LICENTIATE THESIS

Wayside Condition Monitoring Technologies for Railway Systems

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Wayside Condition Monitoring Technologies for Railway Systems

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PREFACE

The research work presented in this Licentiate thesis was carried out between August 2011 and December 2013 at the Sub-division of Operation and Maintenance Engineering, Luleå University of Technology and Luleå Railway Research Center (JVTC). The interest and financial support of Trafikverket (the Swedish Transport Administration) were the means to this end.

I would like to express my gratitude to my supervisor, Professor Uday Kumar, and my co-supervisors, Dr Matti Rantatalo and Professor Per-Olof Larsson-Kråik, who have placed great confidence in my capability to conduct this research work.

I am grateful to Melker Pettersson, Annika Renfors, Dr Arne Nissen, Anders Backman, Lars Wikberg, Professor Peter Söderholm, and other personnel at Trafikverket for supporting this research with their ideas and good advice, and for providing relevant information. Many thanks are due to Dan Larsson at Damill AB for his assistance with a large amount of useful data and information for this research.

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Matthias Asplund
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Luleå, Sweden

ABSTRACT

The railway is an important mode of transport, due to its environmental friendliness, high safety level, and low energy consumption, among other reasons. Railways provide a sustainable means of transporting a large amount of freight and passengers, in a cost-effective and comfortable way. The railway system has a large number of stakeholders and a small improvement in the system will give many advantages, including financial savings and an increase in the quality of service. The Swedish railway network is old and there has been almost no expansion of the network during the past few decades. There is currently a demand for more track capacity and there are no more tracks availably at the network; therefore, the existing network is expected to deliver more capacity.

The railway operators are the largest cause of train delays and wheel failures are one major contributor of the delays caused by operators. The infrastructure manager is the second largest owner of train delays, and a large contributor of their train delays is switches and crossings (S&Cs).

This thesis shows proposals for how condition monitoring technology can be used more efficiently for both the infrastructure and the rolling stock to increase the reliability of their critical items by decreasing train delay.

Firstly, the condition of the wheel-rail interface is important, in that a bad wheel influences the rail and vice versa. The monitoring of rail profiles is already in use, but the monitoring of wheel profiles is still in the development phase. This thesis shows the performance of a wheel profile measurement system (WPMS) for an extreme climate, and a case study of performance measures such as the accuracy and reliability of the system is presented. An additional topic dealt with is how the information from the WPMS can be combined with that from the wheel defect detectors to find early indications of wheels with bad behaviour.

Secondly, the S&C is an essential component of a railway system in that it increases the flexibility by diverting traffic, but S&Cs need adequate support to work properly. A camera-monitoring method for S&Cs is presented which increases the inspection frequency and decreases the human activities on the track and the train delay.

In conclusion, this thesis shows that the WPMS investigated works well with a high level of performance concerning measurement accuracy and reliability in an extreme climate, and that there is still some potential for improving the system. The combination of the WPMS and wheel defect detectors shows that wheels with a high flange height have a higher probability of ending up as wheels suffering from failures. A new maintenance limit for the flange height can reduce the number of wheel defects on the track. Camera-monitoring of the S&C will increase the availability and reliability of this item and even reduce the time on the track required for the maintenance action “check” through fewer inspections and maintenance actions. These proposed monitoring techniques can improve the railway system reliability by reducing the consequential train delay times, by decreasing the number of failures of wheels and S&Cs.

KEYWORDS: Wayside condition monitoring, automatic inspection, health management, railway system, wheel profile measurement system, wheel defect detector, FMEA, switches and crossings (S&Cs), turnouts.

LIST OF APPENDED PAPERS

PAPER I:

Asplund, M., Gustafsson, P., Nordmark, T., Rantatalo, M., Palo, M., Famurewa, M.S., Wandt, K. (2013). “Reliability and measurement accuracy of a condition monitoring system in an extreme climate: a case study of automatic laser scanning for wheel profiles”. Submitted for publication in: *Proceedings of the Institution of Mechanical Engineers. Part F: Journal of Rail and Rapid Transit Special Issue*.

PAPER II:

Asplund, M., Palo, M., Famurewa, S., Rantatalo, M. (2013). “A study of railway wheel profile parameters used as indicators of an increased risk of wheel defects”. Submitted for publication in: *Proceedings of the Institution of Mechanical Engineers. Part F: Journal of Rail and Rapid Transit.*

PAPER III:

Asplund, M., Larsson, D., Rantatalo, M., Nissen, A., Kumar, U. (2013). “Inspection of railway turnouts using cameras”. In: *World Congress on Railway Research (WCRR) Australia, Sidney*.

LIST OF OTHER PAPERS

Asplund, M., Famurewa, M.S., Rantatalo, M. (2014). “Condition monitoring of railway wheels - study of wheel defect pattern and e-maintenance solution for decision support”. Accepted for publication in: *Journal of Quality in Maintenance Engineering (JQME) Special Issue 2014.*

Asplund, M., Famurewa, M.S., Rantatalo, M. (2012). “Prognostic and health management of wheel condition: integration of wheel defect detection and wheel profile monitoring data”. In: *Proceedings of 2nd International Workshop and Congress on eMaintenance.*

Asplund, M., Gustafsson, P., Nordmark, T., Rantatalo, M., Palo, M., Famurewa, M.S., Wandt, K. (2013). “Automatic laser scanning of wheel profiles: condition monitoring to achieve greater capacity for existing infrastructure in an extreme climate”. In: *International Heavy Haul Association Conference, New Delhi.*

Famurewa, M.S., Asplund, M., Galar, D., Kumar, U. (2013). “Implementation of performance based maintenance contracting in railway industries”. In: *International Journal of Systems Assurance Engineering and Management*, 4(3), pp. 231-240.

Famurewa, M.S., Asplund, M., Kumar, U. (2012). “Framework for performance based maintenance contracting”. In: *Nordic Maintworld Congress.*

Famurewa, M.S., Asplund, M., Parida, A., Kumar, U. (2012). “Railway maintenance performance measurement: perspective for improvement”. In: *Proceedings of the 2nd*

Maintenance Performance Measurement and Management Conference (MPMM), 12-13 September, Sunderland, UK.

Famurewa, M.S., Asplund, M., Rantatalo, M., Kumar, U. (2012). “Maintenance improvement: an opportunity for railway infrastructure capacity enhancement”. In: *International Heavy Haul Association Conference, New Delhi.*

Famurewa, M.S., Stenström, C., Asplund, M., Galar, D., Kumar, U. (2013). “Composite indicator for railway infrastructure management”. In: *COMADEM Helsinki*.

Lin, J., Asplund, M. (2014). “Bayesian semi-parametric analysis for locomotive wheel degradation using gamma frailties”. In: *Proceedings of the Institution of Mechanical Engineers. Part F: Journal of Rail and Rapid Transit.* Published in 2014. http://dx.doi.org/10.1177/0954409713508759.

Lin, J., Asplund, M. (2014). “A comparison study for locomotive wheels’ reliability assessment using the Weibull frailty model”. Accepted for publication in: *Eksploatacja i Niezawodnosc - Maintenance and Reliability.*

Lin, J., Asplund, M., Parida, A. (2014). “Reliability analysis for degradation of locomotive wheels using parametric Bayesian approach”. In: *Journal of Quality and Reliability Engineering International. Published in 2014*. DOI: 10.1002/qre.1518.

Lin, J., Asplund, M., Parida, A. (2013). “Bayesian parametric analysis for reliability study of locomotive wheels”. In: *The 59th Annual Reliability and Maintainability Symposium (RAMS® 2013)*, January 28-31, Orlando, FL, USA.

Lin, J., Pulido, J., Asplund, M. (2014). “Analysis for locomotive wheels’ degradation”. Accepted for publication in: *The 60th Annual Reliability and Maintainability Symposium (RAMS® 2014).* January 27-30, Colorado Springs, Colorado, USA. 2014.

Lin, J., Pulido, J., Asplund, M. (2014). “Reliability analysis for locomotive wheels’ degradation: classical and Bayesian semi-parametric approaches”. Will be submitted for publication.

Palo, M., Galar, G., Nordmark, T., Larsson, D., Asplund, M. (2013). “Condition monitoring at wheel/rail interface for decision-making support”. Accepted for publication in: *Proceedings of the Institution of Mechanical Engineers. Part F: Journal of Rail and Rapid Transit Special Issue*.

Palo, M., Galar, G., Nordmark, T., Larsson, D., Asplund, M. (2013). “Wheel/rail condition monitoring to support rolling stock maintenance action”. In: *International Heavy Haul Association Conference, New Delhi.*

DISTRIBUTION OF WORK

Paper I: Matthias Asplund developed the initial idea in discussion with Dr. Matti Rantatalo. The literature review, model development, data collection and analysis were done by Matthias Asplund supported by Dan Larsson. The data analyses and results were discussed with Dr. Matti Rantatalo, Mikael Palo and Stephen Famurewa. The first version of the manuscript was prepared by Matthias Asplund and improved by suggestions and comments from all authors.

Paper II: Matthias Asplund and Dr. Matti Rantatalo developed the initial idea. The literature review was done by Matthias Asplund. Data collection and analysis were done by Matthias Asplund and Mikael Palo. The results were discussed with Dr. Matti Rantatalo, Mikael Palo and Stephen Famurewa. The first version of manuscript was prepared by Matthias Asplund and Dr. Matti Rantatalo, and the manuscript was improved by suggestions and comments from all authors.

Paper III: Matthias Asplund, Dr. Matti Rantatalo and Dan Larsson developed the initial idea. The literature review, model development, data collection and analysis were done by Matthias Asplund. The results were discussed with Dr. Matti Rantatalo and Dan Larsson. The first version of manuscript was prepared by Matthias Asplund and improved by suggestions and comments from all authors. Prof. Uday Kumar provided input for improvement of the manuscript.

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1. INTRODUCTION

Society is at present exerting pressure on the railway industry to make the railway system a safe, attractive, affordable and available mode of transport for freight and passengers. The railway is a transport mode with great competitive power because of its low pollution emission, its environmental friendliness and its sustainable way of transporting large amounts of freight and passengers in a cost-effective and comfortable way. Other advantages are its low energy consumption, owing to its high transport capacity, and its high level of safety (Patra, Kumar & Kraik, 2010). However, the railway system is a system with one degree of freedom, which implies poor flexibility and low redundancy. This is particularly noticeable when a system failure occurs and makes it possible for unwanted events to propagate in other systems and even disturb other traffic. High reliability is a key factor for a stable railway system, but when an abnormal incident occurs, it can take a long time to recover the system.

The railway system has a large number of stakeholders; for instance, the stakeholders of the Swedish railway system comprise the Government (the owner of the track), the infrastructure manager, the maintenance contractors, the passengers, the train operators, the owner of the rolling stock, the freight companies, trade and industry, people living close to the track, and different organisations, e.g. environmental organisations. All of these stakeholders are to some extent making demands on the railway service. Any improvement of the railway system would benefit a large number of people and could even save money for the infrastructure manager and the train operators through a decrease in the disturbances caused by damage, a prolongation of the service life of the infrastructure and vehicles, and an increase in the quality of service (greater punctuality or less delay, greater regularity, reliability, robustness, recovery potential and resilience, less congestion, and greater safety and comfort); for more information on quality of service, see Nyström (2009), CEN (1999) and Söderholm & Norrbin (2011), etc.

The mean annual growth of the Swedish railway traffic from 1960 to 2010 was 1.1%, which can be compared with the values for the mean annual growth, during the same period, for waterborne transports and road traffic, i.e. 0.02% and 3.0%, respectively (Trafikverket, 2012b).

The expected further increase in the transportation of people and goods will make the advantages associated with the railway even more important in the future. Consequently, there will be higher traffic volumes on the railway based on a demand for greater capacity and higher reliability on the track for passenger and freight transportation without jeopardizing safety. Safety is well developed within the railway system (Evans, 2007; Asplund, Famurewa & Rantatalo, 2012), which gives the railway a competitive edge over other transport modes.

1.1. Swedish railway system and requirements

The Swedish railway system consists of 11,176[a] switches and crossings (S&C) and 13,400 km of track (Trafikverket, 2012c).

In the year 2010 the traffic volume of the Swedish railway network was 140 billion train kilometres, which represents an increase of 10.8% from the level of 2006 (Trafikverket, 2011).

The market for passenger and freight traffic in the Swedish network is unregulated. In 2014 there are 46 different companies competing for times on the track, 27 of them for passenger traffic, 13 for freight traffic and six for maintenance of the assets and other track work (Trafikverket, 2013a).

Some of the assets of the Swedish railway network, e.g. some S&Cs, rails, sleepers and ballast, have already exceeded their technical service life. Their high age is increasing the risk of more failures due to acceleration of deterioration. Some assets are at the end of their life and probably do not have any useful remaining life (Trafikverket, 2013b).

