

Condition Monitoring of Railway Vehicles

*A Study on Wheel Condition for
Heavy Haul Rolling Stock*

Mikael Palo

CONDITION MONITORING OF RAILWAY
VEHICLES
A study on wheel condition for heavy haul rolling stock

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*A man who has never gone to school
may steal from a freight car,
but if he has a University education,
he may steal the whole railroad.*

—Theodore Roosevelt

PREFACE

The research presented in this thesis has been carried out during the period 2009 to 2011 in the subject area of Operation and Maintenance Engineering at Luleå Railway Research Centre (Järnvägstekniskt Centrum, JVTC) at Luleå University of Technology and has been sponsored by Swedish Transport Administration (Trafikverket) and LKAB mining company.

First of all, I will thank Uday Kumar and Håkan Schunnesson for being my supervisors for this thesis. I have enjoyed our conversations on and discussions of what should be part of the thesis. My colleagues at Operation and maintenance engineering also need a big thank you for all their support and comments.

I would also like to thank my fiancée and two lovely daughters for putting up with me when I have had to give a lot of time and thought into writing this thesis.

Mikael Palo
Luleå, 2012

ABSTRACT

A railway is an energy efficient mode of transport as it uses the low resistance contact between wheel and rail. This contact is not frictionless and causes wear on both surfaces. The wheel-rail guidance is made possible by the shapes of wheel and rail profiles. To increase revenue for train operators and decrease cost for railway infrastructure owners, there is a need to monitor the conditions of the assets. A major cost-driver for operators is the production loss due to wheels, especially from maintenance costs when changing and re-profiling wheels.

The research in this study has been performed on the Iron Ore Line (malmbanan) in northern Sweden and Norway. Large parts of this railway line are situated north of the Arctic Circle with temperature variations from -40°C to $+25^{\circ}\text{C}$ and a yearly average around freezing. Running trains in this environment strains all components.

The purpose of this research is to evaluate how condition-based maintenance should be implemented for railway wagons. Research methods include a literature review, interviews, and data collection and analysis. Manual wheel profile measurements have been combined with maintenance data, weather data and wheel-rail force measurements to make comparisons between seasons and wagons.

The analysis shows that there are different lateral force signatures at the wheel-rail interface dependent on the wheel's position within the bogie. It also shows the need to change both wheel sets of the bogie simultaneously. Finally, it proves there is greater wheel wear at low temperatures.

KEYWORDS:

Railway, Condition Monitoring, Wear, Wheel Wear, Wheel Profile, Heavy Haul, Maintenance, Decision-support

LIST OF APPENDED PAPERS

- PAPER A M. Palo, H. Schunnesson and U. Kumar, "*Condition monitoring of rolling stock using wheel/rail forces*,"
Accepted for publication and presentation in BINDT 2012
- PAPER B M. Palo and H. Schunnesson, "*Condition monitoring of wheel wear on iron ore cars*,"
Accepted for publication in COMADEM Special Issue on Railway, 2012
- PAPER C M. Palo, H. Schunnesson, and P.-O. Larsson-Kråik, "*Maintainability in extreme seasonal weather conditions*,"
Presented and published in Proceedings of Technical Session of International Heavy Haul Association, 2011

DIVISION OF WORK BETWEEN AUTHORS

In this section, the distribution of the research work is presented for all the appended papers. The content of this section has been communicated to and accepted by all the authors who have contributed to the papers.

- PAPER A Mikael Palo developed the main idea. The literature review, data collection and analysis was performed by Mikael Palo. The results, discussion and conclusion were discussed with Håkan Schunnesson and Uday Kumar.
- PAPER B Mikael Palo developed the main idea. The literature review, data collection and analysis was performed by Mikael Palo. The results, discussion and conclusion were discussed with Håkan Schunnesson.
- PAPER C Mikael Palo developed the main idea. The literature review and data collection was performed by Mikael Palo. The data analysis was performed by both Mikael Palo and Håkan Schunnesson. The results, discussion and conclusion were discussed with Håkan Schunnesson and Per-Olof Larsson-Kråik.

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Part I

SUMMARY

INTRODUCTION

1.1 BACKGROUND

Railways use the low resistance of movement between wheel and rail, in order to be an energy efficient mode of transport. The development of fast or heavy trains affects the vehicle-track dynamic interaction (9). Vehicle-track interaction includes ride comfort and safety, vehicle stability, wheel-rail forces, wheel-rail corrugation, wheel out-of-roundness, noise propagation, etc., and is influenced by a variety of factors (10). Safety is the most important attribute of quality of service and operation for railways (35). The condition of wheels and rails have a great impact on railway safety. Therefore, having railway vehicles and especially wheels in an acceptable condition is a major concern for both railway operators and infrastructure owners. Infrastructure managers always try to reduce the number of potential risk areas that can lead to accidents.

In the early days of railroad the infrastructure and vehicles were run to failure. Following the technological progress of the industrial world all investigations were then made by maintenance personnel manually inspecting both the infrastructure and the vehicles. As technology advances the condition monitoring and analysis tools to evaluate the current railway load are embraced by the industry.

Wheel sets are regarded as fundamental components of railway vehicles; they support the vehicle during rolling, guide it and transfer longitudinal forces at traction and braking (9). The wheel-rail interface is the most important parameter in the dynamics of railway vehicles and their condition (11, 23). This interface is where most of the cost for maintenance on both railway vehicles and infrastructure occurs. The change in rail profiles is a major maintenance cost driver (15). The profile change on wheels can also be significant, especially in curves. Damage mechanisms such as wear and plastic deformation are the main contributors to profile change.

The wheel-rail contact is typically the size of a small coin, 100 mm². Rails and wheels are commonly made from plain carbon-manganese pearlitic steel. A wheel set for a railway vehicle is almost always fixed on a solid shaft. With the wheel set centered on straight track, and if the left and right wheel rolling radii are equal, the wheel set can roll normally. The steering load contributes to increased wear and rolling contact fatigue, especially in curved tracks. (42)

The Iron Ore Line (Malmbanan) in northern Sweden starts in Luleå and ends in Narvik in Norway, see Fig. 1.1. The traffic on the Line consists of both passenger and freight trains. The freight traffic consists primarily of heavy haul trains with axle loads of 22.5 tonnes and more. Running heavy-haul railway traffic in a mountainous area north of the Arctic Circle is a challenging task (32). The trains operate in harsh climate conditions, including snow in the winter and extreme temperatures ranging from -40°C to $+25^{\circ}\text{C}$ (21). There are many tight curves along the track that experience high wear (7).

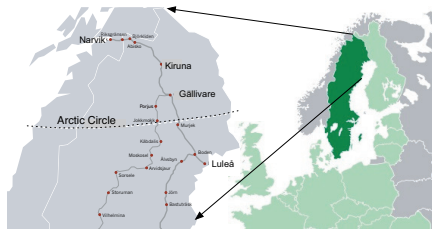


Figure 1.1: Map of northern Sweden

However, competition in the world market has forced the Swedish iron-ore mining company LKAB to make its transport chain more efficient (25). As a result LKAB are now transporting iron-ore with an axle-load of 30 tonnes and at speeds of 60 km/h.

Outside Luleå there is a research station which measures the wheel-rail forces, both lateral and vertical, in a curve with 484 m radius at track speed. This will be described further in section 2.1.1 on page 8; see paper B.

1.1.1 *Weather and climate*

All of Sweden experience temperatures below freezing most years. In the southern parts it might only be for a few days. In the north it is usually below zero for up to seven months of the year.

1.1.2 *Operating trains*

On Malmbanan there are primarily heavy-haul trains from LKAB mining company. These trains consist of two IORE locomotive with 68 wagons, 750 meters long and a total train weight 8,500 tonnes. On Malmbanan there are passenger, freight, steel-slab and copper-ore trains. The freight trains consist of lighter wagons up to 18 tonnes of axle load, the copper-ore trains have an axle-load of 22.5 tonnes and the steel-slab trains have an axle-load of 25 tonnes.

1.2 MOTIVATION OF THE STUDY

The motivation for this study is to have a better utilization of wagon population by optimizing inspection and maintenance with less down-time. Simply stated, there is a need to go from time-based to condition-based maintenance. Large cost-drivers are manual labor and wheel re-profiling. The aim is to define cost effective maintenance thresholds based on measurement data.

1.3 PROBLEM DESCRIPTION

The railway industry has a desire/need to improve the process of maintenance program development from the present tonnage or kilometer based programs to a condition-based maintenance regime. Introducing condition-based maintenance requires both technical solutions to monitor the condition and change at the organizational level.

The wheel-rail guidance is made possible by the shapes of the wheel and the rail profiles. To increase revenue for train operators and decrease cost for railway infrastructure owners there is a need to monitor the condition of the assets. A major cost-driver for operators is production loss due to wheels. This is mainly from maintenance costs when changing and re-profiling wheels.

This study will analyse and process the measurement data from wheel-rail force measurements at the research station outside Luleå. This is a first step in finding thresholds for condition-based maintenance on wheels. In this study the relationship between wheel profile wear, the measured lateral force, and weather conditions are analysed.

1.4 RESEARCH GOAL

The overall research goal is to evaluate different existing methodologies as tools for cost effective implementation of condition-based maintenance for railway vehicles, in particular the wagon wheels. The goal is to increase the life length of the wheels by knowing the condition of the wheel profile. We also plan to show the impact of maintenance actions and the influencing factor on wheel set life.

1.5 RESEARCH QUESTIONS

In order to fulfill the stated goals above, the following research questions have been raised:

1. What is the best method to collect data from the wheel-rail interface for condition monitoring?

2. How can data collected from the wheel-rail interface be used in maintenance decision-support?
3. How do Arctic weather conditions influence the need for railway vehicle maintenance?
4. How do the different wheel and axle positions influence the maintenance decisions?

These research questions are answered by the three appended papers. Each paper makes its own contribution toward the research questions; see Table 1.1.

Table 1.1: Relationship between the appended papers and research questions

	PAPER		
	A	B	C
RQ 1	X	X	
RQ 2	X	X	
RQ 3		X	X
RQ 4	X	X	

1.6 LIMITATIONS OF THE STUDY

The research seeks to optimize the maintenance of railway vehicles, with a focus on wheels.

There are some limitations in this study. Only heavy haul vehicles are considered due to their heavy load on the infrastructure. Thus, only northern Sweden will be investigated since this is where the vehicles are used. Lastly only wheel profile data from LKAB mining company are studied.

CONDITION MONITORING OF WHEEL-RAIL INTERFACE

2.1 CONDITION MONITORING

Information regarding health and physical status of wheels or components is key to successful maintenance planning. Therefore, many maintenance actions are directed towards collecting information on wheel conditions (22). A definition of the term condition monitoring (CM) is the continuous or periodic measurement and interpretation of data to indicate the condition of an item to determine the need for maintenance (28). This is normally carried out with the item in operation, in operable state or removed but not subject to major strip down.

The monitoring can be executed with different levels of automation, from relying entirely on human senses to assess the condition to fully automated and integrated monitoring systems, measuring and analyzing e.g. vibrations, temperatures, pressures etc (6).

Traditional inspection techniques used in the railroad industry such as drive-by inspection, are not as accurate and reliable as more rigorous and quantitative inspection methods (39). On-board measuring can measure the chosen parameter along the whole route where the test trains runs, while wayside measuring can measure the parameters for the full train set as it runs through the measuring points (26). Wayside detection systems provide a means of monitoring the condition of vehicles, ensuring that they are in a serviceable condition (4).

