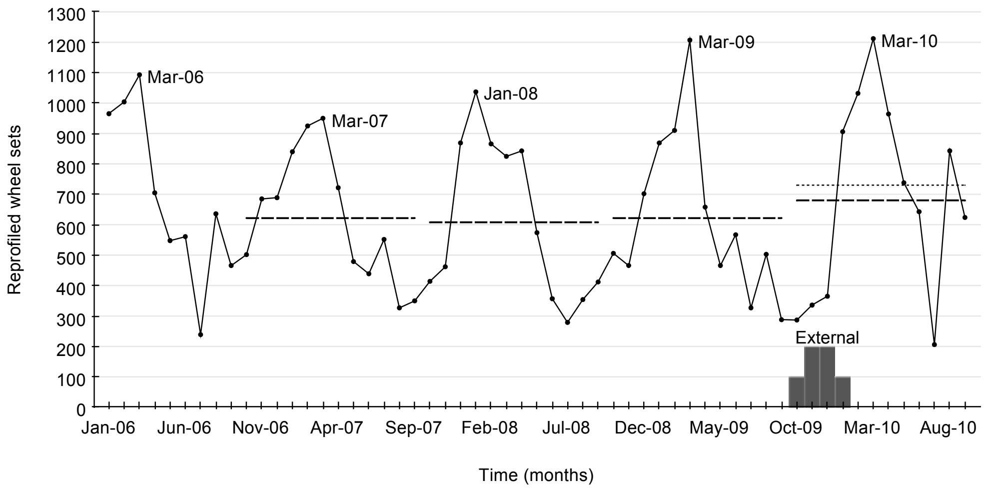

Figure 6. Number of wheels re-profiled per month from January 2006 to September 2010

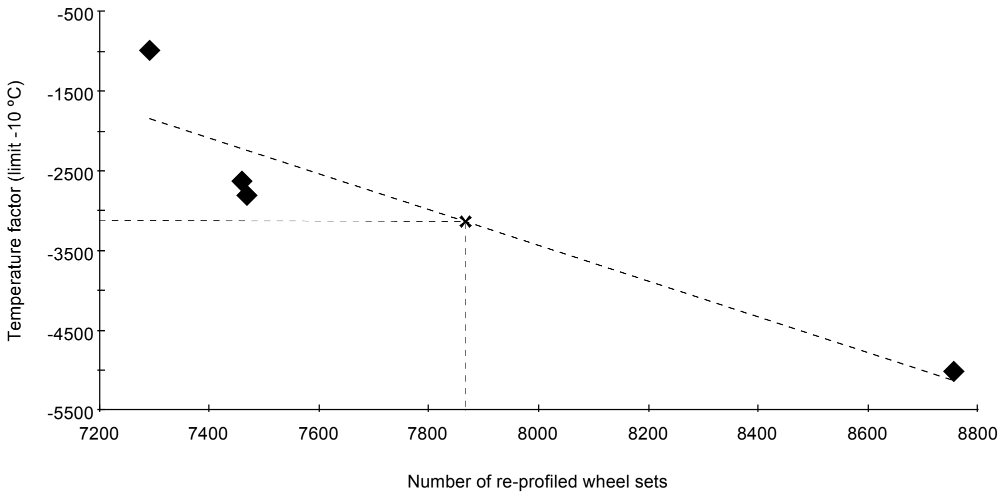

Figure 7. Number of re-profiled wheel sets as a function of degree-days

During the project, we conducted a detailed interview survey of key planning personnel at the wheel workshop in Luleå. The interviews provided anecdotal evidence that in cold temperature operations, RCF is the dominant wheel surface damage, including shelling and spalling; there is almost no other wheel damage. Seasonal statistics from the workshop indicate that this type of damaged wheel starts to appear about two weeks after the first few days of weather below -10°C. The majority of wheels with shelling or spalling are from the steel shuttle; the iron ore trains almost never experience this kind of damage.

The iron ore train and the steel train also differ in when wheels are sent for re-profiling. The steel shuttle sends more wheels at the start of winter. The iron ore wheels start to appear around March, when there are fewer wheels from the steel train. During spring and summer the damage is mostly tread wear for both.

Both the iron ore and the steel shuttle car have the same wheel material, but to reduce train speed, the steel shuttle cars use cast-iron blocks and the iron ore cars use composite blocks.

5. Discussion

The winter of 2009-10 was colder than normal in Sweden, and the whole country was covered in snow for longer than usual. However, the temperature deviation in the investigated geographical areas varied significantly. Compared to the average temperatures, there were many more cold days in the south than in the north, as shown in Fig. (4,5).

The study shows that temperature change impacts the maintenance and the number of re-profiled wheels, and it confirms the relationship between temperature and wheel wear. The wear rate increases as temperatures decrease.

Wheel surface damage in low temperature and snow conditions are reported by other railways operating in cold climates, and this has been linked to braking systems. Tracks covered by snow and the subsequent swirl snow created by the moving train will lead to the deposit of snow crystals on the wheel treads, whose temperatures usually exceed 0°C, during braking. When cast-iron braking blocks are used, the melted snow leaves a film of water-oxide slurry on the wheel surface for prolonged periods of time; hence, increased surface damage is observed [7].