For the Swedish railway network, the accumulated train delays caused by the infrastructure were 27,809 h in 2010, 23,760 h in 2011 and 21,655 h in 2012 (Trafikverket, 2013b). Assuming that one delay minute costs the public SEK 1,200 (Arasteh khouy, 2013) for a passenger train and SEK 800[b] for a freight train and that the mix of passenger trains and freight trains is 50/50, then the total cost for these delays is SEK 1.6-1.3 billion for 2010-2012. Reducing the delays by 10% would result in savings of around SEK 100 million each year, only in terms of reduced delay costs.

One measure of the deterioration of the track is the track geometry. Based on track geometry measurements, the track deterioration of the Swedish railway network can be divided into three stages, A, B and C faults. An A fault is less severe than a B fault, and a C fault is the most severe fault. If remedial activities are not performed in time before the C level has been exceeded, faults can cause derailments. The amount of C faults in the Swedish network increased between 2009 and 2010 by 21%, between 2010 and 2011 by 83%[c], and between 2011 and 2012 by 27%. The main reasons for this increase can possibly be linked to a reduction in preventive maintenance and to the fact that many assets have exceeded their technical service life (Trafikverket, 2013b).

The statistics for train delays and the inspection remarks paint different pictures of the status of the track. The amount of delays has decreased in recent years, the trend is good, and fewer and fewer delays are due to failures in the infrastructure. At the same time, the number of

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[a] S&Cs owned by Trafikverket, on mainline tracks 7119 S&Cs, information form BIS (28/01/2014).

[b] Internal value for freight trains, Dr Arne Nissen, UHabv, Trafikverket.

[c] The number of assets included in OPTRAM has increased and this can be a part of this high value.

inspection remarks has increased, indicating that the risk of failures in the future will increase, which will lead to a decrease in the reliability of the assets; there is a risk that the good trend of recent years will be broken. To preserve the same level of reliability as before, the assets need more attention, because otherwise the distribution of train delays can be expected to be higher and the operational capacity lower.

At the highest level of classification, train delays can be divided into six different categories, i.e. delays belonging to the traffic control, delays with no report recorded, delays resulting from secondary causes originating in a previous problem, delays belonging to the infrastructure, delays belonging to the railway operators, and delays resulting from accidents and other causes. The trends show that the train delays have in total been decreasing for the past four years. The largest category of train delays is those belonging to the railway operators, whose trend has been heading towards less delay for each year that passes. Furthermore, except the secondary causes, the second largest category of delays is delays belonging to the infrastructure, whose trend is heading towards smaller decreases in the delay time from year to year. The average number of delay hours/year for each delay category is presented in Figure 1.

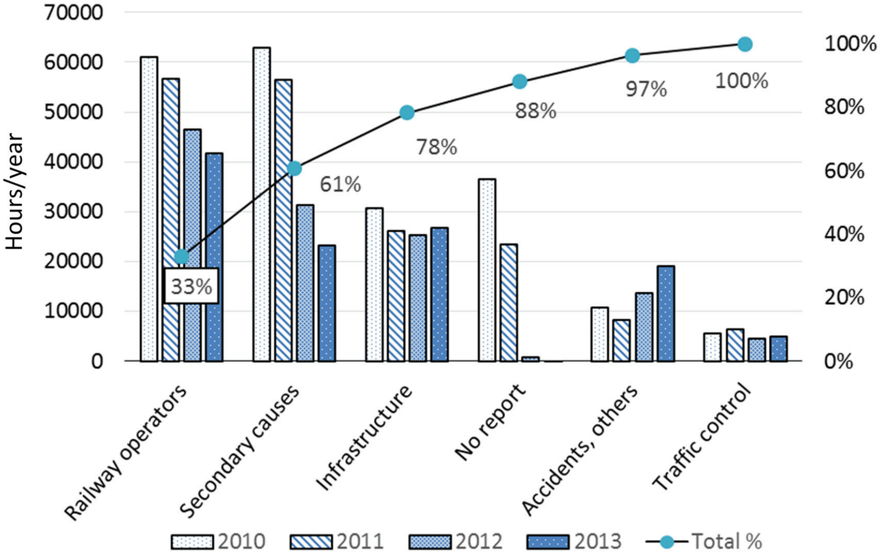

Figure 1: Delay categories for the Swedish network 2010-2013. The Y-scale on the right-hand side is the number of delay hours/year, while that on the left-hand side is the cumulated hours; the X-scale is the delay categories.

Train delays can be broken down further according to the systems causing the delay, e.g. delays caused by track, S&Cs and wheels. The total delay, the delay due to track, the delay due to S&Cs and the delay due to wheels are shown for the first seven months of 2013 in Table 1. This table shows that the winter season has the largest problem with train delays due to S&Cs and wheels; for the first three months, from January to March, S&C problems consumed 1,204 h and wheel problems consumed 1,100 h. During the other months, the delay caused by wheels was much less, but the S&Cs still generated a large amount of delays.

Table 1: Train delays in the Swedish railway network during 2013[d].

TD_f (Train delays due to failures)

Month	Total delays Infrastructure	Delays due to Track	Delays due to S&Cs	Delays due to Wheels
Jan.	3281	912	456	405
Feb.	2115	437	496	248
March	2601	721	252	447
April	1963	419	263	66
May	4145	917	270	6
June	3036	840	138	5
July	2345	415	217	11
Aug.	3003	932	210	11
Sep.	2445	337	159	50
Oct.	2337	225	459	11
Nov.	2677	1163	207	5
Dec.	2140	253	390	21
Total	32088	7571	3517	1286
Mean/month	2674	631	293	107

Using the values for the delay cost from Arasteh khouy (2013), SEK 1,200/min. for passenger trains and SEK 800/min. for freight trains, and assuming that the mix of passenger trains and freight trains is 50/50, the cost for delays caused by S&Cs is SEK 211 million and the cost for delays caused by wheels is SEK 77 million. The cost of remedying primary or secondary failures generated by S&Cs and wheels has not been considered in the calculations, nor has the cost of a shorter operating life due to failures of S&Cs and wheels.

The requirements being placed upon the railway are on many different levels. Examples of requirements placed upon the Swedish railway system are presented below, from the European level down to the route level, together with some statistical predictions.

- The European Commission is demanding that more transports should be shifted from the road to the railway. The goal set for the European transport systems is that 50% of the medium-distance intercity passenger and freight transports should be shifted from the road to the railway and waterborne means of transport by 2050. Furthermore, CO_2 emissions from transports have to be cut by 60% by 2050 (EC, 2011).

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[d] The data for this table come from an internal document of Trafikverket, “Driftrapport järnväg januari-december 2013”, as stated by Leif Lindmark, cUHae, Trafikverket.

- Analyses have shown that the annual freight transport volume on the strategic lines in the Swedish railway network will increase from 18.9 billion tonnes/km (which is the value for the base year 2006) to 27.7 billion tonnes/km in the year 2050 (Trafikverket, 2012b).

- Trafikverket has issued a new requirement stating that the present number of deaths on the track is to be halved by 2020 (Trafikverket, 2012a).

- The yearly predicted growth of the Swedish railway traffic in tonnage up to 2050 has been estimated to be 1% annually, which means an overall growth of 56% from 2006-2050 (Trafikverket, 2012b).

- The Iron Ore Line has the largest predicted traffic increase compared to all the other railway lines in Sweden, with a predicted growth of 136% between 2006 and 2050 due to the expansion of the mining industry in the north of Sweden (Trafikverket, 2012b).

Additional requirements include an increase in axle loads and train speeds (Lichtberger, 2005).

The above-mentioned requirements and statistical predictions have to be taken into consideration by the railway stakeholders, especially by the infrastructure manager.

1.2. Problem statement

To increase the operational capacity of the track, the first step necessary is to address the largest failure-driven capacity consumers and try to minimise them by finding failures at an early stage and reducing them and their effects to a minimum. This is the fastest and most cost-effective way to create more capacity without rebuilding and extending the track. These actions are categorised as step 1 and 2 in the “four-step principle” that the infrastructure manager uses to prioritise activities on the track to gain more available capacity in the short term. Activities in step 1 have the highest priority and those in step 4 are selected when all the other steps are impossible to implement (Trafikverket, 2002).

In addition to the track, there are two other large capacity consumers, namely the wheels and the S&Cs. The wheels are owned by the train operator or by some company that leases wagons to the operator, and the S&Cs are managed by the infrastructure manager. This thesis is focused on the condition monitoring and inspection of wheels and S&Cs to improve the system reliability on the track by decreasing the train delay caused by failures of S&Cs and wheels.

1.3. Purpose and objective

The purpose of the research presented in this thesis has been to increase the operational capacity of the existing Swedish network by improving its reliability through effective and efficient condition monitoring of critical items (for definition of item see CEN 2010).

The research objective has been to investigate the condition monitoring of S&Cs and the wheels to improve the reliability of the railway system. A detailed description of the sub-objectives follows:

- to study systems which can be used for monitoring railway wheel profiles and which are available on the open market, focusing on performance measures such as reliability and measurement accuracy;
- to study how a wheel profile monitoring system (WPMS) can deliver data in a reliable way in the extreme climate of northern Sweden;
- to study how the wheel defect detector (WDD) and the WPMS can be combined to give more information on wheel failures and minimise the failure-driven capacity consumption on the track;
- to study tools and methods needed to define measurement parameters for monitoring S&Cs and investigate the benefits of automatic inspection of S&Cs in terms of capacity gain.

The research questions formulated are presented in Sub-section 1.4, where they are answered briefly through short synopses of the three attached research papers. The research questions are, of course, answered in greater detail in the appended papers.

1.4. Research questions and structure

The research structure is presented in Table 2, and the research questions formulated from the research objective are as follows.

RQ1: How can infrastructure managers monitor railway wheel profiles in an effective way, in order to control the effect of the wheels on the wheel-rail system for different operators?

RQ2: How can the information from the wheel profile measurement system be utilised by the infrastructure manager to enhance the operational capacity through higher reliability of the wheel-rail system?

RQ3: Can an on-line inspection system for S&Cs reduce the capacity-consuming failures in the railway network?

Table 2: Mapping of the appended papers and the research structure.

	Paper I	Paper II	Paper III
RQ 1	x		
RQ 2		x	
RQ 3			x

Paper I: "A case study of a condition monitoring system: reliability and measurement accuracy of automatic laser scanning for wheel profiles in an extreme climate" – This paper describes the performance of the automatic laser scanning system for wheels in use on the

Swedish Iron Ore Line (Malmbanan). The uniqueness of this study consists of its focus on the operation of a wheel condition monitoring system in a harsh and extreme climate. This case study summarises two years of the system's operation and investigates the system reliability and the accuracy and reliability of the measurements.

Paper II: "A study of railway wheel profile parameters used as indicators of an increased risk of wheel defects" – This paper investigates the relations between different wheel parameters already measured by wayside stations (force levels from wheels) and wheel parameters which can be measured by wayside stations (flange width, flange thickness, flange angle and hollow wear). The wheel flange dimension indicates a correlation with high vertical force levels from wheels.

Paper III: "Inspection of railway turnouts using cameras" – This paper describes the feasibility of automatic inspection of S&Cs (or turnouts) using cameras and the advantages to be gained through such inspection. The paper presents a decision support model developed for the implementation of a condition monitoring system for critical items; the model can be used in other railway applications, as well as in other branches of industry. Furthermore, the paper shows a case study of five S&Cs installed close to Stockholm Central Station to which camera-inspection can be applied. The study shows that there are S&Cs which have problems that appear and disappear; this study only considers the maintenance action "check". It has been found that camera-inspection of critical S&Cs can reduce the maintenance delay time and train delays.

1.5. Scope and limitations

The scope of this research is the study of condition monitoring technologies suitable for the monitoring and inspection of critical items in service on the railway, to identify potential failures in advance so that maintenance and other preventive actions can be planned to make the railway robust and reliable. The research has concerned three different system phases, i.e. the mature, the new and the future system.

The research is limited in two ways; firstly, it only deals with one monitoring system for each phase, with one system monitoring the infrastructure and two systems monitoring the rolling stock. Secondly, the research studies only concern two separate line sections, on the one hand the Iron Ore Line, with a high axle load in northern Sweden, and on the other hand a high-density line with respect to passenger train traffic in the south of Sweden, close to Stockholm Central Station. Furthermore, the research studies excluded all organisational and management issues, including planning and scheduling aspects.

1.6. Outline of the thesis

Chapter 1: INTRODUCTION
This chapter explains the background, the problem, the purpose and the objective of the research, the research questions, and the scope and limitations of the research.

Chapter 2: THEORETICAL FRAMEWORK

This chapter shows the theoretical framework for the research, starting with condition monitoring in general and condition monitoring in the Swedish railway network in particular. Then the wheel-rail system is explained briefly and, finally, summary of the literature in this field are presented.

Chapter 3: RESEARCH METHODOLOGY

This chapter deals with the research methodology and the data and information collection, and explains the data sources utilised for the research, as well as the analyses performed.