2.1.1 *Wheel-rail forces*

Force measurement detectors make it possible for vehicles with defective wheels, which are likely to cause damage to the permanent railway structures, to be identified and removed from service immediately (34). Vertical impact loads between wheel and rail resulting from surface anomalies such as wheel flats has been used to create mathematical models of wheel-rail impact behaviour (1). Systems that solely measure the axle load of wheel flats are mostly placed on a tangent track with no gradient or a negligible gradient and where trains do not accelerate or brake (24).

When measuring the lateral forces, it is best to perform measurements in narrow curves, as the vehicles show their steering ability. For a illustration of lateral and vertical forces, see Fig. 2.1(a), and for

bogie/wheel placement in a curve, see Fig. 2.1(b). Lateral forces are the result of poor steering bogie and train speeds outside the track design, and of longitudinal buff and draft forces transmitted through train action and coupler angularity (5). In order to prevent derailment accidents and abnormal wear, it is important to determine the actual state of the contact forces between wheel and rail (26). According to Matsumoto et al. (26) lateral and vertical contact forces are especially important. The knowledge gained from measurement of wheel-rail forces is allowing for reduction in the stress state of the railway (3).

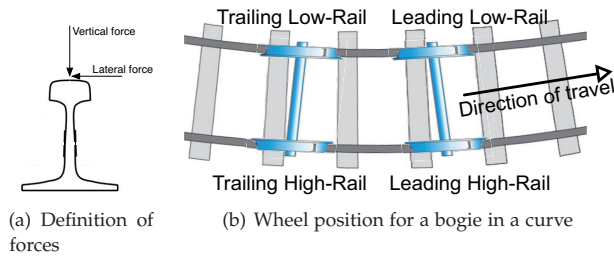


Figure 2.1: Force definition and wheel positions

Research station

The research station outside Luleå is a modified version of a force-based truck performance detector, monitoring the vertical and lateral forces in a single curve with a 484 m radius (24, 33). The measurement system consists of strain gauges attached to the web of the rail, as indicated in Fig. 2.2(a). Fig. 2.2(b) – (c) show how the measurement equipment looks at the site. Mainly iron-ore trains with an axle load of 30 tonnes and a speed of 60 km/h are monitored (24). For more extensive information see Paper A.

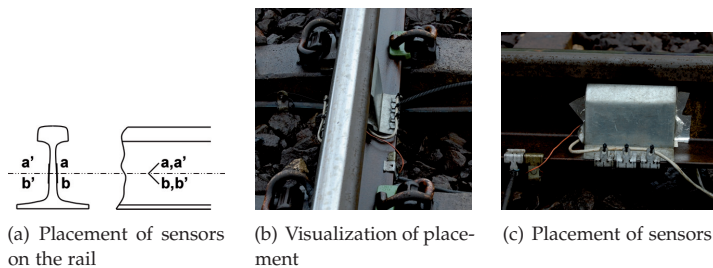


Figure 2.2: All information about the research station

2.1.2 Wheel profile

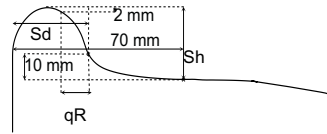
Wheel profile is critical to the railway vehicle's dynamic behaviour, stability and ride comfort; also important are the rate of wear and rolling resistance of the wheel and rail (4, 17). The shape of the profile has a relationship to derailment safety and material strength of heavily worn wheels. Condition monitoring of wheels enables scheduled maintenance of each vehicle.

The MiniProf™ measurement system is used by many railroads to monitor wheel and rail profiles (14). This is one of the most reliable and accurate monitoring systems available. In fact, the results of other wheel profile monitoring systems are often compared to MiniProf to check their accuracy.

MiniProf™ Wheel, see Fig. 2.3(a), has a sensing element consisting of a magnetic wheel which is 12 mm in diameter, attached to the end of two joint extensions. To measure the wheel profile, the MiniProf is magnetically attached to the wheel, as seen in Fig. 2.3(a). The back and top of the wheel are used as the horizontal and the vertical references, respectively (14). The system measures the profile with two degrees of freedom, and a computer calculates the profile in Cartesian coordinates. The resolution is in thousandths of a millimeter. During this calculation the flange thickness (Sd), flange height (Sh), and flange gradient (qR) are also retrieved (see Fig. 2.3(b)).



(a) Picture of MiniProf measurement equipment



(b) Explanation of the different parts of the profile

Figure 2.3: Profile measurement and explanation

Automatic wheel profile monitoring technology uses high speed cameras and lasers to capture the wheel tread profile of each rolling stock wheel as it passes (8, 43). The equipment monitors wheel profiles against a maintenance standard for detection of worn wheels.

2.2 WHEEL-RAIL ROLLING CONTACT AND DETERIORATION

How wheel profiles affect the performance of rail vehicles mainly fall into two main categories. In the first category the safety of the system is related to the wheel profiles. The second category is related to the dynamic performance of the vehicle, for instance vehicle dynamic stability, vehicle-track force levels and ride comfort. (16)

Wheel and rail profiles are designed to meet certain desired properties of conicity, gravitational suspension stiffness and resultant contact stresses (41). The wheel and rail then enter service and change shape over time. The interaction between wheel and rail resulting in material deterioration is a complicated process, involving vehicle-track dynamics, contact mechanics, friction wear and lubrication (11). The course of events called wear is similarly complicated, involving several modes of material deterioration and contact surface alteration (13). Two important deterioration mechanisms are wear and rolling contact fatigue (RCF). Frictional 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 (19). As martensite is much harder and more brittle than the surrounding material, it can break and initiate cracks. In addition, freight car wheels in service may develop tread irregularities in the form of slid-flats, shells or spalls (37). Any of these irregularities can cause high wheel impact forces (37, 39), with slid-flats, also called wheel flats, being the most common.

2.2.1 *Wheel profile wear*

Wear is the loss or displacement of material from a contacting surface (15). Material loss may be in the form of debris. Material displacement may occur by transfer of material from one surface to another by adhesion or by local plastic deformation. In wheel-rail contact, both rolling and sliding occur in the contact zone.

The nature of the shape change in the wheel is a function of the wear and material flow caused by various contact conditions between the two bodies (41). These contact conditions depend on track curvature, vehicle alignment, axle load, vehicle speed, vehicle type, traction and braking. See Fig. 2.4 for a visualization of the different parts of the wheel profile.

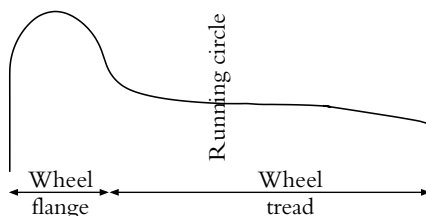


Figure 2.4: Profile parts explained

Most techniques to reduce the wheel profile change are based on limiting the wear, or material removal (16). Wear is not generally a critical failure mode in rolling contact (18).

2.2.2 *Wheel flats*

Wheel flats are formed when a wheel set is locked and skids along the rail (2, 31). The reason for this may be that the brakes are poorly adjusted, frozen or defective. The friction between wheel and rail causes the surface of the wheel to become flat instead of round (39).

2.2.3 *Rolling contact fatigue*

Rolling contact fatigue is the principal mode of failure of rolling surfaces and governs the safe life of a components under a prescribed load (18). Wheel damage occurs as fatigue cracks, initiated at or below the surface, result in material fall-out like shelling or spalling (13).

Shelling is a term normally used for all types of subsurface induced cracks (31). 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 (29). Typically, shelling cracks grow at an acute angle to the surface. Impact load can affect shelling in both crack initiation and crack propagation modes (38).

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 (31). It is associated with cracking induced by high transformation stress caused by surface martensite formation (29). Cracks from spalling form both perpendicular and parallel to the wheel tread surface.

RESEARCH METHODOLOGY

The term "research" has been defined in different ways, but Kumar (20) calls it an intensive and scientific activity undertaken to establish a fact, a theory, a principle or an application.

A research approach can be quantitative or qualitative or a combination of both. In simple terms, quantitative research uses numbers, counts and measures of things, whereas qualitative research adopts questioning and verbal analysis (40). Both qualitative and quantitative research methodologies have been applied in the research presented in this thesis.

3.1 DATA COLLECTION AND ANALYSIS

Data can be defined as classification of facts obtained by researchers from a studied environment (12). Data can also be defined as the empirical evidence or information that scientists carefully collect according to rule or procedures to support or reject theories (30).

For the qualitative information used in this thesis, a literature survey was carried out based on peer-reviewed journal papers, conference proceedings articles, research and technical reports, Licentiate and PhD theses. Quantitative information was obtained from measurements and the databases of the Swedish Meteorological Institute (SMHI), LKAB, the research station, and DUROC Rail. Specific keywords were used to search for information in well-known online databases, including Google Scholar, Elsevier, Science Direct and Emerald etc.

3.1.1 *Wheel data*

In this research railway vehicle wheels have been studied in a bid to optimize maintenance planning of wheel sets. For this purpose manual profile measurements have been performed using MiniProf™ Wheel equipment.

Data on wheel re-profiling have been collected from either the DUROC Rail maintenance workshop in Luleå or from LKAB maintenance database.

3.1.2 *Wheel-rail force data*

Force data from the wheel-rail interface have been collected by the research station outside Luleå. All data from each train passage are

put into separate text files. For each train the axles of that train are broken up into different data types in separate columns.

For this research wheels have been sorted out and merged in order to determine a timeline for lateral and vertical forces.

3.1.3 Weather data

The weather data in this research have been collected either from SMHI or from the research station outside Luleå. For each train passage at the research station, temperature and relative humidity is stored in a database with the time and train data. From SMHI, daily temperature and humidity data were collected between 2000 and 2010 for 13 different weather stations, see Table 3.1. For each day, the daily temperatures, including both the lowest and average and the average humidity were recorded.

The collected temperature data were separated for each station and the temperature factor was calculated using Equation 3.1. Results from this can be seen in Fig. 3.1 and 3.2 and paper C.

$$\text{Temp. factor} = \sum_{1 \text{ Oct.}}^{30 \text{ Apr.}} (T_D - T_L) \text{ for all } (T_D \leq T_L) \quad (3.1)$$

Where: T_D = Daily temp. average, T_L = Temp. limit

Table 3.1: Weather stations used

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

3.1.4 Information from experts

Discussions have been held with various experts to obtain information on explanations of the extracted data. For example, the data from DUROC only contained the numbers of wheel re-profiling and not their causes. The information about their extent is confined to either RCF or wheel wear. It also indicates during which part of the year or train operator affected a particular failure mode. The crack growth, the risk of wheel fracture and the wheel removals due to flange height increases at low temperatures (19, 31, 36).