Each train type has a different braking system. The steel shuttle uses mechanical brakes on the locomotive and on every car; these brakes generate friction heating which, in combination with the rapid cooling of all wheels in the cold weather, initiates cracks. The iron ore operation engages the electro dynamic brakes of the locomotive 70-80% of the time, thereby reducing the frictional heating of car wheels and considerably lessening the cold-weather damage.

Out of all wheel damage reported in this study, shelling and spalling generate the greatest loss of wheel diameter when re-profiling, due to the crack growth rate. During winter and in snowy conditions, micro-cracks can grow in size and length, increasing the hazard by making the wheel either shell or spall. In the summer and dry weather conditions, tread wear is more significant.

Another interesting finding is the difference between the iron ore train and the steel train as to when wheels are sent for re-profiling. The steel shuttle sends more wheels at the start of winter; the iron ore wheels start to appear around March when there are fewer wheels from the steel train. Arguably, using the mechanical brakes of the train cars, instead of locomotive break, increase the risk of major wheel damage.

Both shelling and spalling are difficult to detect with traditional inspections or wayside monitoring until it is too late for preventive maintenance.

6. Conclusion

- In low temperatures, an increased number of wheels are re-profiled, confirming the relationship between cold temperature and wheel surface damage.
- RCF, with spalling and shelling, is the dominant wheel surface damage during cold temperature operations.
- Further investigation of the influence of the train braking system on crack initiation and wheel wear is needed.

7. Acknowledgement

The authors would like to thank Thomas Aro at DUROC for providing data and commentary. Luleå Railway Research Center (JVTC) is gratefully acknowledged for its financial support.

8. References

[1] G. Charles, R. Dixon, R. Goodall, Condition Monitoring Approaches to Estimating Wheel-Rail Profile, Proceedings of the UKACC Control Conference, Manchester, (2008)

[2] D. Barke, W.K. Chiu, Structural Health Monitoring in the Railway Industry: A Review, Structural Health Monitoring 4 (1) (2005) 81-94

[3] F. Braghin, R. Lewis, R.S. Dwyer-Joyce, S. Bruni, A mathematical model to predict railway wheel profile evolution due to wear, Wear 261 (2006) 1253-1264

[4] R. Enblom and M. Berg Simulation of wailway wheel profile development due to wear – influence of disc braking and contact environment, Wear 258 (2005) 1055-1063

[5] J. Sandström, A. Ekberg, Predicting crack growth and risk of rail breaks due to wheel flat impacts in heavy haul operations, Journal of Rail and Rapid Transit 224 (2009) 153-161

[6] J.C.O. Nielsen, A. Johansson, Out-of-round railway wheels – a literature survey, Proceedings of the Institution of Mechanical Engineering, 214 (2) (2000) 79-91

[7] J. Kalousek, E. Magel, J. Strasser. Tribological interrelationship of seasonal fluctuations of freight car wheel wear, contact fatigue shelling and composition brakeshoe consumption, Wear 191 (1996) 210-218

[8] M. Palo, I. Arasteh Khouy, H. Schunnesson, D. Larsson, Condition monitoring of train wheel wear and track forces: A case study, Proceedings of the 1st international workshop and Congress on eMaintenance, Luleå University of Technology (2010)

[9] C. Esveld, L. Gronskov, MiniProf Wheel and Rail Measurements, 2nd Mini Conf. on Contact Mechanics and Wear of Rail/Wheel Systems, Budapest, (1996)

[10] R. Enblom S. Stichel, Industrial implementation of novel procedures for the prediction of railway wheel surface deterioration, Wear*,* (2010) doi:10.1016/j.wear.2010.10.037

[11] D.H. Stone, S.F. Kalay, A. Tajaddini, Statistical Behaviour of Wheel Impact Load Detectors to Various Wheel Defects, International Wheelset Congress, Sydney Australia (1992)

[12] B. Stratman, Y. Liu, S. Mahadevan, Structural Health Monitoring of Railroad Wheels Using Wheel Impact Load Detectors, Journal of Failure Analysis and Prevention, 7 (2007) 218-225

[13] J. Ahlström, B. Karlsson, Microstructural evaluation and interpretation of the mechanically and thermally attected zone under railway wheel flats, Wear 232 (1999) 1-14

[14] D.H. Stone G.J. Moyar, Wheel spalling and shelling – an interpretive review, Rail transportation, 1989; presented at the winter annual meeting of ASME. San Francisco, USA, (1989) 19-31

[15] G.J. Moyar, D.H. Stone, An analysis of the thermal contributions to railway wheel shelling, Wear 144 (1991) 117-138

[16] K. Bladon, D. Rennison, G. Izbinsky, R. Tracy, T. Bladon, Predictive Condition Monitoring of Railway Rolling Stock, Railway Engineering Conference, Darwin 20-23 June 2004

[17] A. Ekberg, E. Kabo, H. Andersson, An engineering model for prediction of rolling contact fatigue of railway wheels, Fatigue & Fracture of Engineering Materials & Structures, 25 (2002) 899-909

[18] S. Kumar, U. Espling, U. Kumar, A holistic procedure for rail maintenance in Sweden, Proc. IMechE Part F: J. Rail and Rapid Transit, 222 (4) (2008) 331-344