Chapter 4: RESULTS OF APPENDED PAPERS

This chapter presents the three appended papers, which focus on different condition monitoring technologies.

Chapter 5: DISCUSSION AND CONCLUSION

This chapter explains research contribution, research findings, general observations, recommendations and proposals for future research.

2. THEORETICAL FRAMEWORK

The sources used for the theoretical framework were conference proceedings, journals, international standards, company standards and different documents from the infrastructure manager. All of the literature used could be found through searches in Internet-based online databases containing scientific literature and via search machines on the Internet.

2.1. Condition monitoring in general

Condition monitoring systems can decrease the operational risk, enhance the performance and in the long run contribute to cost reduction. Condition monitoring methods can be categorized into analysis, process monitoring, performance monitoring, functional testing and inspection (Utne, 2012).

The EN-13306 standard describes 14 different types of maintenance policy, one of which is the condition-based maintenance policy. The standard shows a maintenance overview with condition-based maintenance placed under preventive maintenance and comprising scheduled, continuous or requested maintenance actions. The information for requested maintenance actions can come from the condition monitoring system.

Monitoring, inspection and condition-based maintenance can be defined as follows (CEN, 2010).

- **Monitoring:** Activity, performed either manually or automatically, intended to observe the actual state of the item. Monitoring may be continuous, over time interval or after a given numbers of operations. Monitoring is distinguished from inspection in that it is used to evaluate any changes in the parameters of the item with time.

- **Inspection:** Check for conformity by measuring, observing, testing or gauging the relevant characteristics of an item. Generally inspection can be carried out on before, during or after other maintenance activity

- **Condition-based maintenance:** Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions.

Condition-based maintenance (CBM) implies a maintenance that is scheduled and dynamic, depending on the status of the system that is being condition monitored.

The task designed to detect failures is known as condition monitoring, and the general concept of condition monitoring of an item is shown in Figure 2. Here the P-F interval is the warning period, the period between the point at which the onset of failure is detectable and the point of functional failure. If the condition monitoring is performed at intervals longer than the P-F interval, the potential failure may not be detected, and if the condition monitoring is performed at too high a frequency compared to the P-F interval, resources are wasted. It is essential to find the right monitoring interval to match the P-F interval. The length of the P-F interval can vary and the monitoring interval needs to be fixed in such a way that it matches the prevailing condition, for either the shorter or the longer case. The time to monitor and the time to take action should be less than the P-F interval, because otherwise the condition monitoring action will not give any benefit (American Bureau of Shipping, 2004). The monitoring interval has to be selected in consideration of the cost and risk; the cost often increases with a higher monitoring frequency and the risk increases with a lower monitoring frequency (Zio, 2009). In this connection it is important to find the right balance and have a holistic approach to condition monitoring and maintenance.

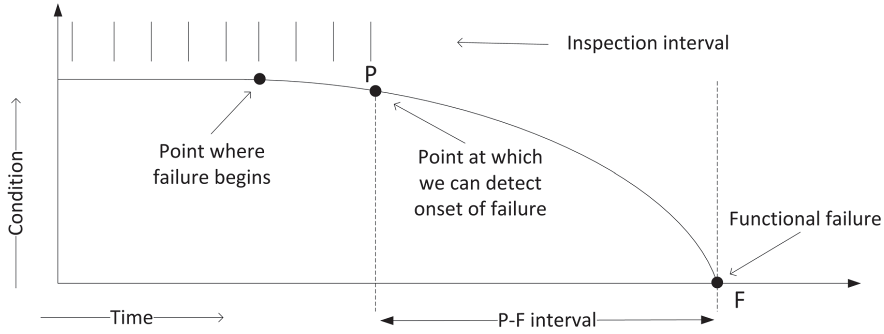

Figure 2: The concept of condition monitoring.

The following considerations must be made for the condition monitoring task to be regarded as applicable and effective (American Bureau of Shipping, 2004).

- The onset of failure must be detectable. There must be some measurable parameters that can be used to detect the status of the equipment.
- There must be a reasonably consistent P-F interval. The P-F interval needs to be consistent to ensure that corrective actions are not implemented prematurely or that a failure does not happen before corrective actions are implemented.
- There must be a practical interval in which the condition monitoring task can be performed. A failure with too short a P-F interval is not a good candidate for condition monitoring.
- There must be sufficient warning so that corrective actions can be implemented.
- The probability of failure must be reduced to an appropriate level.
- The condition monitoring task must be cost-effective. The cost of the task over a certain period of time should be less than the total cost of the consequences of failure.
- It is important to have high reliability in order to prevent false alarms, because every false alarm needs a decision (Zio, 2009).

There is a high risk of false alarms occurring with an unreliable condition monitoring system; i.e. there is a risk of a large number of false alarms resulting in maintenance personnel travelling to infrastructure where no action is required (Zio, 2009).

2.2. Condition monitoring of track and wheels

The requirements for components on the railway such as track and S&Cs depend on the inspection classes. In the Swedish regulations for safety inspections, there are five different classes, and the categorization of track into classes depends on the annual tonnage and the velocity on the track. Figure 3 shows how the inspection classes are allocated; the lowest class is B1 and the highest class B5 (Trafikverket, 2005).

If the S&C is to meet the requirements placed upon it, preventive maintenance actions are needed, as well as corrective actions to a greater or lesser degree.

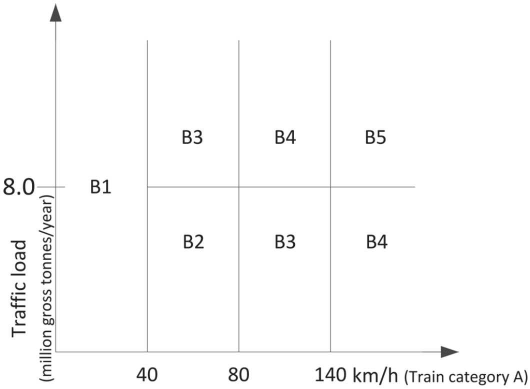

Figure 3: Inspection classes for the Swedish railway system.

The condition monitoring systems on the railway can be divided into two different types, namely wayside monitoring systems and on-board monitoring systems. The wayside systems measure the train and the on-board systems measure infrastructure such as the track and catenary wire.

Wayside monitoring systems: In the Swedish railway network, wayside equipment for monitoring rolling stock was first installed in 1996, and today there are 190 wayside inspection devices. There are wayside inspection systems for the detection of hot boxes, hot/cold wheels, damaged wheels, overloaded cars, unbalanced loads, contact wire lift, the pantograph condition and wheel-rail forces (Stenström, 2012). In the southern loop of the Iron Ore Line there is also a new WPMS, which scans all the railway wheels passing the station at Sunderbyn (in northern Sweden). This system has been in use since 2011 for maintenance optimising of the wheels of iron ore trains. There is also the JVTC research station for measurements of the wheel-rail force in the lateral and vertical direction (Palo et al., 2012). A good survey of all the wayside monitoring systems available can be found in Brickle et al. (2008) and Barke & Chiu (2005). Furthermore, research has been performed on the potential of wayside monitoring systems for preventing derailments and on the further development of such systems (Vasić et al., 2013). A detailed summary of wayside condition monitoring technologies is done (Lagnebäck 2007). All these monitoring systems presented work one by one; no comparison of data between them are performed, either manually or automatically, to obtain more information from the systems.

On-board monitoring systems of infrastructure: The reasons for performing on-board measurements are as follows: to maintain the safety on the track, to plan and prioritise maintenance, to maintain a high level of travelling comfort, and to optimise the economy and service life of the track. On-board measurements are carried out by special track recording cars which measure the rail and the track, as well as performing video imaging (Lichtberger, 2005). The frequency of the track measurements depends on the track classes; in Sweden there are five different classes, which are allocated depending on the load on the track, the speed and the yearly gross tonnage (Figure 3). For instance, track with speeds over 140 km/h and loads over 8 MGT/year is placed in the highest class, with three safety inspections and one ultrasonic inspection of the track each year; track placed in the lower classes undergoes fewer inspections, see Table 3 (Trafikverket, 2005).

Table 3: Number of inspections each year for the different inspection classes (Trafikverket, 2005).

Asset	No. of safety inspections/year				
	B1	B2	B3	B4	B5
Track	1	2	3	3	3
Track/Rail-ultrasonic	1/4	1/3	1/2	1	1
Track/S&C-track position	1	3	4	6	6
S&C	1	3	4	6	6
S&C-ultrasonic	1/4	1/3	1/2	1	1

Inspection of S&Cs: Inspections of S&Cs can be divided into four types: simple visual inspections, detailed visual inspections, measuring inspections, and non-destructive testing. The current methods for inspecting S&Cs comprise the following: geometry cars, continuous monitoring using sensors, mechatronic systems, measuring instruments and ultrasonic tests (Stenström, 2012). Actions resulting from the inspection reports or failures include adjustments, lubrication, cleaning/rinsing, functional checks, repairs, replacement, grinding and tamping (Nissen, 2009a). Many papers discuss the application of tools such as machine vision algorithms and a filter approach to improve the performance of S&Cs (Molina et al., 2011; Resendiz et al., 2010; García Márquez, 2007). A vehicle has also been developed to inspect S&Cs; it has been used in field tests to determine the wear of S&Cs (Zarembski, 2011). Cost benefits have been studied using condition monitoring equipment and LCC calculations in a real case study, adopting an approach including penalty costs and maintenance savings (Marquez et al., 2008). There is also on-going research aiming to develop trolleys to inspect S&Cs using lasers (Rusu, Roberts & Kent, 2012).

Inspections of wheels: The inspection and monitoring of wheels are performed either through visual inspections or using measurement equipment. Visual inspections are carried out by inspectors working around the train, while measurements are performed with handheld measurement equipment (MiniProf[e]). This equipment is attached by magnets to the wheel, and then a small arm with a small magnetic wheel is moved mechanically over the wheel profile to record it (Esveld & Gronskov, 1996). This is time-consuming work and the train needs to stand in a safe place during the whole procedure. Measuring a whole iron ore train with 568 wheels can take hours. In the literature in this field, different WPMS are presented; for the advantages and disadvantages of these systems, see Table 4 (Brickle et al., 2008).

Table 4: The advantages and disadvantages of WPMS.

Advantages	Disadvantages
Improved safety, reliability & efficiency	High up-front cost
Increased inspection frequency	Potential reliability issues with automated systems
More consistent inspections	Increased complexity
Increased train availability	Lower trust in data from automated systems
Potential for fewer false alarms	Change in current railway practices
Reduced number of train delays	System maintenance costs
Prioritised & focused maintenance	Potential for too much data
More effective maintenance actions	
Extended vehicle service life	
Cost benefits over time	
Historical database for trending and eventual predictive maintenance	

2.3. Common defects for wheels and S&Cs

Wheel defects can be grouped into four groups: surface defects, polygonization, profile defects and subsurface defects; Table 5 shows the different wheel defects.

Table 5: Wheel defects divided into four groups, adapted from UIC (2004a) and Nielsen & Johansson (2000).

1. Polygonization	2. Profile defects	3. Surface defects	4. Subsurface defects
Corrugation	Thin flange	Flats	Residual stress
Eccentricity	High flange	Shelling	Hardening
Periodic non-roundness	Small flange angle	Spalling	Cracks
Non-periodic non-roundness	Wide flange	Cracks	Contamination
	Hollow wear		
Roughness			
Discrete defects			

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[e] http://www.greenwood.dk/miniprof.php

An out-of-round (OOR) wheel (group 1 and 3 in Table 5) is a wheel with some kind of deformation on the surface of the circumference; this deformation can have a large number of shapes and different root causes. This wheel defect causes dynamic-force damage to the rolling stock and the track. The development of the irregularities on the wheels depends on the dynamics of the system, i.e. the rolling stock and the track (Nielsen & Johansson, 2000; Barke & Chiu, 2005). One type of surface defect is a wheel flat, which is a flat part on the circumference of the wheel, and there are many causes of wheel flats, e.g. locking brakes, brakes in a bad condition, frozen brakes, and bad adhesion between the wheel and rail, for instance due to leaves on the rail. A wheel flat is classed as an OOR Type A defect (UIC, 2004a). A typical parametric description of a wheel flat includes the length and height of the defect, as illustrated in Figure 4.

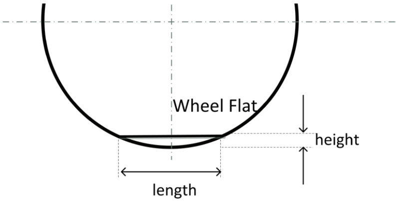

Figure 4: Wheel flat, the length and the height of a flat.

The approximate length of a flat for an alarm to be triggered is around 60 mm (Madejski, 2006).

The classification of OOR wheels can be made according to the following categories: eccentricity, discrete defects, corrugation, periodic non-roundness, non-periodic non-roundness, roughness, flats, spalling and shelling (Nielsen & Johansson, 2000). These defects can also be divided into two main types: Type A, tread defects initiated, and Type B, polygonisation (UIC, 2004a).