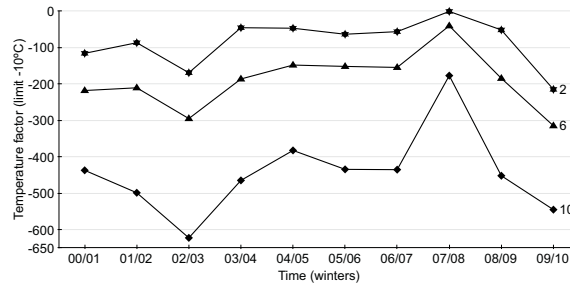


Figure 3.1: An example of temperature factor between 2000 and 2010 for three weather stations, from south to north

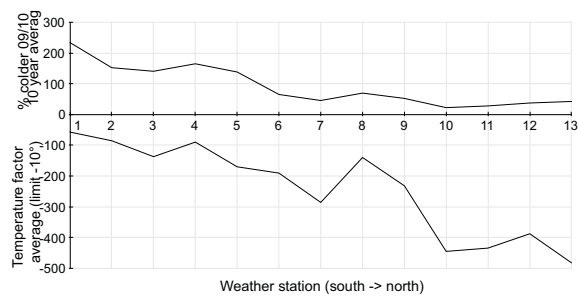


Figure 3.2: Temperature factor for 09/10

EXTENDED ABSTRACT OF APPENDED PAPERS

4.1 PAPER A

TITLE: Condition monitoring of rolling stock using wheel/rail forces
AUTHORS: M. Palo, H. Schunnesson and U. Kumar

Purpose

This paper has two purposes. The first is to present condition monitoring techniques for railway vehicles, so that maintenance of wheels can be optimized, leading to improved life length and minimized cost. One cost-driver in rolling stock is the maintenance of wheels. The second purpose is to present and analyze measurement data from the research station outside Luleå Sweden.

Method

To fulfill the first purpose, a literature survey was done. This survey studied several different methods of condition monitoring for railway vehicles. Two measurement systems are discussed, wheel impact load detectors and truck performance detectors. The research station itself is a modified version of a truck performance detector. It measures forces exerted on the rail by all passing trains at up to 100 km/h in a curve with 484 m radius.

To fulfill the second purpose, a search into all possible data from the research station was done. Vertical and lateral forces, speed, temperature and relative humidity from March 2009 to May 2010 was sorted according to train type. Out of the 20 000 trains that passed through the research station, 600 trains with two specifically marked wagons were studied. The data points for each parameter for these wagons were then analyzed with respect to travel direction of the wagon. The forces were also divided for wheel position in the bogie.

Findings

There are differences in lateral forces between leading and trailing axles and between the wheels of an axle. This give a clear indication that each position has to be considered separately. There are also differences when changing direction of the wagon. To be able to collect data for both left and right turns for a bogie, there is a need for a second measurement station.

The measurement system at the research station can be seen as a robust system because the forces from leading high-rail are within the limit of variation. Seasonal changes seem to have no influence.

4.2 PAPER B

TITLE: Condition monitoring of wheel wear on iron ore wagons

AUTHORS: M. Palo and H. Schunnesson

Purpose

The purpose of this paper is to present the study performed during 15 months on two LKAB iron-ore wagons. The purpose of the study was to improve the condition monitoring of the wheels on these wagons. The data from the research station used in paper A are also part of this paper.

Method

The literature survey in this paper focuses on inspection and non-contact condition monitoring with respect to wheel condition.

The wheel/rail forces have been gathered according to wheel position and vertical or lateral forces. There is also a calculation on the lateral over vertical, L/V ratio, to see how prone the wheels are to climb over the rail.

The wheel profile condition monitoring equipment is presented and a short description of how the data from measured profiles were calibrated. This profile data for each wheel have been combined with travel distances and temperatures to show the progress of wheel wear.

Findings

The wheel wear is greater at lower temperatures, at -10°C and, in general, five times more wear is observed than at $+25^{\circ}\text{C}$. There is a need to investigate a larger population of wheels to confirm this hypothesis.

The lateral force from the leading low-rail wheel can reach 130 kN, which is alarmingly large. This would correspond to a L/V ratio of 0.9, indicating poor steering.

The L/V ratio is seasonally dependent, but there is a need to investigate all parameters that influence this ratio further to know what parts make large contributions.

4.3 PAPER C

TITLE: Maintainability in extreme seasonal weather conditions

AUTHORS: M. Palo, H. Schunnesson, and P.-O. Larsson-Kräik

Purpose

The purpose of this paper is to investigate the difference of wheel damages during winter conditions in northern Sweden compared to warmer and humid weather.

Method

The literature survey in this paper is focused on wheel deterioration and how cold weather influences it.

Weather data from SMHI have been collected for 13 different weather station. These stations are all close to the railway line from Borlänge in the middle of Sweden to northern Sweden. In order to compare these different geographical positions a temperature factor equation was formed.

Findings

During the colder winters, more wheels need to be re-profiled. This confirms the relationship between cold temperature and wheel surface damage.

Rolling contact fatigue, especially shelling and spalling is the dominant wheel surface damage during the cold. There is a need to investigate how the braking method influences wheel surface damage.

RESULTS AND DISCUSSIONS

In this chapter, the findings of conducted research are discussed and presented according to the stated research questions.

5.1 FIRST RESEARCH QUESTION

RQ₁: What is the best method to collect data from the wheel-rail interface for condition monitoring?

The first research question is answered by the research presented in Papers A and B.

In the interface between wheel and rail, forces are transmitted. These forces are vertical for load, lateral for steering and longitudinal for traction and braking. For condition monitoring, only vertical and lateral are used. There are different measurement systems and sensor types that measure these forces. The wheel impact load detector (WILD) is used in tangent track to measure vertical loads. For lateral forces, there is a need to measure in a curve, and the truck performance detector (TPD) is used for this purpose. The TPD will also measure the vertical load, but its primary aim is to monitor steering performance.

Infrastructure owners will install either system to monitor the vehicles using the track and to keep them in good condition. Vertical impact loads from damaged wheels are especially important. The WILD system was invented to help detect these wheels and inform the wagon owner of the need to replace the wheel. Both systems are good but the TPD is more versatile tool than the WILD that measures the only vertical load in tangent track.

The degradation of wheel and rail over time differs. The wheel will degrade faster than the rail due to the material chosen, and they are easier to change and maintain in proper running condition. A MiniProf™ can be used to monitor either wheel or rail. This data can also be collected using automated monitoring systems either mounted to a vehicle, for rail, or on the track, for wheels. Automated systems are preferred if a large population of wheels is to be monitored.

5.2 SECOND RESEARCH QUESTION

RQ2: How can data collected from the wheel-rail interface be used in maintenance decision-support?

The second research question is answered by the research presented in Papers A and B; however, some important findings are briefly discussed here.

Vertical forces are typically monitored for an impact threshold of 400 kN. When a wheel passes a measurement point with this force, an alarm is sent to the operator and train driver. The wheel has to be checked, and if the damage is severe, the wagon will be parked along the track. Another possibility is to drive it to the maintenance workshop for replacement of the wheel.

In Sweden, lateral forces are not monitored by the infrastructure owner. Therefore, there is no threshold for a wagon trafficking the railway. While certifying a new wagon, there is a limit of 80 kN, and this can be used as a starting threshold to start with.

To prevent flange climb derailment, a ratio between lateral and vertical forces is calculated, L/V ratio. This ratio will tell if a wheel is prone to start climbing over the rail. The friction coefficient is a major factor in this formula, see paper B. Also wheel wear is influenced by the wheel-rail contact angle. A project to assess the wheel-rail detectors states that a TPD can indicate poor bogie performance via measured forces and corresponding derived values such as the L/V ratio (27).

The wheel profile has several thresholds which determine when to replace a wheel. Flange height and width are the most common in CM. Flange height progress linear with running distance, see Fig. 5.1. The use of flange height for CM is sufficient a mechanical equipment, if an automated system is used the whole profile should be considered.

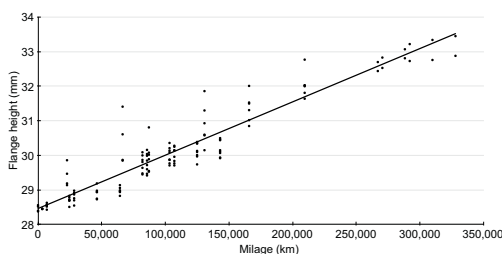


Figure 5.1: Flange height as a function of running distance

5.3 THIRD RESEARCH QUESTION

RQ3: *How do Arctic weather conditions influence the need for railway vehicle maintenance?*

The third research question answered by the research is presented in Papers B and C. Some findings from colder climate will be briefly discussed here.

In Paper B the monthly-average for Gällivare, between 2000 and 2010 was calculated, see Fig. 5.2. The temperature for Luleå is the yearly average of 2°C. This gives an indication of weather and temperature conditions. There is greater wheel wear at lower temperatures. Already at 0°C there is an increase in wheel wear, see Fig. 5.3. Also RCF damages, shelling and spalling, occur more frequently at temperatures below freezing. This indicates a greater need for re-profiling in a cold climate.

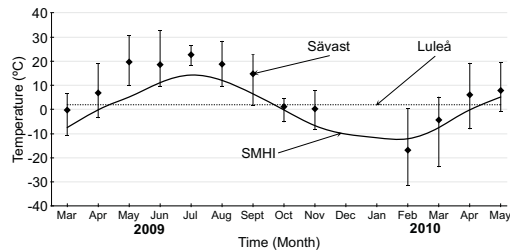


Figure 5.2: Temperature data for Gällivare, Luleå and Research station

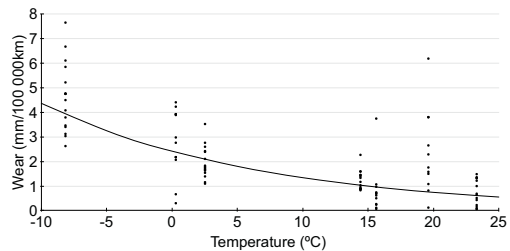


Figure 5.3: Wheel wear at running circle versus temperature

L/V ratio for leading high-rail changes with the seasons has a lower value during the summer, see Fig. 5.4, when there is more moisture in the air and the rail lubrication system is turned on. At such times, the friction coefficient is low, which is indicative of the large influence of friction in the L/V ratio calculation.

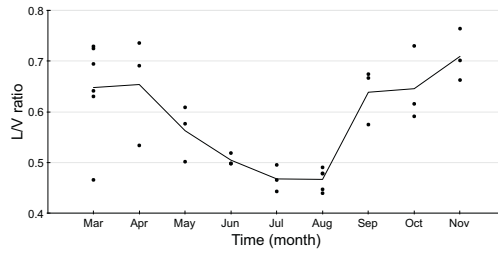


Figure 5.4: L/V ratio on leading high-rail for one wheel during 2009

5.4 FORTH RESEARCH QUESTION

RQ4: How do the different wheel and axle positions influence the maintenance decision?

The fourth research question is answered by the research presented in Papers A and B, and some important findings are briefly discussed here.

There are significant differences in signature between the various wheel and axle positions, see Fig. 5.5 and Fig. 2.1(b) for explanation on positions. This figure shows the number of times each wheel position has passed the research station with a certain force. Leading high-rails (Fig. 5.5(d)) have the forces in a narrow span, while leading low-rails (Fig. 5.5(b)) show the most spread span and have the largest peak force.

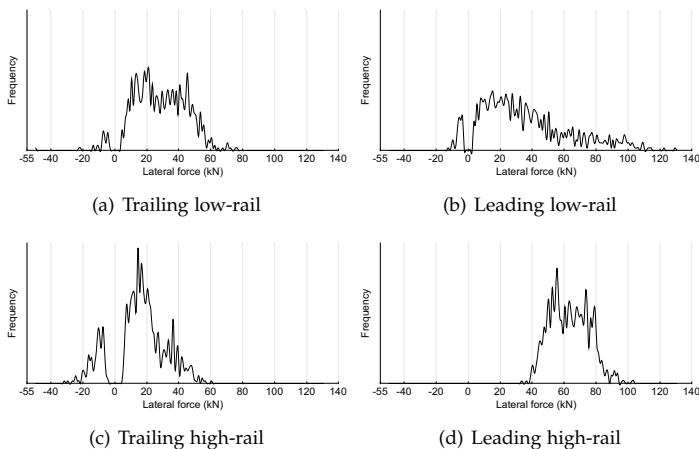


Figure 5.5: All wheels and directions for each position

Fig. 5.6 shows the lateral forces for the leading axle of a specific bogie traveling in one direction. The lateral force for the high-rail

wheel is consistently large as there is no change in travel distance. For the low-rail wheel there is a significant difference in the lateral forces as the wheel travel distance increases.