Furthermore, studies have shown that flats grow rapidly at the beginning and that afterwards, with sliding taking place, the growth decreases. Cracks are usually initiated on wheel flats after sliding, and research has shown that almost 66% of all wheels after sliding have cracks (Jergéus, 1999).

S&Cs include many different subsystems and parts, and therefore there are a large number of different failures of S&Cs. The most frequent real failures of S&Cs are shown in Table 6 (Nissen, 2002).

Table 6: Different failures of S&Cs (Nissen, 2002).

Real failures from work orders	Percentage
Impossible to define	30.8
Break	26.6
No fault	10.7
Wear	7.5
Material break (fatigue)	7.0
Deformation	4.8
Cut circuit	4.4
Corrosion	4.2
Isolation fault	1.6
Rail crack	0.6

Those subsystems with the highest number of failures are the control system, point machine, switch heater, switch blade, crossing, and locking mechanism (Nissen, 2002).

Failures of S&Cs cause a large number of problems for the train operation in terms of costs and train delays. Of all the infrastructure-caused train delays in the Swedish network from 2004 to 2006, 17% were attributed to S&Cs (Granström, 2008). S&Cs account for about 13% of the yearly maintenance budget for the Swedish railway infrastructure (Nissen, 2009b). The degradation of the S&C has a significant relation to the load (Zwanenburg, 2006). The S&Cs on the Iron Ore Line in northern Sweden are those which have the highest maintenance cost in Sweden, owing to the higher axle load of that line and the more extreme climate in that part of Sweden (Nissen, 2009b).

The maintenance actions for the track can be divided into manual and mechanical maintenance work. Manual maintenance work comprises actions such as adjustments, lubrication, cleaning/rinsing, functional checks, repairs, replacement, grinding, tamping and welding; mechanical maintenance work consists of tamping, ballast regulation, ballast stabilizing, ballast cleaning, grinding, joint strengthening and treating of spots (Esveld, 2001; Nissen, 2009a).

The S&C fleet in Sweden is old, many S&Cs have already exceeded their technical service life, and many more will do so in the next ten years (Trafikverket, 2012c). Therefore, we can expect even higher maintenance costs, combined with increased traffic disturbances, in the near future, which signals the need for more inspections and better condition monitoring of S&Cs.

2.4. Wheel-rail system

The track guidance of the wheel is achieved using two different techniques in conjunction; firstly the wheel tread is conical and on straight track the wheel finds the right position depending on the rolling diameter, and secondly the flange on the inside of the wheel prevents derailment and supports the train in narrow curves (Esveld, 2001).

The focus on the wheel-rail interface has increased with increasing train speeds and axle loads (Lundén & Paulsson, 2009). There are two main focus areas when managing the wheel-rail interface: the wheel profiles and the friction between the wheel and rail (Grassie, 2009). The key reason for striving to achieve a good wheel-rail interface is to reduce costs, especially for heavy haul lines with high axle loads; for example, in the case of the Swedish Iron Ore Line (Sweden's heavy haul line), 42.5% of the total infrastructure maintenance cost concerns maintenance of the wheel-rail interaction (IHHA, 2009).

Wheel failures have a large impact on the capacity consumption of the track (see Table 1). A good wheel status and good control of the wheels lead to less wear and a lower probability of failure, while a bad wheel status increases the wear and the probability of rail failure. The responsibility for the wheel-rail interface is shared by the infrastructure manager and the train operators, and there are more than 40 different companies operating trains in the Swedish network. Since no single organisation has responsibility for maintaining the whole system, the wheel-rail matching is not as good as it should be, which leads to sub-optimisation of one part of the system. Consequently, some organisation has to take overall responsibility for maintenance of the whole wheel-rail interface and the infrastructure manager is usually the most suitable organisation to fulfil this role (Smith, 2003).

The optimisation of the wheel-rail system has increased since the end of the 20th century and tools for developing this system have been developed, such as GENSYS, VAMPIRE and SIMPAC. The wheel-rail interface is shown in Figure 5a using the simulation tool GENSYS, and in Figure 5b with a photograph of the wheel of an iron ore train on a rail.

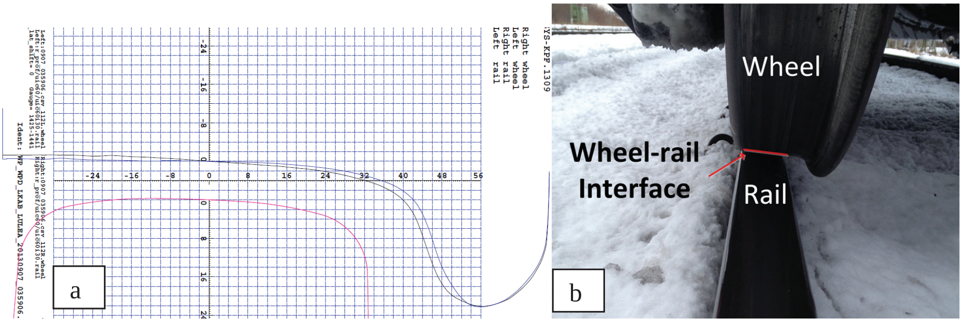

Figure 5: a) Wheel and rail profile from the simulation software GENSYS. b) Wheel-rail interface for an iron ore wagon on the Iron Ore Line in northern Sweden.

Figure 6 shows that damage to the wheel-rail interface is caused by both parts of the interface, the wheel and the rail. Both surface damage and geometrical damage can occur and the causes of such damage can be rolling contact fatigue (RCF), breaking, abnormal profiles, and poor alignment, etc. The damage categories can be created in different ways; for instance, Bombardier categorises damage into four main headings: wear fatigue, deformation, thermal damage and infrastructure damage. For classifying failure there are 24 so-called "Why Codes", which explain why the re-profiling or replacement of a wheelset is performed (Deuce, 2007). A great deal of research has been conducted to develop and improve the wheel-rail interface.

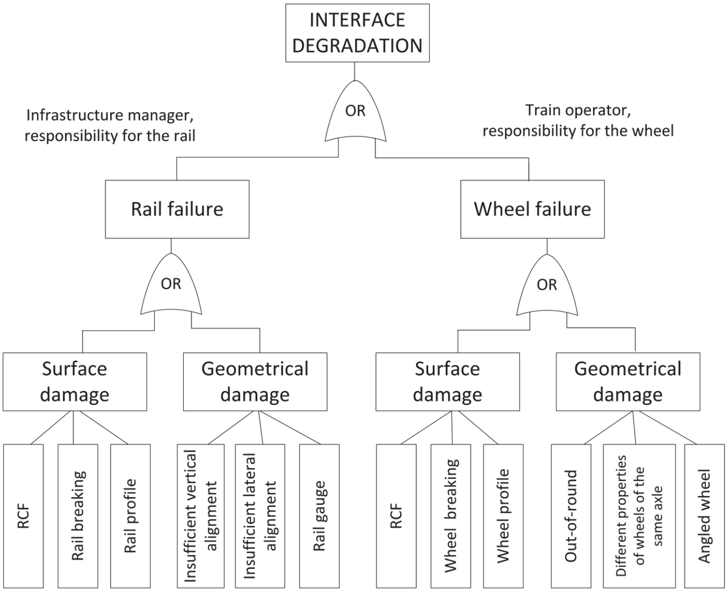

Figure 6: Possible failure modes causing damage to the wheel-rail interface.

2.5. Summary of framework

According to the literature review on WPMS, there are no published studies evaluating which existing WPMS can meet the stipulated requirements and conditions in the best possible way. By "existing system" is meant a system that is available for purchase in the market. In this connection a gap was identified in the literature in that no publications were found which investigate the system reliability and measurement accuracy of WPMS in such a harsh climate as that prevailing in northern Sweden. There were no publications showing that WPMS deliver data in a reliable and accurate way for the purpose of optimizing the maintenance of wheels.

No literature is found that describe: “If there are some relations between data from different way-side monitoring systems and if this information can be used as an indicator of a higher probability of failures”.

No information in the literature was found concerning the possibility of performing automatic inspections of S&Cs with cameras. Moreover, no decision support model could be found which was adapted for railway applications. What tool can be used to find the critical measurements and how much time can be saved in the maintenance of S&Cs? Which characteristic should an S&C have so that advantages can be gained through automatic inspection using cameras? Can the automatic inspection of S&Cs with cameras improve the reliability, decrease the delay time and enhance the operational capacity of the track?

3. RESEARCH METHODOLOGY

Research can be classified into different categories with different goals, namely exploratory, descriptive and explanatory research. Further subdivisions can be made according to the approach adopted, namely research using quantitative methods and research using qualitative methods (Neumann, 2003). The research presented in this thesis is exploratory and, using quantitative methods, tries to explain the connections between condition monitoring and inspection, on the one hand, and, on the other hand, the reliability of the railway system and the operational capacity on the track. The research has adopted a case study approach (Yin, 2009). Figure 7 shows the research methodology used. Inputs to this research are field data from automatic and manual measurements, work order records, asset data and train delay information. The output from this research is the basis for proposals for further research, general observations, research findings and recommendations.

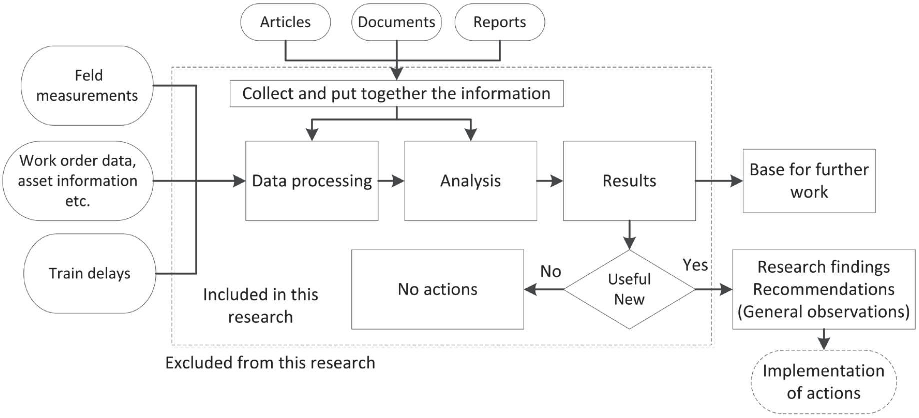

Figure 7: The research methodology.

3.1. Data and information collection

The data on which this thesis is based are maintenance data such as work orders and inspection data, assets data describing the infrastructure, operational data concerning train delays, and measurement records. The data are real field data recorded by the maintenance contractors, the traffic control centre, the infrastructure manager, railway measurement companies, and automatic measurement stations for rolling stock, as well as manual measurements of wheel profiles. The data were collected by the supplier of the measurement system, the measurement company Damil AB, and by the authors of the appended papers. The data were cleaned, structured and transformed into information by the authors; the information has been interpreted in the papers appended to this thesis.

Paper I: The data for this paper come from the WPMS and manual measurements of wheel profiles with MiniProf equipment. Information for this paper was obtained from the publications referenced in the paper, as well as from the project work, which involved the participation of the infrastructure manager, the rolling stock operator LKAB, and the railway measuring company Damill AB. Furthermore, information was collected from many railway measuring companies through brochures, surveys and physical meetings. The information comes from all the project stages, i.e. the planning, preparation, installation and operational phases of the WPMS.

Paper II: The data for this paper come from the wheel defect detectors (WDD) via the DPC III database and the WPMS. Information was obtained from the publications referenced in the paper.

Paper III: The data for this paper come from three of Trafikverket's databases: 0felia, BIS and LUPP. Information for the FMEA was obtained from an expert group consisting of personnel from the infrastructure manager and researchers from Luleå University of Technology. The information from field tests with cameras was provided by the railway measurement company Damill AB.

3.2. Data sources and analyses

The data for the research performed for this thesis come from databases at Trafikverket, wayside measurement stations and manual measurements of wheels. The amount of data stored in the databases at Trafikverket is vast and the quality and accuracy can vary. The data used for the research presented herein come from the DPC III, 0felia, BIS and LUPP databases; the data maintain a high quality and are sufficiently abundant to have been used in the investigations performed in Paper I-III. The data for the wheel studies come from the WPMS and manual measurements of wheel profiles performed using MiniProf equipment. For more information on the databases used, see Table 7.

For Paper I the data were cleaned and structured manually by experienced personnel belonging to the supplier of the measurement system, the measurement company Damill AB, and by the authors; the data were analysed using statistical methods with Excel and Matlab and were shown as tables and figures. The data for Paper II were cleaned by the authors, analysed using graphical methods, and presented in tables and graphical figures. For Paper III the data were cleaned by the authors, analysed through calculations, and shown as tables and figures.

Table 7: Data sources for Paper I-III.

No	Name	Description	Information	Paper
1	BIS	Asset information data and data on some maintenance actions	All the current information on the assets is recorded here, including track, geotechnical, signalling, and power distribution data. This system shows when a certain item was installed and detailed information on the item. Also recorded are some maintenance actions, e.g. grinding, tamping and regulation of the rail.	III
2	LUPP	Data collection and integration tool for showing train delays	This tool collects data on train delays. The system combines information from Trainplan, Opera, 0felia, BIS, BESSY, DUVAN and TFÖR.	III
3	0felia	Work orders and records of all the failure data for the infrastructure	Here failures are recorded and around 60,000 work orders are input every year. The following data can be found: failure observations, assessments, maintenance actions and feedback. Furthermore, the times for each maintenance step and the reasons for failures are recorded here. This system has been fully in use since 2001. Older data are stored in the system, but are not reliable.	III
4	DPC III	Collects data from wayside measurement stations	Information from the wayside detectors is collected. Here one can find information from wheel impact, hot-box and hot-wheel detectors, as well as cameras.	II
5	WPMS	Wheel profile data, automatic measurements	This information comes from the WPMS at Sunderbyn.	I, II
6	Manual measurements	Wheel profile data – manual measurements	These data come from manual measurements of wheel profiles using a MiniProf measurement tool.	I

4. RESULTS OF APPENDED PAPERS

4.1. Paper I

Reliability and measurement accuracy of a condition monitoring system in an extreme climate: a case study of automatic laser scanning for wheel profiles

This paper shows the performance of a WPMS in Swedish conditions. This sub-section covers Paper I, as well as new information concerning the WPMS. The WPMS investigated was installed during the autumn of 2011 in the southern loop of the Iron Ore Line in northern Sweden. This was the first WPMS to be installed on the Swedish railway and it can monitor trains with speeds up to 130 km/h. The system has two main units, the far and the near unit, and each unit has two cameras, one on each side of the rail. The far unit captures images of wheels on the left-hand side and the near unit captures images of wheels on the right-hand side, see Figure 8.

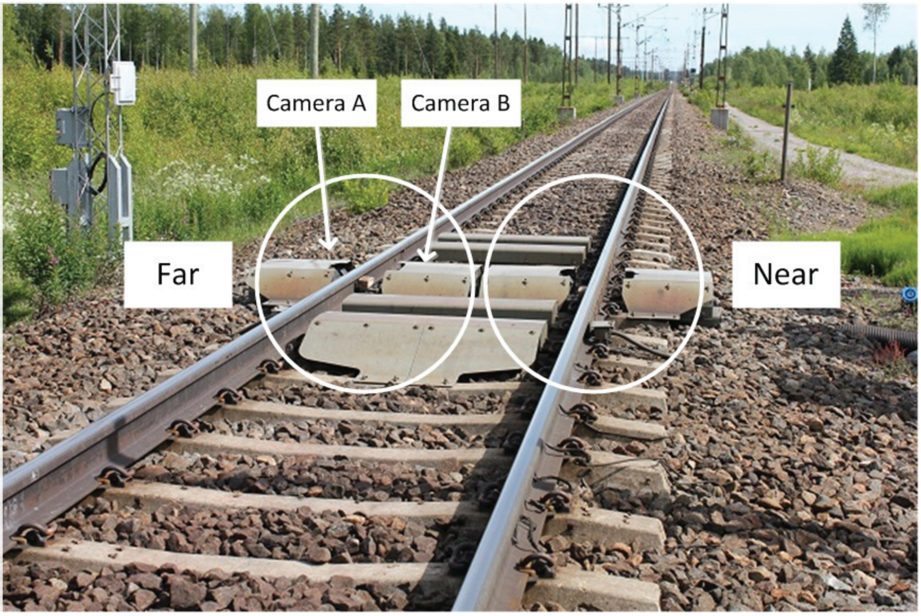

Figure 8: The wheel profile measurement system (WPMS) located on the Iron Ore Line in northern Sweden. The system contains two measurement units, the far and the near unit, for the wheels on the left-hand side and those on the right-hand side, respectively.

Paper I documents the selection of the most suitable system out of systems from 12 different suppliers, using the V-model representing the system life cycle from RAMS for railways (CEN, 1999) and based on the defined requirements. The paper describes the project steps of the V-model, from "concept and idea" to "decommission and disposal", and then reports on an evaluation of the performance of the system (Figure 9).

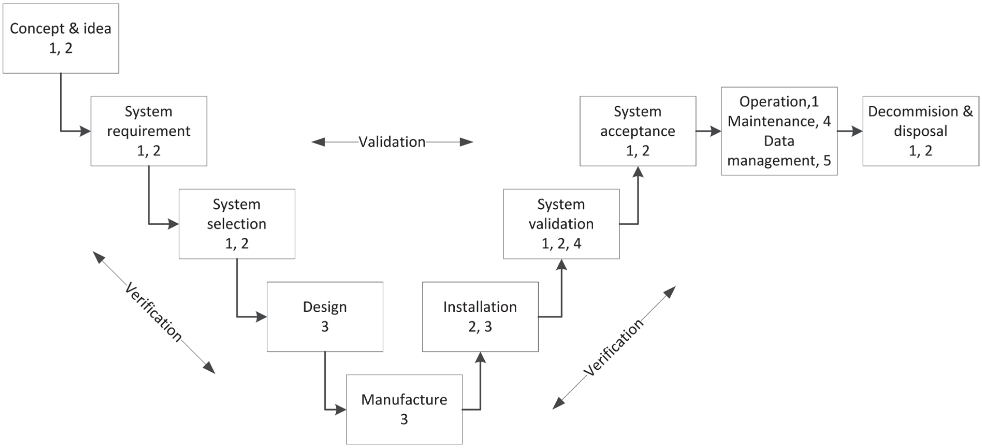

Figure 9: V-model representation of the life cycle of a WPMS (adapted from CEN (1999)). 1-Infrastructure manager, 2-Train operator, 3-Supplier/Manufacturer, 4-Equipment maintenance company, 5-Data management organisation.

Six of the WPMS passed the system requirements test, which comprised the following requirements: commercial availability, general requirements, submission of a screening questionnaire, and special requirements (climate-resistance, measurement accuracy, photographing speed, vehicle identification, ease of calibration, maintainability and ease of installation). The next step for the system selection was to contact the suppliers by way of a questionnaire and by holding meetings. This last step resulted in the selection of one supplier and the preparation of the start of the installation; after the installation, performance tests were conducted.

The performance tests covered measurement accuracy, measurement reliability and system reliability. The measurement accuracy test was performed by comparing the WPMS and the MiniProf equipment, and the results showed that the error for the flange height, flange thickness and flange slope was between 0.77 and -0.4 mm; the results are presented in Figure 10. All the wheels of wagon 4011, 4012, 4019 and 4020 were included in the test, except wheel 1 in wagon 4012, whose results were wrong due to a problem with the MiniProf measurements. The tread hollow wear was not presented, since the measured value was zero in most of the cases.

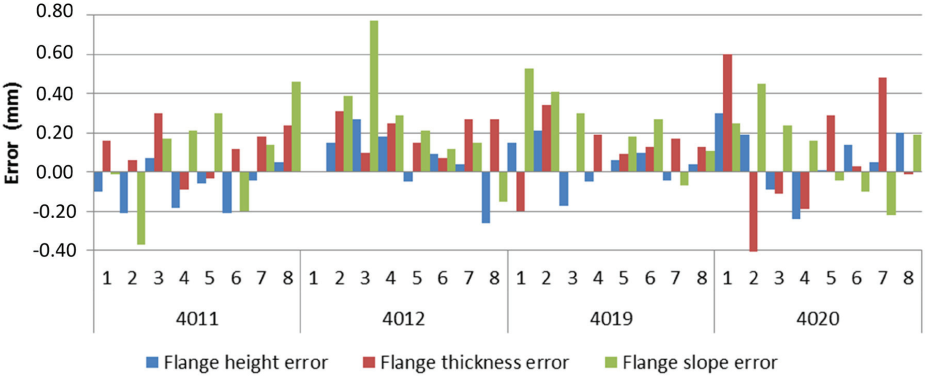

Figure 10: The errors of all the wagons and wheels that were measured; 4011-4020 are the wagon numbers and 1-8 are the wheel numbers.

A boxplot diagram shows that the different measurements have a different behaviour. The flange height error is closest to zero and has a smaller spread compared to the others. The flange slope error has the largest spread of all the measurement errors and the largest positive weight. The flange thickness error has a smaller spread than the flange slope error, but a larger spread than the flange height error. Figure 11 shows the boxplot of the measurement errors. The reason why the flange thickness error has a large spread can be the combination of two cameras (camera A and B, see Figure 8) used when capturing the flange thickness (Fröhling & Hettasch, 2010). The reason why the flange slope error has a spread in the plot can be the fact that the measurement reference of the slope has an accuracy problem or the fact that there is one large difference in the wheel circumference.

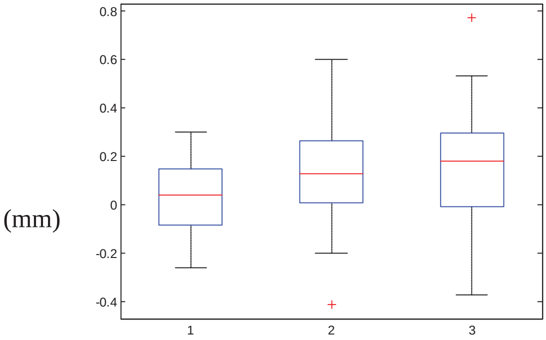

Figure 11: Boxplot of the measurement errors for the flange height (1), flange thickness (2) and flange slope (3).

Table 8 shows the statistics of the measurement accuracy excluding the circumference error and including the circumference error (Fröhling & Hettasch, 2010). The grouping information was obtained using the Tukey method of multiple comparison, and the test shows that the flange height error belongs to group A, the flange thickness error to group A and B, and the flange slope error to group B. The A and B groupings can be considered as low and relatively high measurement error, respectively. This can be further interpreted to mean that the flange height measurements have a consistently low level of error, the flange thickness measurements have a low error level at times and a high error level at other times, while the flange slope measurements have a consistently high level of error. Moreover, it can be inferred that the flange height error and flange slope error do not have the same behaviour, which is consistent with Figure 11. The Anderson-Darling goodness-of-fit test shows that all these three measurements belong to a normal distribution, see Table 8.

Table 8: Performance test of the wheel profile measurement system – accuracy of the system compared to that of the MiniProf handheld measurement tool.

Statistics	Measurement information		
	Flange height	Flange thickness	Flange slope
Mean (mm)	0.02	0.13	0.17
SD (mm)	0.15	0.20	0.24
circumference error included	0.151	0.275	0.315
Belongs to group	A	A and B	B
A-D goodness-of-fit test	Normal distribution	Normal distribution	Normal distribution

The measurement reliability is good in the season without snow, but during the snow season the reliability is lower; for instance, in April 2012 it was around 45%, see Figure 12. A process rate below 70% for a train means that the measurement has failed.

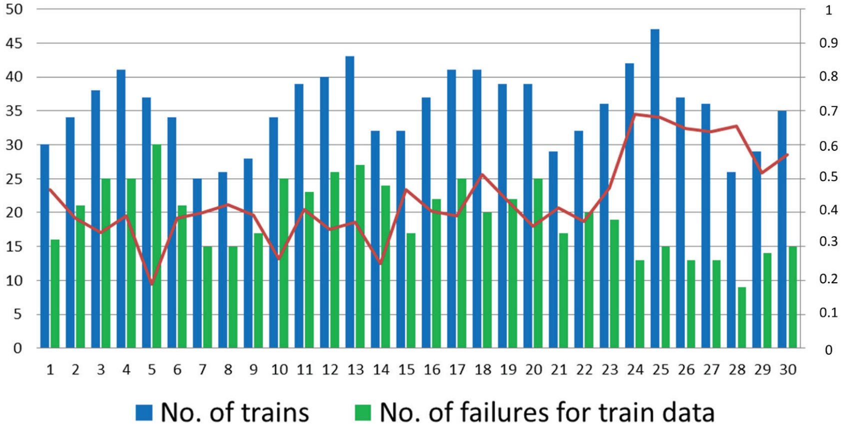

Figure 12: Measurement data from the WPMS for the month of April for the first year (2012); a process rate under 70% for each train means measurement failure.