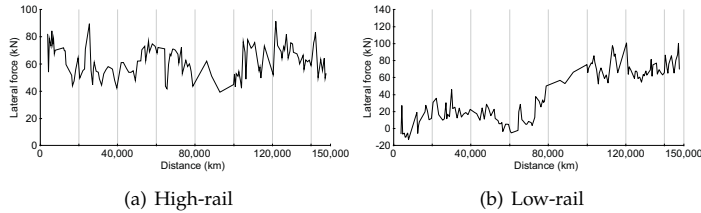
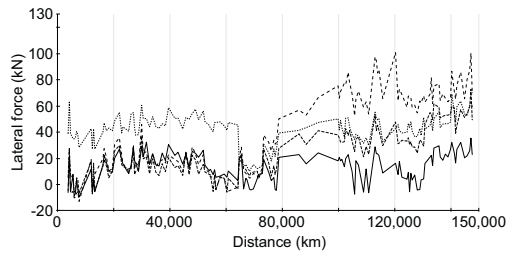
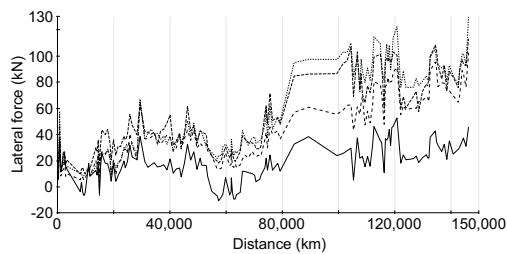


Figure 5.6: One wheel axle as leading in the bogie

During the study, the investigated wagons passed the research station with different wagon ends leading. In Fig. 5.7 the differences in the forces on the leading low-rails are shown as separate graphs. This indicates that the wagon and bogies behave differently depending on which way they travel.



(a) Scenario 1, wagon 43 traveling first



(b) Scenario 2, wagon 44 traveling first

Figure 5.7: Leading low-rail showing changes with direction of travel

In Fig. 5.8 the L/V ratio for all wheels, either high-rail or low-rail, are plotted for each month. The high-rails show a narrower span between the measured values, see Fig. 5.8(a), while the low-rails (Fig. 5.8(b)) are quite spread out. The low-rails also have negative values which are due to the direction of the lateral force. This difference be-

tween rails and wheels indicate a need to separate all data into wheel and axle position, even though the leading high-rail L/V ratio appears to be the best approach to find poor performing wagons. This is also indicated in the literature (27).

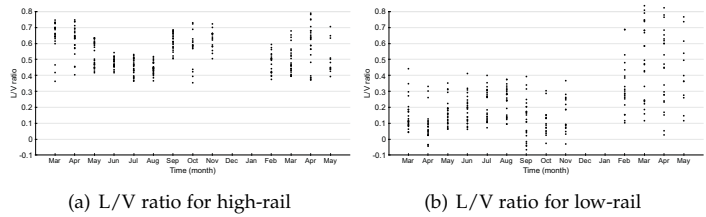


Figure 5.8: L/V ratio for all passing of the wagons

CONCLUSIONS

The following conclusion have been made in this thesis:

In the interface between wheel and rail forces are transmitted. Different measurement systems and sensor types are available to monitor the force and the profiles. There is also a difference between way-side measuring stations and on-board measurement systems. However, an automated condition monitoring system is preferred to sample large quantities of data from either wheel or rail.

The degradation of wheels and rails over time is different due to their material, the contact and the environmental conditions. It is more costly to maintain the rails, and therefore it is essential to know and monitor the condition of the wheels using the track system. This is usually done by using vertical impact force measurements or wheel profile measurements. In this research, the wheel profiles have been monitored using a MiniProfTM. The commonly used threshold of flange height and flange width is a good way to start but when an automated system is used the whole profile should be considered. When the wheel wear of flange height versus the running distance was plotted, it was found to progress linearly, which follows the physical and tribological hypothesis. This shows that flange height is a sufficient failure mode for monitoring while using mechanical equipment.

The research station used to measure the forces the trains is situated in a single curve and cannot measure when the wagon and bogie turn left or right. The difference in left and right turns for passing the station can only be detected when the wagons are turned and the other end travels first. Therefore, the wagons show differences in lateral forces depending on their travel direction while passing the research station.

The measured lateral forces for the wheel position of leading high-rail are consistently large for all wheels independent of travel direction and they indicate no change with the wheel running distance. The lateral over vertical (L/V) ratio for leading high-rail changes with the seasons. During the warmer period, the ratio is lower; this is consistent with the rail lubrication being turned on and more moisture in the air. This demonstrates the large influence of friction coefficient in L/V ratio, also found in Nadal's formula. The L/V ratio from the wheel position of leading high-rail appears to be the best approach to finding poorly performing bogies and wagons.

When the temperature decreases, there is an overall greater wheel tread wear. As the temperatures drop below freezing there is an increase in RCF damages, shelling and spalling. Therefore, there is clearly a greater need for wheel re-profiling in a colder climate.

FUTURE RESEARCH

Based on the research conducted in the thesis, the following ideas are presented as suggestions for further research:

When trying to draw conclusions on wheel profile wear it is useful to be able to draw on automatic measurements. The installation of an automatic wheel profile measuring station outside Luleå will make it possible to investigate a large population of wheel profiles. The conclusions drawn from these measurements will help in the maintenance planning of wheels.

The forces collected at the research station only uses the peak values from when the wheel passes. In the database, the pulses from the entire train, each wheel and sensor separated. One hypothesis is that a normal wheel should have a predictable and smooth pressure profile as it goes over the sensor, a damaged wheel/bogie will have more information in the signal. This information could then be extracted statistically or spectrally.

The research questions in the thesis cover condition monitoring and briefly discuss influences for maintenance decisions. The next step is to start using this monitoring data for maintenance decision and planning.

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Part II

APPENDED PAPERS

M. Palo, H. Schunnesson and U. Kumar "*Condition monitoring of rolling stock using wheel/rail forces,*"

Accepted for publication and presentation in BINDT 2012

Condition monitoring of rolling stock using wheel/rail forces

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Abstract

The efficiency of railway vehicles are due to the low resistance in the contact zone between wheel and rail. In order to keep this efficiency both train operators and infrastructure owners need to keep rails, wheels and vehicles in acceptable condition. Wheel wear affect the dynamic characteristics of vehicles and dynamic force impact on the rail.

The shape of wheel profile affect the performance of railway vehicles in different ways. Wheel condition has historically been managed by identifying and removing wheels from service that exceed an impact threshold. Condition monitoring of railway vehicles are nowadays mainly done with for example wheel impact load detectors and truck performance detectors. These systems use either forces or stress on the rail to interpret the condition.

This paper will show measurements done at the research station outside Luleå in northern Sweden. The station measure the wheel/rail forces, both lateral and vertical, at point of contact in a curve with 484 m radius at speeds up to 100 km/h. Data is analyzed in order to show difference for different wheel positions as well as the robustness of the system.

1 Introduction

Railway use the low resistance of movement between wheel and rail in order to be a energy efficient mode of transport. The most important element in the dynamics of a railway vehicle is the interaction between the wheel and the rail⁽¹⁾. Keeping wheels and vehicles in an acceptable condition is therefore a major concern for both railway operators and infrastructure owners. Wheel impacts on railroad track can cause large damages with an ultimate form being rail break. Apart from affecting the actual rail, dynamic impacts can also degrade and cause premature damage to sub grade of the track. Depending furthermore on the track curvature and the type of bogie design, each wheel/rail system may exhibit significant differences in steering and dynamic stability⁽²⁾.

To evaluate loads generated by wheel/rail interaction, North American railways have adopted the use of detections and condition monitoring technologies⁽³⁾. The technique of placing condition monitoring equipment along the track is referred to as wayside detection⁽⁴⁾. Wayside detectors are mostly used for exception reporting, for example large wheel impact forces from a wheel flat, which is the simplest use of these detectors⁽⁵⁾. A more sophisticated use of wayside detector data is to monitor the changes in forces with time, which in combination with temperatures and wheel position can be used to predict when a threshold condition will be reached.

In a study performed on a metro line only few real-time alarms caused by traditional track force threshold limits was registered⁽⁶⁾. In this case structured condition monitoring

was used in combination with structured maintenance planning. In contrast to that study there are also issues regarding differences in track structure and climate to consider when trying to compare data or information from different track systems or geographical locations. In this paper an analysis of the different wheel/rail force data collected from the research station is done and the robustness of field measurements shown.

2 Condition monitoring of railway vehicles

Condition monitoring aims to record the current (real-time) condition of a system⁽¹⁾. Traditional inspection techniques used in the railroad industry such as drive-by inspection, are not as accurate and reliable as more rigorous and quantitative inspection methods⁽⁷⁾. Wayside detection systems provide a means of monitoring the condition of vehicles, ensuring that they are in a serviceable condition⁽⁴⁾. How track friendly a vehicle is depends not only on its design, speed and axle load, but also on its maintenance condition⁽⁸⁾. It is not uncommon for wheels on both sides of a wheel axle to degrade differently despite having the same axle load and initiating tread defect⁽⁶⁾. Wheel condition has historically been managed by identifying and removing wheels from service that exceed a vertical impact load threshold⁽⁶⁾. These thresholds are typically based on when a wheel/rail impact is presumed to cause sufficient stresses to the track structure.

Force measurement detectors make it possible for vehicles with defective wheels, which are likely to cause damage to the permanent railway structures, to be identified and removed from service immediately⁽⁹⁾. Systems that solely measure the axle load of wheel flats are mostly placed on tangent track with no gradient or a negligible gradient and where trains do not accelerate or brake⁽¹⁰⁾. When measuring the lateral forces, it is an advantage to perform measurements in narrow curves, where the vehicles show their steering ability.

2.1 *Wheel impact load detector*

Increasing concern about damage to track components arising from high impact loads generated by damaged wheels led in 1985 to the installation of the first wheel impact load detector (WILD) on British Rail⁽⁹⁾. The WILD system were originally installed to monitor damaging track forces and obvious benefits are obtained from the early detection of rolling-stock wheel defects.

The installation of WILDs require no radical modification of the existing track structure⁽⁷⁾. WILD sites consist of strain gauges arranged along a 30 foot stretch of track and the strain gauges are welded to the web of the rail⁽¹¹⁾. WILDs have been dependent on for identifying wheels with shells, spall, and out-of-rounds since early 90s and has continued to protect railroads from damaging loads and from derailments due to broken rails⁽⁵⁾. The impact load detecting system also offer the opportunity to define criteria for removal of railway wheels not only based on visual inspection of wheel tread defects but also on the impact loads measured by the detectors⁽¹²⁾.

2.2 *Truck performance detector*

Truck performance detectors (TPD) measure both vertical and lateral forces/stresses when a vehicle passes. TPDs can evaluate bogie performance, vehicle lubrication conditions, prevent derailment, and increase the safety and efficiency of the railway as a whole⁽³⁾. Proper curving of vehicle bogies (trucks) is essential to insure proper system performance⁽¹³⁾. Conventional visual bogie inspection methodology does not and cannot detect all bogie defects that cause poor curving performance.