For a one-year period (from 19/3/2012 to 18/3/2013), the measurement reliability was divided into near and far side reliability with a process rate lower than 70%, see Figure 13 and Figure 14. There were four different periods (1-4) with a low process rate; the first (1) was at the end of April and beginning of May, the second (2) was during the whole of December, the third (3) was at the end of January and the beginning of February, and the fourth (4) was from the middle of February to the end of March. This shows that the winter season had more problems with the process rate than the summer season. The first period had more problems with the near side unit, while the fourth period had more problems with the far side unit, which can be an indication of special problems with the measurement equipment concerning failures. During the first period with a low process rate, there was a problem with a camera for one unit (requiring replacement of the grabber card), and this period is also shown in Figure 12; during the fourth period the problem was that the contacts of the laser in one unit were loose. In the second and third period with a low process rate, there was no problem with any failures of the system. During the second period, December 2012, there was a large amount of snow and the precipitation in December was three times larger than that in January, which could be the reason for the low process rate, since the new snow led to snow smoke and it was difficult to obtain clear pictures of the wheel. The third period with a low process rate does not seem to have been caused by the weather, since the precipitation then was lower than in December and January and the temperature was warmer than in December and January.

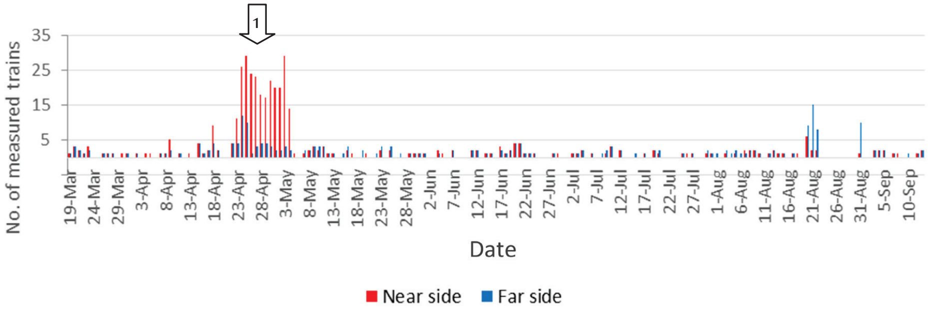

Figure 13: Process rate for trains measured for one year, the first period.

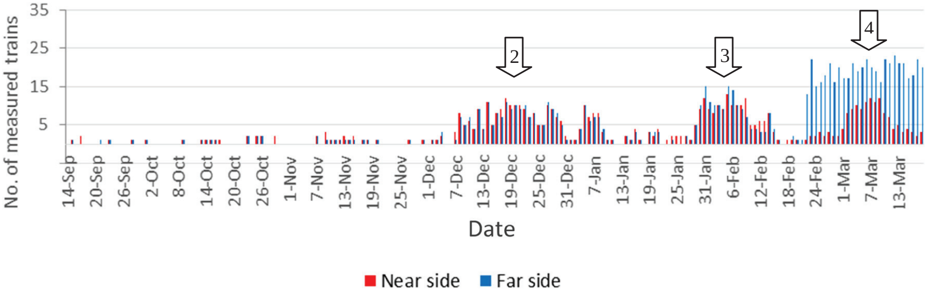

Figure 14: Process rate for trains measured for one year, the second period.

During a typical winter week, the amount of useful data concerned around 65-95% of all the measured trains, see Figure 15; the information in Figure 8 is presented according to the measurement unit which provided it, the near or the far unit. The secondary scale presents the amount of successful measurements; "100%" means that all the data are useful, while "0%" means that no data are useful.

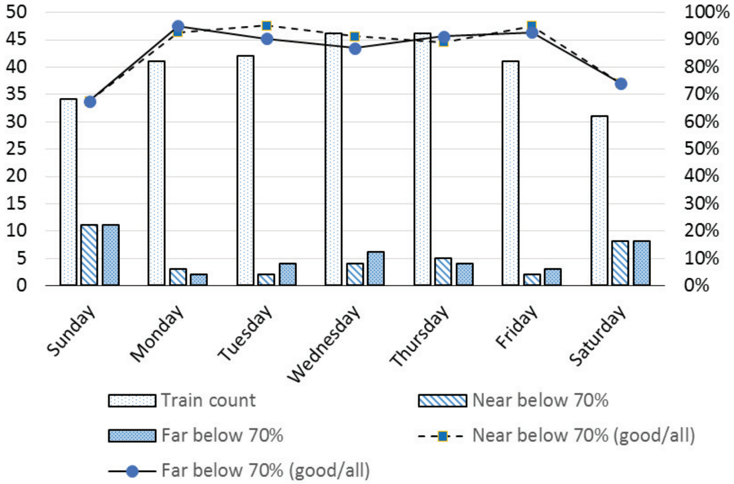

Figure 15: Process rate during a typical winter week (the average value was around 65-95% of all the measured trains).

The WPMS has a high reliability in general and a good measurement accuracy in this harsh and extreme climate, and the information from this system can be used safely and reliably. By being able to monitor the wheel profiles automatically with the WPMS, it is possible to acquire good knowledge of the wheels through the high measurement frequency and the good accuracy of the measurements. The system provides a good picture of the status of the wheels and the information generated can be used for improving the overall status of the individual wheel, as well as the whole fleet of wheels. By automatically measuring the wheels in service, one does not have to perform a large number of manual wheel measurements, which are time-consuming and require human activities on the track.

Wheel defects that can be detected with WPMS are high flanges, thin flanges, small flange angles, wide flanges, hollow wear and abnormal wheel diameters (the wheel diameter is not recorded in the system investigated). Since the wheel and rail are closely related to each other as integral parts of the wheel-rail system, an improved wheel status will influence or improve the status of the rail, which is supported by Sub-section 2.4.

To improve the railway system, the data from the WPMS can be used to develop the maintenance strategies for the wheels by introducing CBM. This concept involves the performance of maintenance based on the actual need for maintenance, but CBM will place greater demands on maintenance planning and scheduling. Applying this maintenance approach, wheel defects can be detected, even those representing a risk to safety. The information from the WPMS can also improve the safety on the track by pointing out the "bad actors" on the track, and such information can be delivered to the train operators and enable them to remove these wheels from service. This will decrease the deterioration of the track, e.g. by replacing wheelsets that are unevenly worn, with regard to the wear of the right and left wheels. When a wheelset is unevenly worn, this influences the wagon dynamics, as the wagon steers badly and the wear of the rails is thereby increased. All the kinds of defects mentioned above can be removed early and this will increase the safety of the wheel-rail system and enhance the reliability of the track system.

4.2. Paper II

A study of railway wheel profile parameters used as indicators of increased risk of wheel defects

This paper investigate the correlation between wheel defects such as high lateral forces and profile parameters such as the flange height, flange thickness, flange slope and hollow wear. The data for this paper come from the WPMS and wheel defect detectors (WDDs); the WPMS was explained in the previous sub-section and a WDD is shown in Figure 16 below. The two systems are placed close to each other on the Iron Ore Line in northern Sweden. The WDD consists of eight load cells which measure the force level of the wheels of passing trains.

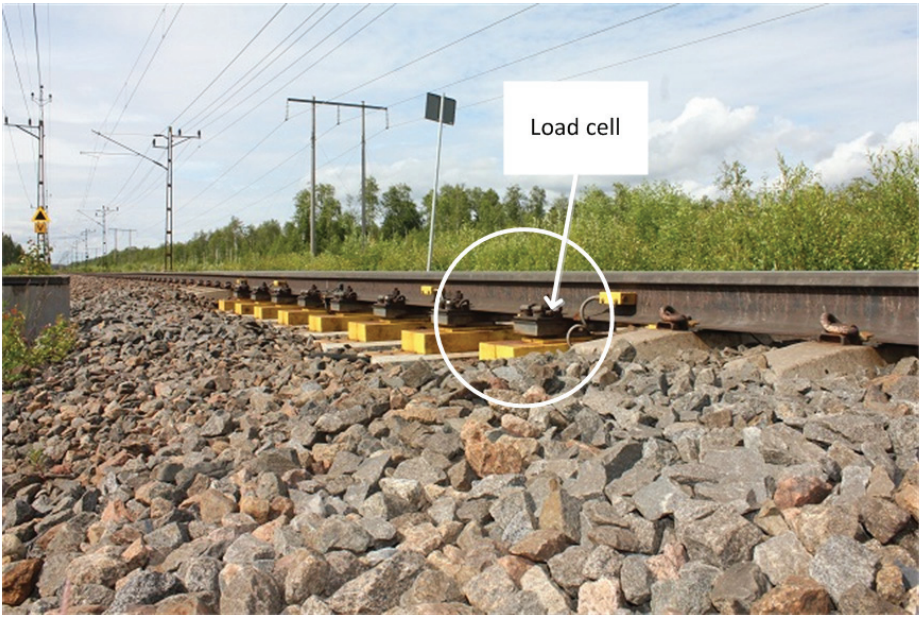

Figure 16: Wheel defect detector (WDD) installed along the Iron Ore Line in northernmost Sweden. The WDD consists of eight load cells which measure the wheel forces.

High lateral wheel forces often originate in wheel defects such as polygonization and surface defects; see Figure 17 for the most common wheel defects.

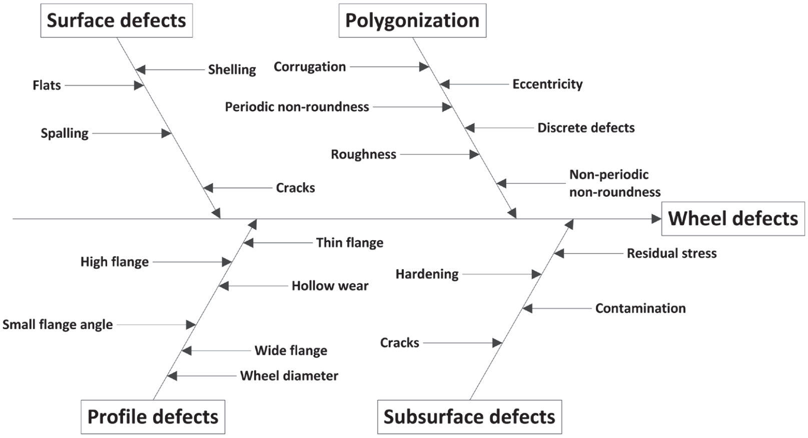

Figure 17: Wheel defects divided into four groups: surface defects, polygonization, profile defects and subsurface defects (Nielsen & Johansson, 2000; UIC, 2004a).

The research study presented in Paper II included 6,933 wheels, of which 29 generated warnings and two generated alarms due to high vertical forces. Wheel parameters such as flange thickness, flange slope and hollow wear seems to have no correlation with the probability of high vertical wheel forces; see the figures in the appended Paper II. A combination of the WPMS and WDDs shows that high flange height has a relation to high vertical wheel forces; the distribution plots for healthy wheels and wheels with warnings due to high force levels do not coincide. The results indicate that, if one sets the wheel maintenance limit to a flange height of 30.46 mm instead of 34 mm, more than half of the wheel defect warnings can be removed and resulting capacity-consuming reactive measures can be avoided, see Figure 18.

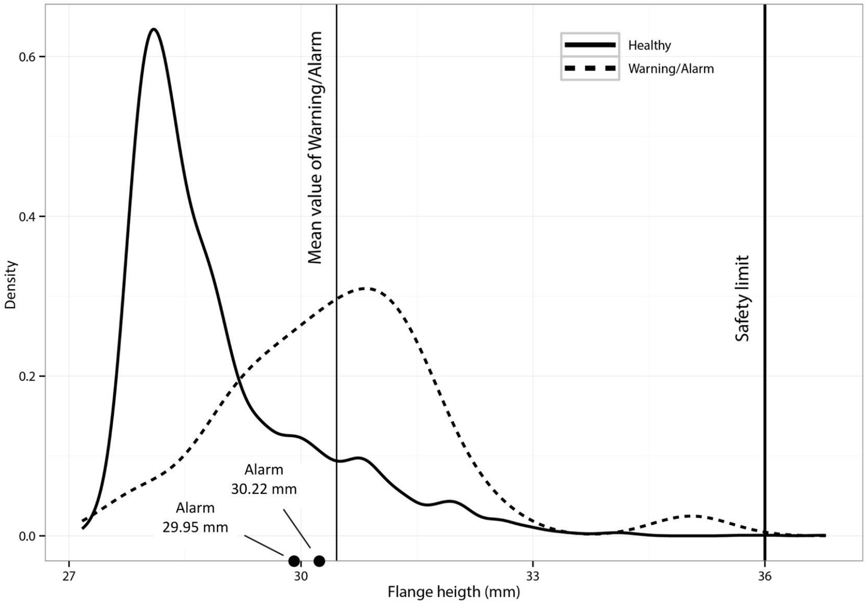

Figure 18: Flange height distribution plotted for healthy wheels and wheels with a defect indication. The values for the two wheels with an alarm indication are marked with black dots and the mean value of both warnings and alarms is 30.46 mm.

Furthermore, it can also be inferred that aggregating the information in the individual wheel profile parameter using a composite indicator will give an appreciated indication of wheel defects. In future work, the reduction in the wheel defects achieved by using the wheel profile parameters as indicators of an increased risk of wheel defects will be ascertained and quantified in terms of its cost implication.