A typical force-based TPD site is designed for evaluation of three-piece freight wagon bogie and consist of an "S" curve arrangement where two narrow curves are in the opposite direction relative to each other⁽¹⁴⁾. These curves should have a radius between 291 and 436 m. The array consist of eight measurement zones (cribs) of gauge, three in each curve and two in the tangent section⁽¹¹⁾. The TPD layout allows for a thorough evaluation of the bogie's "dynamic" curving performance by checking left and right rotation as well as the bogie's ability to return to a neutral tracking position in the tangent section⁽¹⁵⁾.

2.2.1 Research station outside Luleå, Sweden

In a research station outside Luleå the wheel/rail forces are measured, both lateral and vertical, in a curve with 484 m radius for speeds up to 100 km/h^(10,16). The research station is a simplified version of a TPD, consisting of only one measurement zone. Due to the hostile environment of railroads there is a weather proofing shield on top of the strain gauges, see Fig. 1(a).

The measurement system consist of several strain gauges sensors micro-welded to the web of the rail, as indicated in Fig. 1(b). The measured forces are vertical and lateral, see Fig. 1(c), with positive lateral force outwards in the curve. Lateral forces are the result of a poorly steering bogie and trains with speeds different from the optimal curve speed, but they are also the result of longitudinal buff and draft forces transmitted through train action and coupler angularity⁽¹⁷⁾.

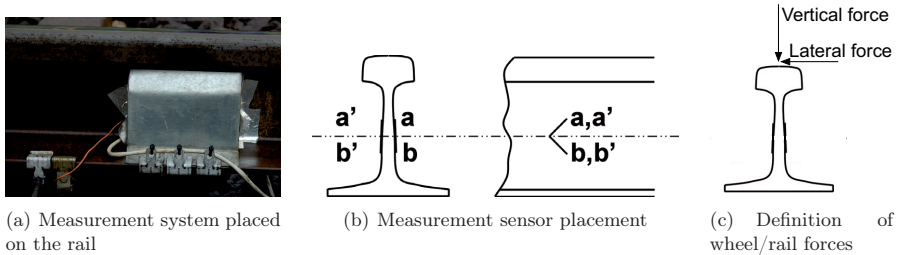


Figure 1: Measurement equipment, sensor placement and force definition

3 Case study description

The only existing heavy haul line in Europe, is called the Iron Ore Line (Malmabanen) and stretches 500 km from Luleå in Sweden to Narvik in Norway, see Fig. 2(a). On the line there is mixed traffic consisting of both passenger and freight trains. The iron-ore freight trains consist of two IORE locomotives accompanied by 68 wagons with a maximum length of 750 meters and a total train weight of 8 500 tonnes, see Fig. 2(b). In 2010 LKAB mining company transported 26 MGT (million gross tonne) from their two mines in Kiruna and Malmberget and 6 MGT out of these were shipped from Luleå harbour. The trains operate in harsh climate conditions, including snow in the winter and extreme temperatures ranging from -40°C to $+25^{\circ}\text{C}$ ⁽¹⁸⁾.

The results presented in this paper are recorded from two iron ore freight wagons with the AMSTED three-piece bogie, designated 43 and 44. The wagons were followed for a period of 15 months, from March 2009 to May 2010. These wagons travel with an average

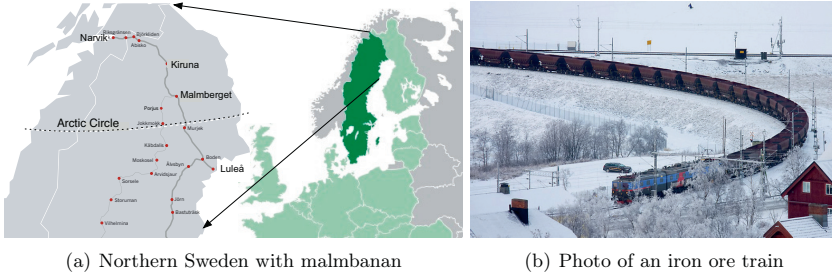


Figure 2: Map of Sweden and an iron ore train

axle load of 30 tonnes and loaded top speed of 60 km/h from Malmberget toward Luleå. During the period the wagons have random positions in the train set from right behind the locomotive to being the two last wagons. The iron-ore trains are closely monitored and all vehicles have RFID-tags for identification and connected to the measurement system.

In Fig. 3(a) is the set up of a wagon with wheel, axle and bogie designation, the two wagons are always connected at the A-end with a steel rod. This means that our two wagons travel as a pair with one wagon having its B-end first and the other the A-end. If they travel in the other direction this is reversed. This present two different scenarios when passing the research station, either 43 or 44 traveling first. In Fig. 3(b) is the designation for the wheels of a bogie when passing the research station.

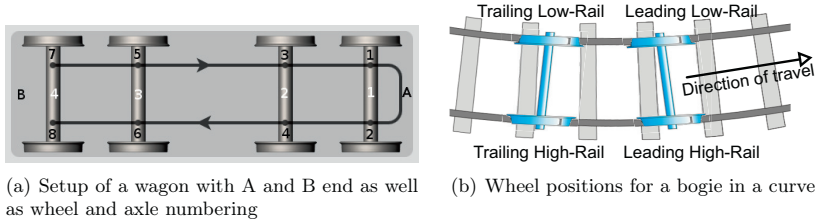


Figure 3: Wagon setup and wheel position when passing the research station

During the project time both speed and vertical load have varied. This variation can be seen in Fig. 4(a)–(b), where train speed are allowed up to 9 km/h over the set limit of 60 km/h. The restrictions of 30 tonnes on vertical load is an average for the whole train set.

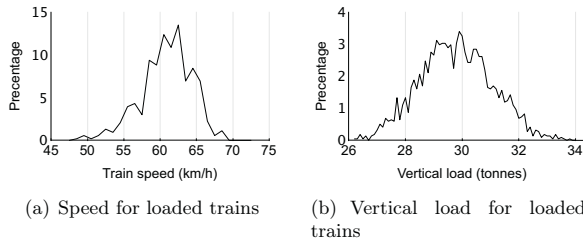


Figure 4: Speed and vertical load

For the test the wheel axles on the two investigated wagons were put together as a mix of new and old, see Fig. 5(b). This was done in order to collect data for a full wheel life cycle, between wheel turnings (re-profiling). During the project, two axles had to be exchanged for new due to wheel damage. In Fig. 5(a) the monthly average temperature for Gällivare and the average, max and min temperature from the research station is shown.

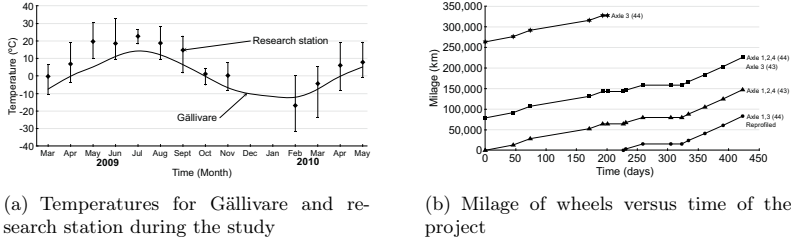


Figure 5: Temperatures and wheel milage

During two periods the wagons were stationary in the maintenance workshop, at 64 000 km or day 193 and 80 000 km or day 259, see Fig. 5(b). The first one was due to wheel damage and the second due to bogie revision and inspection. During the revision measurement of draft sills was made as well as inspection of center bowl liners in the bogie.

Between 80 and 100 000 km there are fewer force measurements due to malfunction in RFID-tag reading between wagons and research station. This was during the months of February and March in 2010.

4 Result and discussion

4.1 Lateral forces for different positions in bogie

The four different wheel positions of the bogie (see Fig. 3(b)) show difference in signature of lateral forces. The leading axle is the first of the two to negotiate the curve and therefore usually have larger lateral forces. The trailing axle follows along and thus have lower lateral forces. In Fig. 6 data from one bogie (43A) traveling loaded toward Luleå when it is the leading bogie of the wagon is shown. The x-axis show the distance the wheel has run since new almost 150 000 km.

Table 1: Average for graphs in Fig. 6 in kN

Fig. 6	(a)	(b)	(c)	(d)
\bar{x}	10.9	18.2	19.3	65.1

Leading high-rail continuously show large lateral forces. This is expected since it is the first wheel of the bogie and wagon to steer through the curve. In Table 1 the average values of each wheel in Fig. 6 is given. The wheels on the high-rail (Fig. 6(c) and (d)) have the largest average values on the bogie. Which is expected since they steer the wagon. Both wheels of the leading axle (Fig. 6(b) and (d)) have larger average values than the trailing axle Fig. 6(a) and (c).

Another interesting parameter is the trend line in Fig. 6. In Fig. 6(a)–(c) there are increasing trends while (d) is steady or decrease. This indicates that there can be a relationship between running distance and lateral forces for all wheel positions except

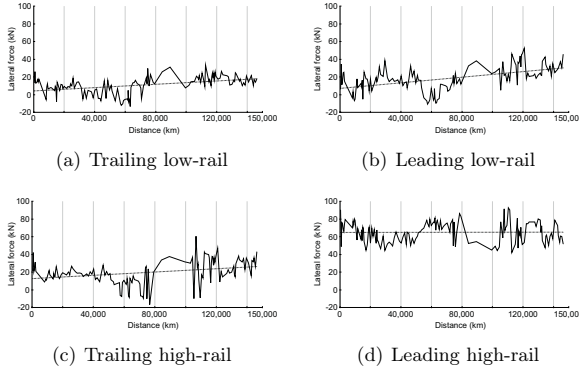


Figure 6: Lateral forces from all wheel position in a bogie for 150 000 km of travel distance

leading high-rail, this clearly highlight that in order to evaluate lateral forces versus running distance the position in the bogie have to be known.

4.2 Robustness of field measurements

Looking at the measurements in Fig. 6 there is a question about the lateral forces that the passing wheels generate from time to time even if the wear of these wheels are approximately the same. There are several possible reasons for these variations such as placement in the train, friction coefficient, temperature, humidity, and bogie configuration. However in the project all of these factors have been monitored and present no explanation to the variation in lateral forces. To find more accurately how the lateral forces compare between measurements the leading high-rail wheel for all four studied bogies have been collected while traveling loaded towards Luleå and always with the same positions of the wheels (wagon 43 first). In Fig. 7 the data from these four wheels have been plotted for the maximum and minimum values.

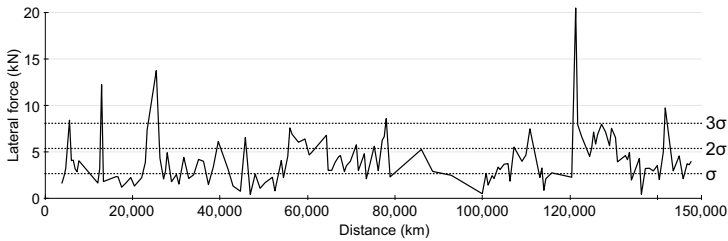


Figure 7: Standard deviation plot for lateral forces on leading high-rail

In Fig. 7 it is possible to see how these four wheels follow each other, even when two axles of one wagon had to be changed for new re-profiled wheels at 64 000 km, C and D from Table 2. The pattern of the peak forces on these wheels are very similar for each passage and they follow each other well between passages. However neither of these wheels are always largest or smallest. There small variations might be from the dynamic force additive, friction coefficient, bogie condition and configuration, or from speed changes.

Some parameters that might change the friction coefficient are water, surface roughness, vertical load, dust or metal particles.