4.3. Paper III

Inspection of railway turnouts using cameras

This paper shows a feasibility study of camera-inspection of railway S&Cs and presents a decision support model for choosing condition monitoring measures, as well as a case study of some S&Cs in track section 401 close to Stockholm Central Station. The presented decision support model includes the following steps: "analysis and selection of critical equipment", "risk management", "analysis of types of condition monitoring activities", and "assessment and decision-making"; the model is shown in Figure 19.

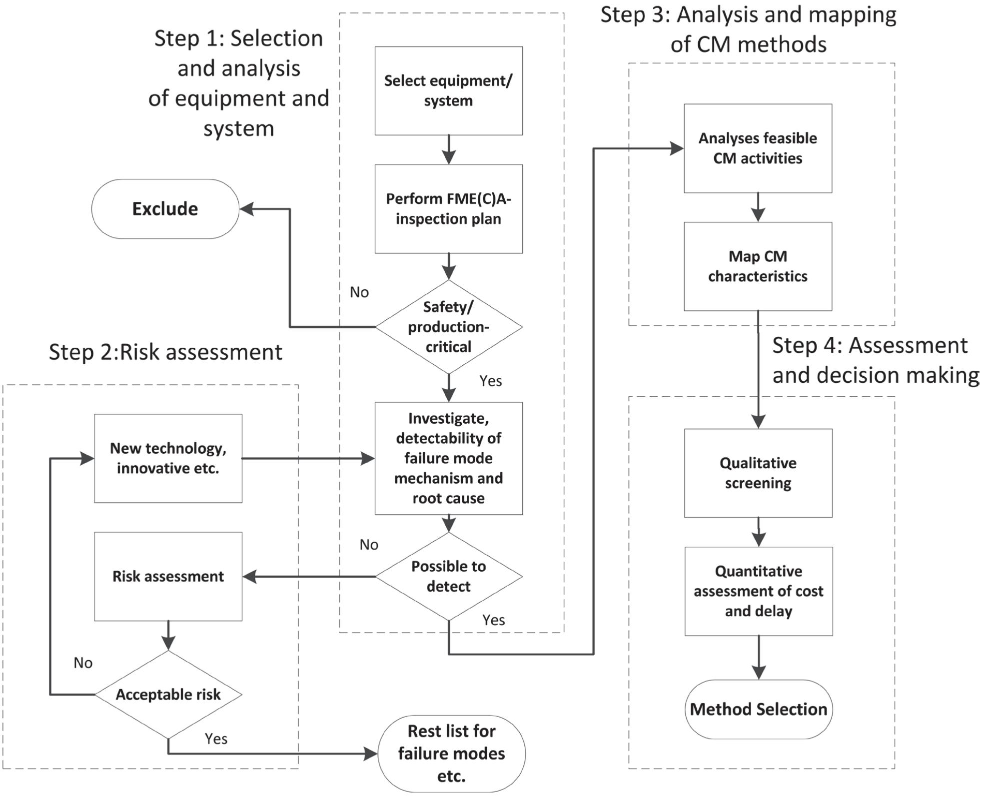

Figure 19: The decision support model.

The decision support model has been adapted to fit the railway industry with its high safety requirements, using a special approach for "risk assessment" not previously used in other branches of industry.

This paper shows the causes of degradation of S&Cs, categorising them into manufacturing, design, maintenance and operation factors, as illustrated in Figure 20. Furthermore, the paper discusses the potential for using failure mode and effect analysis (FMEA) to define the inspection tasks for S&Cs. For the case study some S&Cs were selected which would be appropriate candidates for monitoring to increase the capacity of the selected track section.

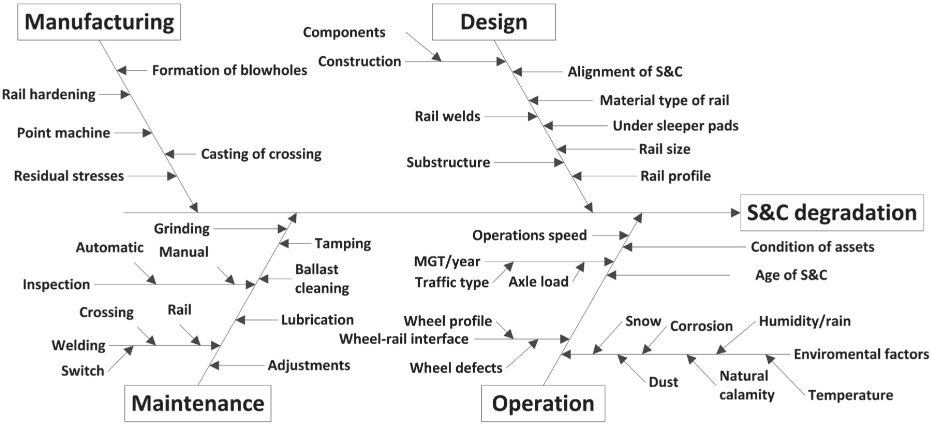

Figure 20: Fishbone diagram of an S&C with the typical causes of degradation, categorised into four main areas: manufacturing, design, maintenance and operation factors.

Through camera-inspection of S&Cs, the inspection frequency and the number of human activities on the track for the inspection of S&Cs can be decreased. The case study shows that the maintenance action “check” results in a large number of maintenance actions, as well as train delays. The total downtime of five different S&Cs in track section 401 in 2011 was 862 minutes, which includes the logistic time for the maintenance actions and the time for performing the maintenance actions. The total train delay for these five S&Cs due to the maintenance action “check” in 2011 was 19 minutes. The case study shows that, if the maintenance action “check” is avoided by using cameras to inspect S&Cs, the system reliability of the track can be increased. Figure 21 shows track section 401 with the five S&Cs with the largest amount of downtime due to the maintenance action “check” (red circles) and the five S&Cs with the largest number of maintenance events (dashed circles) during 2011.

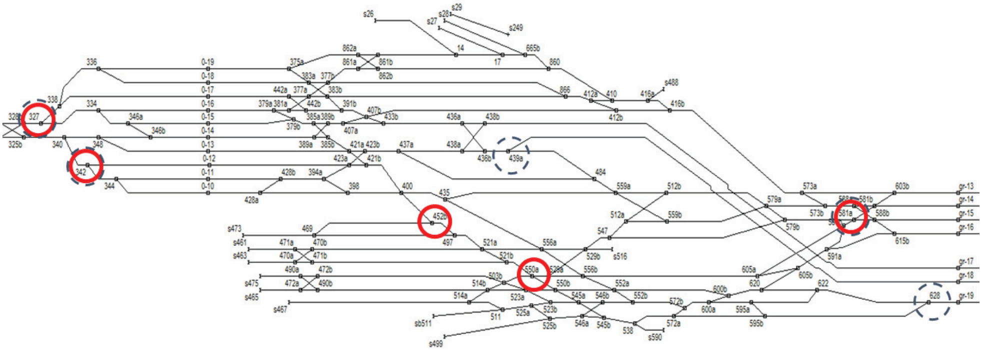

Figure 21: Track layout from track section 401 close to Stockholm Central Station; the red circles are the S&Cs with the largest amount of downtime due to the maintenance action "check" and the dashed circles are the S&Cs with the largest number of maintenance events during 2011.

The camera kit used for the field tests is shown in Figure 22a; the kit consists of standard web-based cameras with a resolution of 1600x1200 pixels and enclosed in a protective plastic housing. The weight of the prototype is approximately 3 kg including the Internet access unit and batteries. A picture taken by the camera is shown in Figure 22b. This prototype was developed, installed and tested by Damill AB.

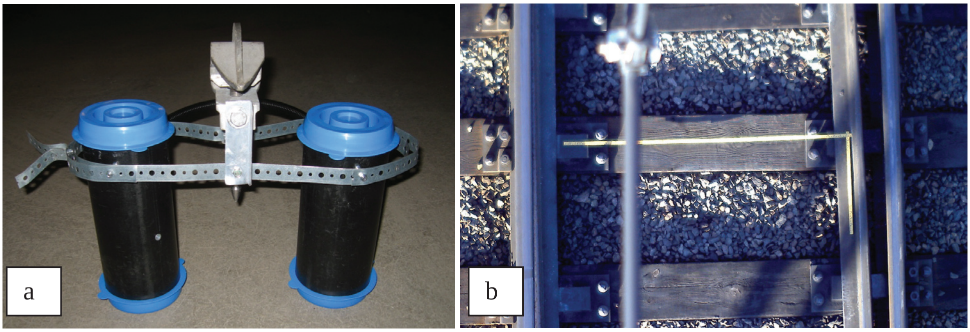

Figure 22: a) Camera kit for the tests. b) Picture of a test installation taken with the camera. (Damill AB)

5. DISCUSSION AND CONCLUSION

The conclusions drawn from the research presented in this thesis and the recommendations based on them can reduce the in-service failures and facilitate planned maintenance actions, leading to an increase in the reliability of the railway system through the use of condition monitoring technology and automatic inspections of the infrastructure and rolling stock. The conclusions and recommendations presented herein need to be assessed in relation to the context and limitations of the research.

RQ1: How can infrastructure managers monitor railway wheel profiles in an effective way, in order to control the effect of wheels on the wheel-rail system for different operators?

- The WPMS performed well in the harsh and cold climate of the Iron Ore Line in northern Sweden. Wheel profiles can be monitored in an effective way with high system and measurement reliability and good accuracy by using the WPMS. Good quality information on rolling stock wheels is available for both the infrastructure manager and the train operator. This information from the WPMS, together with the information from track recording cars, can be used to control the effect of wheels on the wheel-rail system for the benefit of all the operators on the track, and at same time increase the system reliability of the railway, which will increase the operational capacity if necessary actions are taken. Necessary actions can include the replacement of wheels in response to warnings, and the planning and prioritising of maintenance actions for individual wheelsets and whole wheel fleets based on information from the WPMS. For details see Paper I.

RQ2: How can the information from the wheel profile measurement system be utilised by the infrastructure manager to enhance the operational capacity through higher reliability of the wheel-rail system?

- The information from the WPMS can be used to detect wheel profile defects such as high flanges, thin flanges, small flange angles, wide flanges, hollow wear and abnormal wheel diameters. Furthermore, the WPMS shows, based on wheel flange height measurements, that half the population of wheels with high forces have flange heights over 30.46 mm. Removing wheels with a higher flange height than 30.4 mm would increase the reliability of wheels and the operational capacity would thereby increase, and this can be achieved by changing the maintenance limit for the flange height. For details see Paper II.

RQ3: Can an on-line inspection system for S&Cs reduce the capacity-consuming failures in the railway network?

- On-line camera-inspection of S&Cs can reduce the train delay (increasing the quality of service) and in the next step increase the operational capacity. The case study presented in Paper III shows that camera-inspection of five S&Cs close to Stockholm Central Station could save around 19 minutes’ delay time per year resulting from the maintenance action “check”. In 2011 the maintenance action “check” caused a total downtime for these five S&Cs of 862 minutes, including the logistic time and the inspection time. For details see Paper III.

5.1. Research contribution

Papers I-III have contributed knowledge to improve the reliability of the railway system for Swedish conditions, especially for the Iron Ore Line and track section 401 close to Stockholm Central Station, which are included in the studies. The new research contribution is the finding that the WPMS can deliver reliable and accurate data in a harsh and extreme climate, and the devising of ways in which this information from the WPMS can be used to find wheels that have a large probability of exerting high vertical wheel forces, destroying the rail and causing a large amount of delay time. Furthermore, it has been shown how camera-inspection of S&Cs can be used to improve the reliability on the track, by developing a decision support model, how FMEA can be used to find critical measurements and, through a case study, how much maintenance and delay time can be saved by the automatic inspection of five S&Cs in track section 401.

5.2. Research findings

The key findings of the research conducted for this thesis are as follows.

- To select new monitoring systems for the railway, the V-model from EN-50126 can be used. The WPMS can be used after certain improvements have been made, and can generate reliable and highly accurate wheel profile data in the harsh and extreme climate of northern Sweden. The WPMS has a measurement accuracy ≤ 0.315 mm including the circumference error of the wheel; the measurement accuracy for the flange height is higher than that for the flange thickness, while that for the flange slope is the lowest. The measurement reliability depends on the season, but can on the whole be considered good.

- A comparison of the data from wayside monitoring systems, the WDD and the WPMS, indicate that wheels with flanges higher than 30.46 mm have a higher probability of exerting high lateral wheel forces. Furthermore, a comparison also indicates that the flange slope, hollow wear and flange thickness have no relations to higher lateral forces.

- A new decision support model has been developed to define condition monitoring methods for equipment in the railway network. Five S&Cs in track section 401 (close to Stockholm Central Station) have been identified as the S&Cs that cause most of the train delays and require most logistic and inspection time through the maintenance action “check”. In 2011, the total downtime for these five S&Cs due to the maintenance action “check” was 862 minutes, including the logistic and inspection time, and the total train delay was 19 minutes. Three of these five S&Cs have the highest number of corrective maintenance actions for S&Cs for track section 401.