Table 2: Max, min, average forces in kN and wheel starting km for Fig. 7

Fig. 7	A	B	C	D
\bar{x}	63.5	62.4	63.3	60.8
Max	93.6	91.5	93.0	93.6
Min	40.3	39.3	39.6	38.7
Starting km	0	0	78 700	263 580

In Table 2 the average, max and min for the graphs in Fig. 7 have been calculated in order to distinguish any differences of similarities. The variation for these four wheels and all measurements are $\sigma = 2.7$ kN. From the graphs in Fig. 7 and Table 2, it can be seen that these four wheels follow the forces of each other well. Even if D in Table 2 have slightly lower average. One explanation for this behaviour is that this wheel was changed for a new one during the study. From Fig. 7 and Table 2 it is apparent that the forces are not much different for these wheels even if they have different running distances. A new wheel have similar forces to one that has run 140 000 km. The data for these four wheels are consistently similar, during 15 months, for each time of measurement even if they can differ greatly between one measurement and the next. This would indicate that the measurement system have a good repeatability for use on prolonged series of measurements.

The main question is what kind of data is most useful for condition monitoring of wheels and bogie.

4.3 Changes in lateral forces due to direction of travel

From the data leading low-rail in proposed to give the most promise for condition monitoring. In Fig. 8(a) and 8(b) below the leading low-rail have been plotted for the two scenarios described earlier, for travel loaded towards Luleå. The first scenario in Fig. 8(a) is when wagon 44 travel first, and the second scenario in Fig. 8(b).

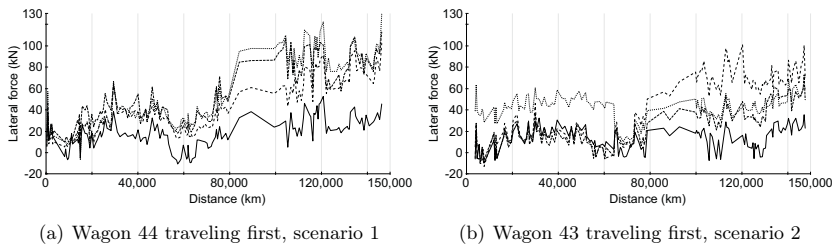


Figure 8: Lateral forces for leading low-rail

There are very different behaviour between the scenarios in Fig. 8(a) and 8(b). From these figures there is a clear assumption that the lateral forces of the a single bogie or wagon may differ dependent on which direction it travels. This indicate that there is a need to measure in two reverse curves (both left and right), to be able to collect both wheels of an axle as leading low-rail for when a bogie travel either as leading or trailing bogie. With this data there should be a better understanding of the condition of wheels and bogie.

From the data collected for 15 months there is no clear indication that weather or seasonal changes influence the lateral force for this wheel position. Otherwise there should be similar magnitude of forces in the beginning as well as the end of the study.

5 Conclusions

The four different wheel positions in a bogie show significantly different force signatures. The leading high-rail have high forces unaffected by the change in running distance, while the three other increase over the distance.

The measurement system at the research station have shown to be robust. During the 15 months of measuring most collected data point for the leading high-rail, for the scenario when wagon 43 travel first, are within 3σ , the limit of variation. The mix of wheels, some starting at 0 km and other at 78 700 km seems to have no or very small influences on the lateral forces on the leading high-rail.

Directional changes of the wagon, from turning around at loading or unloading, show distinctive differences in lateral forces for leading low-rail with running distance. This might be due to the fact that the dynamics of the wagon is little different, from wear, at turning left or right. In order to collect all possible data in one run there is a need for a second measurement point in a reverse curve with the same radius.

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Condition monitoring of wheel wear on iron ore cars

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Abstract

Keeping wheel profiles in an acceptable condition is a major concern for both railway operators and infrastructure owners. The condition of the wheels influences both their wear and the required rail maintenance. Wheel wear affects the dynamic characteristics of vehicles and the dynamic force impact on the rail and, in a worst case scenario, can cause derailment.

This paper studies the correlation of wear rate and wheel force to temperature and seasonal differences, monitoring eight identical wheel axles of different ages for a full life cycle. The study notes differences in wheel wear and wheel/rail forces while operating with a 30 ton axle load and in temperatures ranging from -30°C to $+30^{\circ}\text{C}$. It measures speed, vertical and lateral forces for every train passage and calculates the lateral-to-vertical force ratio at a research station near Luleå, Sweden.

The study concludes that wheel wear is significantly greater at lower temperatures. The magnitude and variation of lateral forces are strongly dependent on the bogie position, with the highest peak value recorded for the leading low rail. The L/V ratio is strongly seasonally dependent with large differences within a month due to changes in friction.

Keywords

Condition Monitoring, Railway, MiniProf, Wheel Wear, L/V ratio, TPD

1 INTRODUCTION

Keeping wheel profiles in an acceptable condition is a major concern for both railway operators and infrastructure owners. For one thing, the dynamic behavior of the vehicle is highly dependent on the shape of the wheel profile. For another, wheel conditions are related to derailment safety. In addition, a significant percentage of vehicle maintenance cost is allocated to wheel maintenance.

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 [2]. Rolling contact fatigue in railway wheels is increasingly important [3]. Even small failures or early cracks are costly, requiring maintenance and possibly causing delays.

To reduce cost and achieve a wheel's maximum life span, maintenance practices must be based on its condition. According to simulations performed by Braghin et al. [4], re-profiling wheels after 200 000km of service would nearly double their service life, thus minimizing life cycle costs. The ability to eliminate non-optimally performing equipment through the use of wayside detectors can translate directly into enhanced operations safety, improved asset life cycle costs, and increased operating efficiency through fewer unscheduled service disruptions [5]. Applying condition-based maintenance requires selecting a proper condition monitoring system, a database for collecting condition data, and an appropriate data analyzing process to make maintenance decisions from condition data.

One of the most difficult aspects of a condition-based maintenance strategy is making good maintenance decisions based on the available condition data. In this paper, we use the correlation of wear rate to temperature, wheel position within the bogie, and track force to pinpoint a cost-effective wheel maintenance interval.

1.1 Inspection and non-contact condition monitoring

An important goal of predictive monitoring is to prevent failure through the early, reliable, and cost-effective detection of faults in rolling stock [6], including the discovery of early cracks [3]. Traditional inspection techniques used in the railroad industry, such as drive-by inspections, are not as accurate and reliable as more rigorous and quantitative inspection methods [7]. For example, condition monitoring uses some level of knowledge of the system of interest to establish its current condition [8]. To this end, the railway industry uses wayside detection [9], a technique of detecting specific faults on rolling stock by interrogating sensors placed along the sides of tracks. This non-contact method can be used on trains travelling at track speed. It provides direct feedback to both operators and track owners on the condition of vehicles passing a wayside monitoring station. A survey mentioned by Stone et al. [10] notes that impact load detectors are effective tools for monitoring high impact load-producing wheels. There is also evidence that in-train inspections procedures are not as effective as shop inspections of the identified wheels.

There are several different methods of detecting dynamic force impact on the rail track. The two most commonly used are strain- and accelerometer-based systems. Accelerometer-based systems measure the motion of the rail resulting from the dynamic load of a passing wheel [9]. Strain-based systems measure the bending of the rail, as it is a direct measure of the applied load on the railhead. There are limitations to both methods. The registered acceleration method does not give a quantitative measure of the size of the impact load [11]. The strain-based system can have difficulty covering the combined circumference of all wheel diameters if not extended by sensors covering at least 3m of the track [12]. High-impact wheels have an impact force of 400 kN or greater; most often they have a flat spot on the tread surface [7]. Major defects in the tread surface can also cause high-impact force; these have a higher probability of leading to catastrophic failure.

2 CASE STUDY BACKGROUND

The iron ore line in northern Sweden starts in Luleå and ends in Narvik, Norway (see Figure 1). It is trafficked by both passenger and freight trains. The freight consists primarily of heavy haul trains with axle loads from 22.5 tons. The train operates in harsh climate conditions, including snow in winter and extreme temperatures ranging from -40°C to $+25^{\circ}\text{C}$ [13].

We studied two iron ore freight cars with a total of eight axles or wheel sets. These two cars are always connected by a steel rod when in use. Figure 2 shows their wheel and axle designations; the cars are connected at the A-end. Technical specifications appear in Table 1.

In order to calculate the wear trend, we made measurements with a MiniProTM for a period of 15 months, from March 2009 to May 2010. We obtained the trends of track forces for the two cars from the research station at Luleå, Sweden, for the same period.

Table 1. Technical specifications for investigated iron ore cars

Maximum speed (loaded)	60 km/h
Wheel diameter (max)	915 mm
Wheel diameter (min)	857 mm
Axle load	30 ton
Bogie	AMSTED three-piece
Wheel profile	UNO wp4

The cars in the case study use three-piece bogies, so called because each comprises one bolster and two side frames. The bogie suspension system has non-linear frictional characteristics. Efficient track twist performance without losing vertical wheel load is an advantage of this structure [14]. At the present time, bogie maintenance is based on travelled distance [12]. A computerized maintenance planning system uses RFID on the cars and wayside antennas on the route to make these calculations. Based on its determination of total mileage, the system can generate lists of cars ready for overhaul. Daily manual inspection at the rail yard complements the system by identifying cars not able to operate until the next service based on mileage.



Figure 1. The iron ore line from Luleå to Narvik

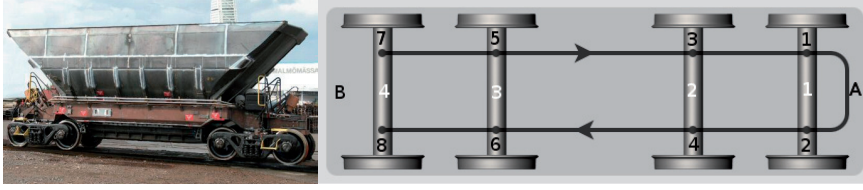


Figure 2. Iron ore train car and designation of wheels and axles

3 MEASUREMENT SYSTEMS

3.1 MiniProf™

The measurement system MiniProf™ is used by many railroads to monitor wheel and rail profiles [15]. MiniProf™ is one of the most reliable and accurate monitoring systems. In fact, the results of other wheel profile monitoring systems are often compared to MiniProf™ to check their accuracy.

The MiniProf™ Wheel (see Figure 4a) has a sensing element consisting of a magnetic wheel of 12 mm attached to the end of two joint extensions. It measures the profile with two degree of freedom, and a computer calculates the profile in Cartesian coordinates. The resolution is in thousands of millimeters. During this

calculation it also retrieves the flange thickness (S_d), flange height (S_h), and flange gradient (qR) (see Figure 4b).

To measure the wheel profile, the MiniProf™ is magnetically attached to the wheel. The back and top of the wheel are used as horizontal and vertical references respectively [15]. Even given the high accuracy of the instrument itself, there can be inaccuracies in measurement procedures, such as dirt or physical inaccuracies at the back of the wheel. Therefore, a calibration must be done to compare measurements at different times. We used a two-point calibration, beginning with a vertical adjustment to the top point of the flange, followed by a horizontal adjustment based on the inclined part of the backside of the flange. Figure 3 shows the procedure.

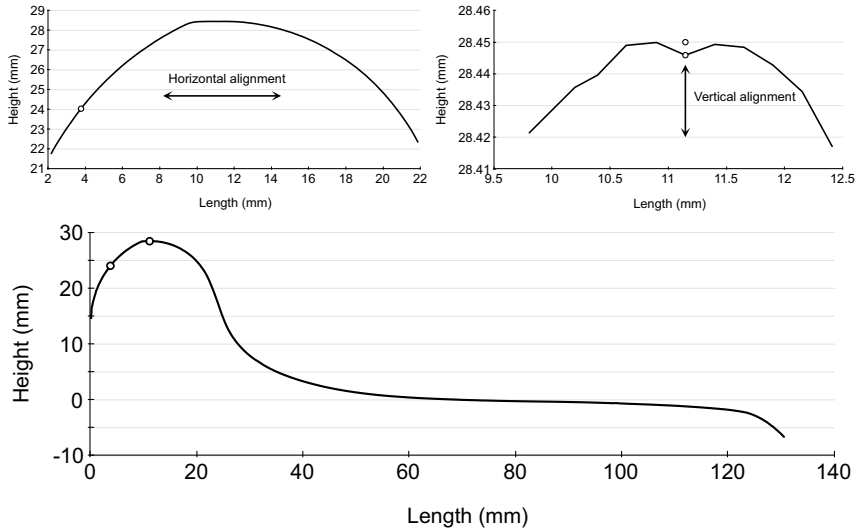


Figure 3. Alignment of profiles between different measurements

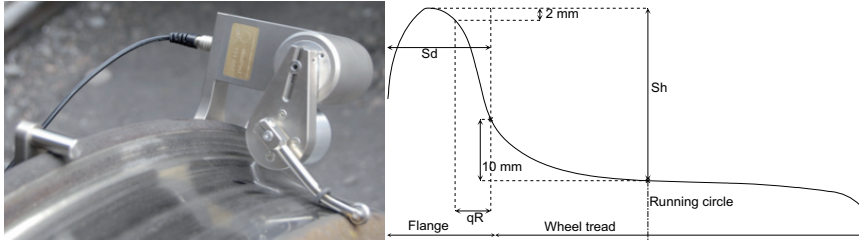


Figure 4. Picture of MiniProf™ Wheel measurement system and an explanation of Sh , Sd and qR calculation

3.2 Research station at Luleå

The optimal Truck Performance Detector (TPD) layout allows a thorough evaluation of the bogie's "dynamic" curving performance by checking left and right rotation as well as the bogie's ability to return to a neutral tracking position in the tangent section [5]. The TPD measures wheel/rail forces *via* strain gauge sensors on the rails in selected reverse curves, with a modified version installed in a single-curve load station [16]. The system measures the lateral and vertical forces produced by each wheel set as it negotiates the curve where the detector is located [17]. A TPD can indicate poor bogie performance *via* measured forces, angle of attack, and corresponding derived values as lateral-to-vertical (L/V) force ratios [16]. The strain gauges quantify the force applied to the rail through a mathematical relationship between the applied load and the strain on the rail web or rail foot.

The research station is a modified TPD station, monitoring forces for all passing trains situated on a curve with a radius of 484m. The measurement system consists of strain gauges attached to the web of the rail as indicated in Figure 5. Figures 5a-b show how the system is attached to the rail.

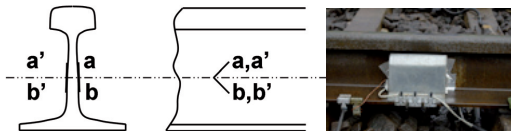


Figure 5. Picture of measurement system placement at the research station

4 RESULT

To monitor wheel wear for a full life cycle, we selected eight identical wheel axles of varying

ages. However, during the project period, two axles had to be changed for newly turned wheels due to the detection of high-impact loads. Figure 6 shows the age of the eight wheel axles and their progression throughout the study. As seen in the figure, we included a service life from 0 to almost 350000 km in the project

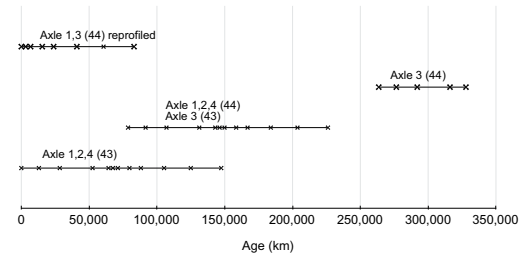


Figure 6. Age distribution of studied wheels

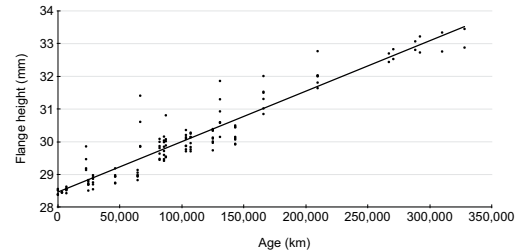


Figure 7. Flange height versus age

The profile statuses of the wheel are characterized by flange and tread wear and are quantified by the flange thickness and flange height [18]. The flange height is calculated as the difference between the running circle and flange top. Figure 7 shows the flange height changes with age for all wheel axles. The wear rate in the same figure shows a clear linear trend with increasing service life. While this agrees with the findings of Wilson et al. [19], their results [19] showed a lower slope. This could be due to differences in the vehicle/track system and/or the climate.

4.1 Wheel wear and temperature

The yearly average temperature for Luleå is $+2^{\circ}\text{C}$. In Figure 8, a monthly average is calculated for the period 2000 to 2010 and appears as the long curved line. Each time the cars pass the research station outside Luleå the temperature is measured. In Figure 8, this is shown as a maximum, minimum, and mean for each month. As shown in the figure, the temperatures are below zero for a long time each year; on some days, they fall below -30°C . It should be noted that in December 2009 and January 2010, the cars were standing still for maintenance.

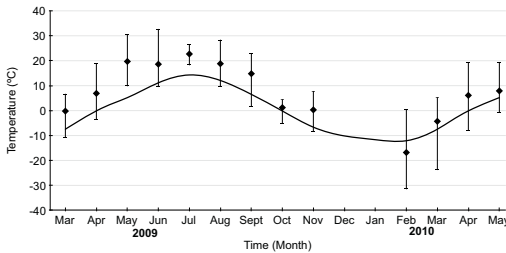


Figure 8. 10-year monthly average and temperatures for each passing of research station

In its depiction of wheel/rail dynamics, the linear trend for flange height in Figure 7 shows some of the complexity of railway systems. In this study, another dimension was also important: namely, the climate differences between summer and winter. According to a study by Kalsousek et al. [20], between 1982 and 1994 there was a two- to five-fold variation in wheels removed, with a large increase in winter wheel removals due to high wheel flanges. This indicates that tread wear rates must be many times higher in winter than in summer. In Figure 9, wheel wear is plotted against the average temperature between two profile measurements. The calculated wheel wear is in mm per 100 000 km travelled distance.

As Figure 9 makes apparent, there is increased tread wear during the colder periods of the year. Most years, snow is present from November to April on large sections of the investigated track. Snow crystals on the wheel tread melt during braking, ensuring that a water-oxide slurry is present on the wheel surface for a prolonged

time [20]. In wet conditions, the slurry will contribute to increased wheel tread wear.

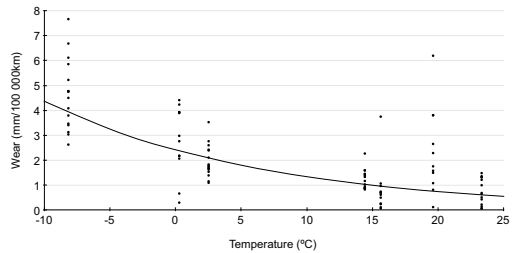


Figure 9. Wear at running circle in mm/100 000 km compared to temperature

4.2 Wheel/rail forces

The research station outside Luleå measures the vertical and lateral forces of all passing trains, as well as their angle-of-attack and speed. Because of the high axle loads, train speed for a loaded iron ore train is restricted to 60 km/h with an allowed 9 km/h extra until the system engages the brakes. Each axle is permitted a 30 ton average vertical load for the whole train. As seen in Figure 10, the trains are within their allowed 9 km/h, and the vertical loads are centered at the targeted 30 ton.

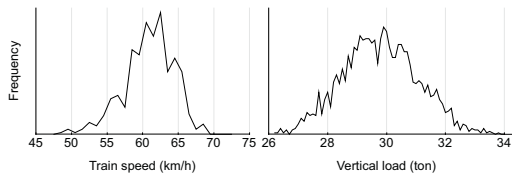


Figure 10. Frequency of speed and vertical load for loaded trains

The lateral force on the wheel set includes the gravitational force created because the plane of contact is not parallel to the track level [21]. The wheel set vertical load thus applies a lateral component of force to the rail, and this is picked up by the wheel set. The lateral forces measured are defined as positive towards the curve center. Figure 11 contains the frequency graph for the lateral force of each wheel position in the bogie.

As seen in Figure 11, the lateral forces for the leading axle are larger than those for the trailing axle. Studies by Wu and Robeda [22] and Elkins and Eickhoff [23] show a difference in lateral forces between leading and trailing axles as well

as between the high and low rail. The leading axle in Figure 11 shows a clear difference between the high and low rail. Also visible is the fact that the trailing axle creates lower lateral forces, possibly because it runs closer to the radial position [24].

In Figure 11, the leading high rail has forces up to 100 kN. That is expected since as Barbosa notes [25], this is the first wheel into the curve. That the leading low rail has forces from -10 to 130 kN is unexpected, but according to Elkins [26], it can be caused by large angles-of-attack.

4.3 L/V force ratio

Flange climb derailment is the result of combined lateral and vertical wheel/rail interaction forces [27]. Nadal's formula [28] is often used to determine the limit of the L/V ratio and is based on a simple force balance to calculate the ratio before a derailment occurs. If the friction coefficient between wheel and rail is μ and the wheel flange angle is α , as shown in Figure 12, changes in wheel and rail wear will influence α . The L/V ratio is given by the following formula:

$$\frac{L}{V} = \frac{\tan \alpha - \mu}{1 + \mu \tan \alpha} \quad (1)$$

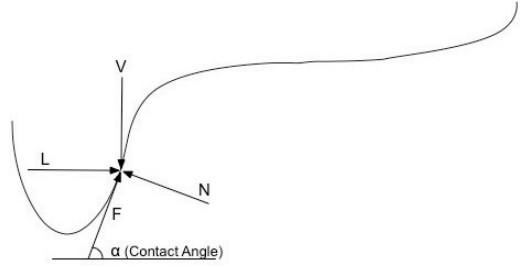


Figure 12. Flange forces at wheel climb

Tests conducted on rail vehicles as well as roller rig laboratory tests have frequently shown L/V ratios in excess of Nadal's limit without derailment [27]. The ratio for the lead outer wheel is indicative of the likelihood of derailment [16, 29], and there is a large curve radius dependency. According to Coe et al. [16], high-rail L/V ratios in the range of 0.3 to 0.4 are indicative of a poorly steering vehicle with a hard flange contact. In a study by Magel et al. [21], high L/V ratios of 0.7 to 0.8 appeared in one to two points per thousand.

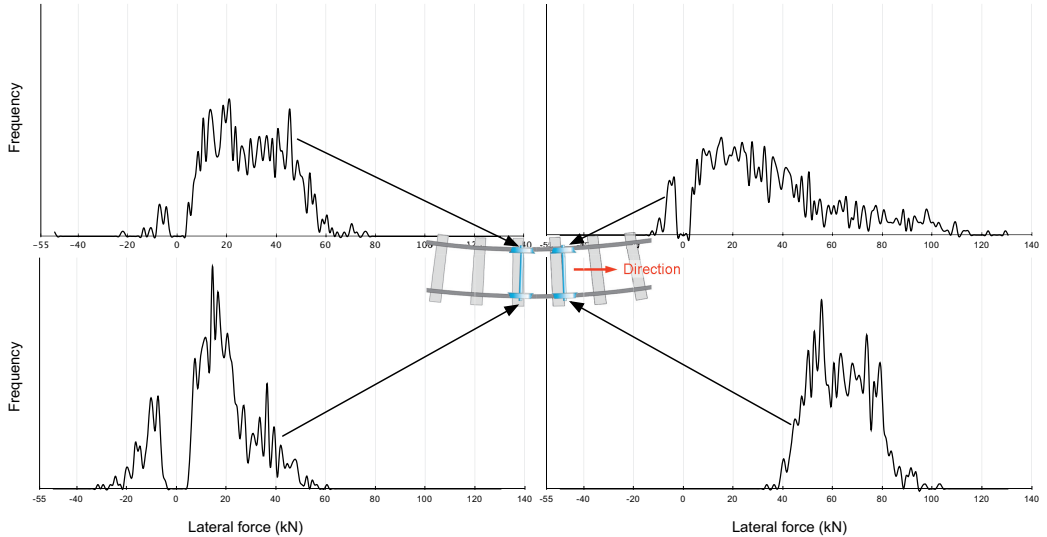


Figure 11. Frequency of lateral forces from different positions within bogie

The vertical forces of the iron ore cars considered in this study are normally distributed with a mean of about 30 ton (see Figure 10). The lateral forces, however, differ significantly between the different wheel positions (see Figure 11). The investigated train cars operate in an area with large temperature variations over the year (see Figure 8). Figure 13 presents the L/V ratios for a year for one wheel when it is on a leading high rail. The figure clearly shows seasonal differences that may affect the wheel's wear conditions.

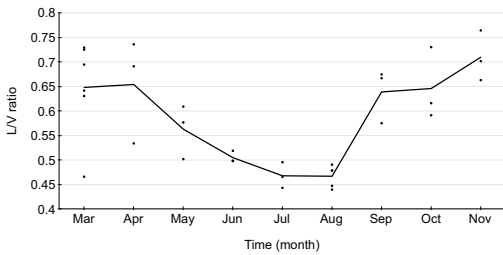


Figure 13. L/V ratio on leading high rail

Changes in the L/V ratio are related to changes in friction between wheel and rail (see formula 1). The friction conditions may vary from adequate adhesion with dry and clean steel-on-steel surface to low adhesion due to contamination, humidity, and applied friction modifiers [18]. Rail lubrication can significantly affect lateral forces when curving [22]. The decreasing trend seen from April to July takes place during a period of mostly dry weather and increasing temperatures. During the warm season, wayside wheel/rail curve lubricators are used. The driver can also use sand if the friction is too low. From August, the temperature starts to drop and the weather changes; hence, the increasing trend.

5 CONCLUSION

From the preceding measurements, we conclude the following:

Wheel wear is greater at lower temperatures, and there is an evident trend. At -10°C there is five times more wear than at $+25^{\circ}\text{C}$. Even for temperatures around 0°C , there is evidence of large differences in wear between different wheels. This makes the issue of wheel wear and temperature extremely intriguing. Further

investigation calls for at least a full year of continuous measurement and a larger population of wheels.

The leading axle in a bogie has larger lateral forces than trailing axles, as mentioned by Wu and Robeda [22], and Elkins and Eickhoff [23]. It is also evident that lateral forces on the high rail are generally higher and have narrower spectra than those on the low rail. The most alarming issue amongst the data is that lateral forces on the leading low-rail can exceed 130 kN. This corresponds to an L/V of 0.9, indicating very poor steering and the possibility of derailment.

The L/V ratio is clearly seasonally dependent. According to Nadal's formula, the L/V is dependent on both μ and α . Since friction changes for each passage, this is an indicator of trend changes and of large differences within a month. Wheel and rail wear change over time, but neither occurs quickly. This issue needs further study on a larger population of wheels.

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Maintainability in Extreme Seasonal Weather Conditions

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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.

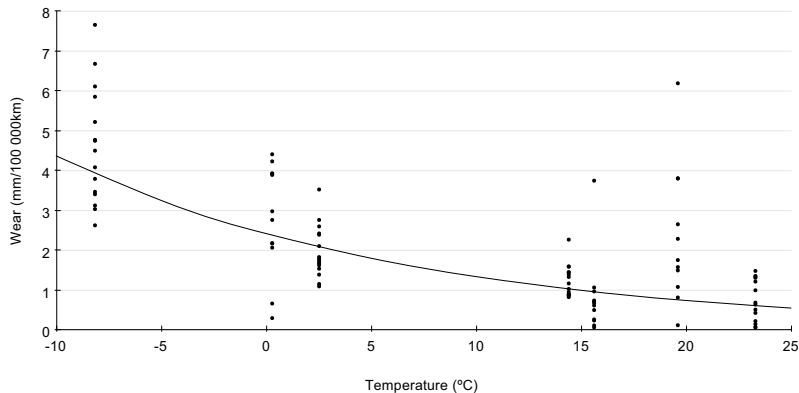


Figure 1. Wear at running circle in mm/100 000 km *versus* temperature

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 $+30^{\circ}\text{C}$ [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

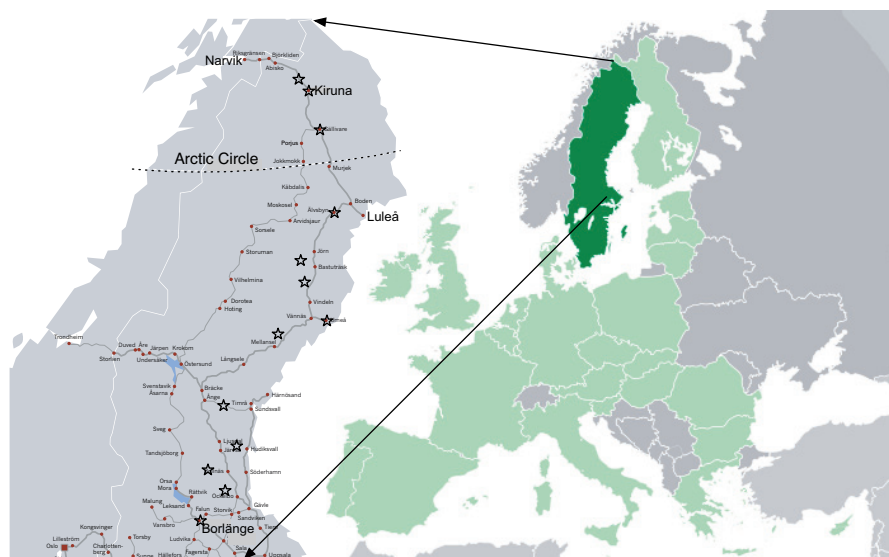


Figure 3. Map of the investigated area, showing the Swedish railroad network with weather stations marked by a star

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 – Ämot	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;

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

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.

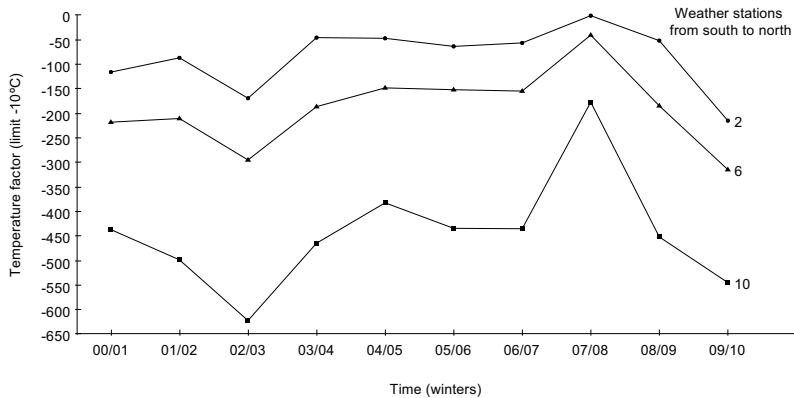


Figure 4. Differences for three weather stations going from the south to north

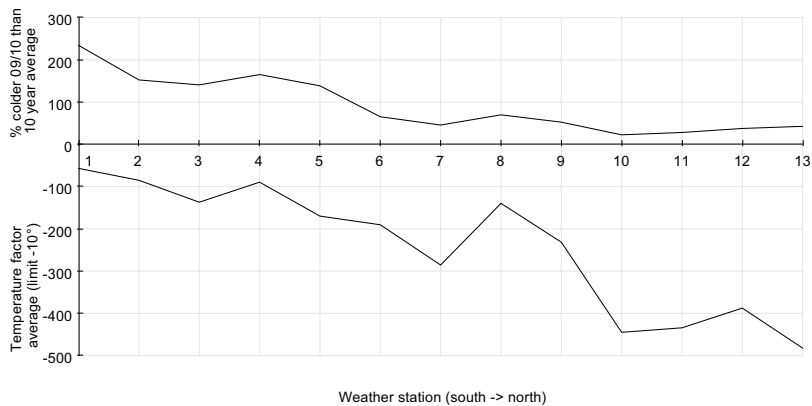


Figure 5. Temperature factor for 2009-10 at -10°C and difference to average

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.

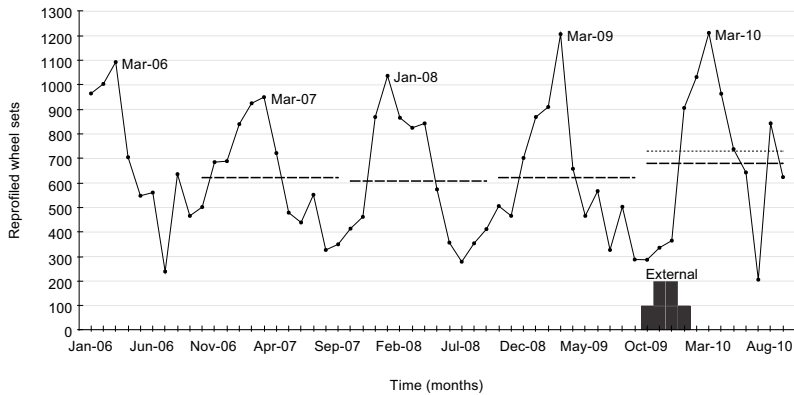


Figure 6. Number of wheels re-profiled per month from January 2006 to September 2010

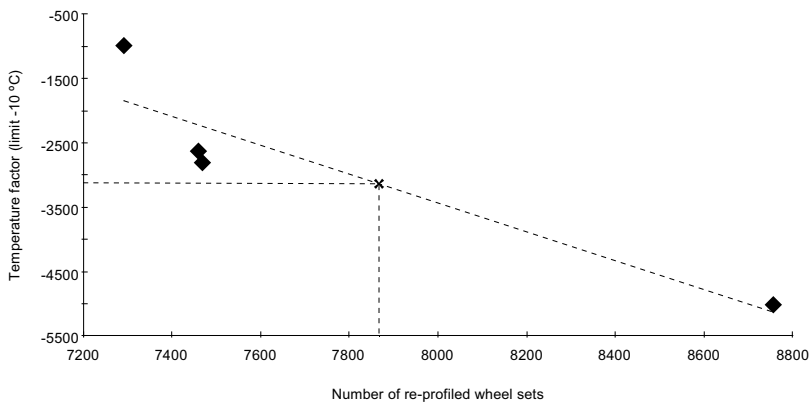


Figure 7. Number of re-profiled wheel sets as a function of degree-days

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

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