By developing the condition monitoring and automatic inspection of critical items of the infrastructure and rolling stock, the reliability of the items can be increased and, thereby, higher operational capacity can be achieved on the track through decreasing the failure-driven capacity consumption.

5.3. Enhanced reliability and capacity

The three appended papers together show that a wayside monitoring system and automatic inspection in railway applications can enhance the capacity of the track by decreasing the train delay through enhancing the wheel and S&C reliability. This is shown in Paper I and II for the rolling stock wheels and in Paper III for the S&Cs. To gain benefits from these improvements, a change in the maintenance limits for wheels may be needed, in addition to the use of innovative and proactive condition monitoring techniques such as the WPMS and automatic inspection of S&Cs. Furthermore, Paper I and II present technologies that are already available for the Swedish railway network, while Paper III demonstrates an innovation that is not in use and cannot be bought as a readily available system in the market.

If all the activities that are mentioned in the appended papers are implemented, this will increase the reliability of the railway system. When the system reliability increases, the operational capacity will be enhanced and the quality of service will be improved, e.g. through a decrease in the number of train delays. Such improvements would be in line with the reasoning in Sub-section 1.3. Without simulations it is not possible to determine how much capacity could be saved, since there are a large number of constraints, e.g. the timetable structure, the capacity allocation process, the design rules, environmental protection considerations, safety aspects, technical constraints and technical capacity (UIC, 2004b).

5.4. Implications of results

To obtain full value from the WPMS on the Iron Ore Line, one needs firstly to use the information from the system to develop the maintenance strategy for wheels, and secondly to extend the use of the system to the whole Iron Ore Line by implementing one more WPMS in the northern loop; now only the southern loop is being monitored by one WPMS. It must be possible to access the information from the WPMS from the train operators' maintenance management system, but this function has not been developed in full yet. The work involved in creating information from data is still an on-going process which will hopefully be completed by the end of 2014. The infrastructure manager has not integrated the WPMS with the data collection tool DLP III, and the work involved in this has not been planned yet. The question is whether DLP III should be the platform for the WPMS or whether a new platform should be developed to fit the WPMS to realise the system's full potential.

Figure 23 shows the share of the train passages for the different iron ore locomotives operating in the northern loop and the number of passages for each locomotive in the northern loop for the period 2010-2013. In 2010 locomotives 108, 109, 110, 116 and 118 and in 2013 locomotive 111 carried out more than 80% of the operations in the northern part of the Iron

Ore Line. Furthermore, 20 locomotives during the period 2010-2013 had more than 70% of the operational time in the northern loop of the Iron Ore line.

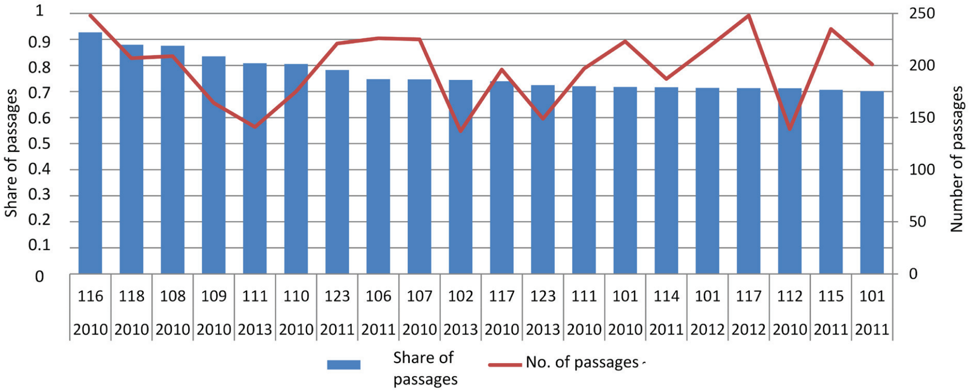

Figure 23: Iron ore locomotives in the northern loop of the Iron Ore Line for the period 2010 to 2013.

Implementation of the results from Paper II requires a discussion with the train operators, as well as further research as to how this can benefit the train operators in terms of short-term costs and life cycle costs. From the perspective of the infrastructure administrator, the reliability of the wheels needs to be improved and the operational capacity needs to be increased, which could be achieved through the proposed changes in the maintenance limit. In short, more research is needed to investigate how the implementation of a new maintenance limit for the wheel flange height would affect the operators in terms of cost and the availability of the wheels.

Inspection of S&Cs with cameras, as shown in Paper III, can be implemented for critical S&Cs that are inaccessible, such as S&Cs on highly loaded tracks and tracks located in the wilderness. Paper III proposes five S&Cs close to Stockholm Central Station that can be equipped with cameras. Field tests have been executed in northern Sweden, on the Iron Ore Line close to Boden, by Damill AB. Some technical issues remain to be solved before an implementation of these concepts can be started. The first issue to be addressed is how this additional monitoring tool can be adapted to the already existing infrastructure of condition monitoring; the second issue is how the information from this tool should be presented to benefit the maintenance contractor in the best possible way, to increase the reliability of the S&Cs and develop the maintenance process and maintenance support.

5.5. General observations

A number of general observations have been generated from the research documented in this thesis; the observations are not unique and can also be found in other publications.

The general observations from this work are as follows:

- The status of the Swedish railway system shows a good trend, but it is possible that this trend may be broken in the future, since one indicator (namely inspection remarks) during the period 2009 to 2012 showed a large increase in the number of negative inspection findings (Trafikverket, 2013b). Many S&Cs in the Swedish network have exceeded their technical service life and many more will do so in the next ten years (Trafikverket, 2013b).
- The high demands that will be made on the Swedish railway system in the future will require short-term and long-term solutions. The research on which this thesis is based deals with short-term solutions. One way to increase the operational capacity in the short term is to increase the reliability of items for the rolling stock and for the infrastructure.
- The wayside monitoring of rolling stock for the Swedish network is well developed in the case of reactive systems. The WPMS is a proactive wayside monitoring system that has been installed in the Swedish railway network. More proactive wayside monitoring systems could support a further increasing of operational capacity of the track by increasing the reliability of rolling stock wheels and S&Cs.
- The wheel-rail system has a big economic and operational impact on the infrastructure manager and the train operator. Wheel problems related to delay time are of a seasonal nature in that there are more problems during the winter than during the summer, see Table 1.

5.6. Recommendations

The following general recommendations can be made based on the research performed for this thesis.

- It is important to consider the wheel and rail together as integral parts of a system, and to develop this system through collaboration between the infrastructure manager and the train operators to create benefits for all the stakeholders by using information form WPMS, see Figure 6, which shows the wheel-rail interface and the damage that influences it. To develop the wheel-rail interface, the infrastructure manager needs to take responsibility for enforcing the fulfilment of obligations; this is in line with what Smith (2003) asserts. Train operators should start to use the information on wheels provided by the WPMS to develop the maintenance of the individual wheel, as well as that of the whole wheel fleet.

- Proactive wayside monitoring of wheels (through the WPMS) should be implemented as a tool for acquiring knowledge of the wheel fleet in service on the track and for maintenance planning of the track in the future. The WPMS should be developed further to provide information for decisions on the maintenance of infrastructure, and one should try to remove the bad wheels on the track to extend the service life of assets and to purchase more infrastructure for the money thereby saved.
- Only a small amount of research work has been conducted to combine different wayside measurement equipment data, and therefore this field of research is still in the development stage. Fröhling & Hettasch (2010) concluded their paper with the following sentence: *"Much is, however, still to be done before the wheel-rail interference system can be managed at a level in line with the available measuring technologies."* This sentence is consistent with the conclusion drawn from the research for this thesis that more research has to be performed concerning the utilisation of already existing information and the integration of new condition monitoring technology with existing systems.
- When analysing different items and systems, one should do so systematically using already developed tools such as FMEA. Such tools make research and development stable and the reliability of the item or system analysed will increase.
- A discussion should be started with maintenance contractors as to how the camera-inspection of S&Cs can in the short term improve the execution of maintenance and in the long term develop the maintenance process (IEC, 2010).

5.7. Future research work

Research should be conducted in the future to find applications of WPMS which would improve our current knowledge of the wheel-rail system and could be used as a basis for track access charges. One application would be the provision of information which would show how each train is wearing the track, which would signal the probability of RCF, and which would indicate when the axle load could be increased based on the RCF in certain conditions. This could be achieved using data from the wheels, data from the infrastructure manager on the track and rails, and data on environmental conditions such as the temperature and the humidity.

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Paper I

Reliability and measurement accuracy of a condition monitoring system in an extreme climate: a case study of automatic laser scanning for wheel profiles

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Abstract

The Iron Ore Line (Malmbanan) is a 473 km long track section located in northern Sweden and has been in operation since 1903. This track section stretches through two countries, namely Sweden and Norway, and the main part of the track runs on the Swedish side, where the owner is the Swedish Government and the infrastructure manager is Trafikverket (the Swedish Transport Administration). The ore trains are owned and managed by the freight operator and mining company LKAB. Due to the high axle load exerted by the iron ore transports, 30 tonnes, and the high demand for a constant ore and pellets flow, the track and wagons must be monitored and maintained on a regular basis. The condition of the wagon wheel is one of the most important aspects in this connection, and here the wheel profile plays an important role. For this reason an automatic laser-based wheel profile monitoring system (WPMS) has been installed on this line using a system lifecycle approach based on RAMS for railways. The system was prepared and installed and is being operated in a collaboration project between the freight operator and infrastructure manager. The measurements will be used to diagnose the condition of the wheels, and to optimize their maintenance further. This paper presents a study of the concepts and ideas of the WPMS, and the selection, installation and validation of the equipment according to a system lifecycle approach based on RAMS for railways. Results from the profile measurements and validation are shown. The system's reliability during performance in extreme climate conditions, with severe cold and large quantities of snow, is presented. Then the benefits, perceived challenges and acquired knowledge of the system are discussed, and an improved V-model for the lifecycle approach is presented.

Keywords

Condition monitoring, wheel profile, lifecycle, laser scanning, extreme climate, wheel maintenance

Introduction

The Iron Ore Line (Malmbanan) has been in operation for over 100 years and was originally constructed for an axle load of 14 tonnes, but has gradually been upgraded to withstand a load of 30 tonnes. The length of a normal iron ore train is 750 m, the number of wagons is 68 and the gross train weight is 8,520 tonnes.[1] The line has a mixed traffic which has a large range of vehicle speeds and consists of passenger and cargo traffic together with the iron ore transports.

The Iron Ore Line has the largest predicted traffic increase compared to all the other railway lines in Sweden, with a predicted growth of 136% between 2006 and 2050 due to the expansion of the mining industry in the north of Sweden.[2] To meet this demand for increased capacity, the asset manager must think in new ways and add more intelligence to the infrastructure, e.g. through automatic asset monitoring. In the words of Ollier,[3] "[Effective] asset management and the use of intelligent infrastructure are key factors in delivering the railway of the future."

For a railway system, the rail-wheel contact is an important factor for which the wheel and rail profiles play a significant role. The rail profile is measured using measurement cars or handheld MiniProf instruments. Due to the high axle load exerted by the iron ore transports and the high demand for a constant ore and pellets flow, the track and wagons must be monitored and maintained on a regular basis.

The condition of the wagon wheel profile is one of the most important aspects in this connection. Traditionally the wheel profile is measured manually using the MiniProf equipment. This is a tedious and time-consuming task and there is a need to increase the inspection frequency and automate the wheel profile measurement procedure in order to track wheel deterioration and remove bad wagons from service. The operator can benefit from this by using the information to optimize the wagon maintenance intervals[4] and reduce the risk of failing wagons causing delays in the delivery chain. The infrastructure manager can also use the information from a wheel profile monitoring system (WPMS) for management purposes, for reducing maintenance costs or even for preventing failures of and damage to the track.[5,6,8] Information on the wheel profile can also give knowledge of the rail degradation process and therefore increase the maintenance quality.[9]

Condition monitoring can be categorized into analysis, process monitoring, performance monitoring, functional testing and inspection.[7] The WPMS can be categorised under periodic inspection. There are numerous wheel condition monitoring systems installed along the Swedish railway network, focusing on warnings and alarms about wheel failures such as wheel flats and other types of out-of-roundness. Automatic measurement of the wheel profile is still an area where little research has been conducted in Sweden. There are still uncertainties regarding the availability and robustness of automated WPMS installed in areas with an extreme climate characterised by low temperatures and large amounts of snow. There is also a need to examine the possibility of reducing the failure-driven capacity consumption on a line by analysing the information from an automated wayside WPMS.

To find the parameters for that which is to be monitored, there is a workflow already proposed.[7] The purpose of the present paper is not to find the condition monitoring parameters, but to show how an already defined standard for railways can be used for a lifecycle approach for condition monitoring.

This paper also describes an adaptation of the lifecycle process in the EN-50126 standard (RAMS for railways) for an automated WPMS, dealing with the following components of that process: the system concept and idea, system requirement, system selection, installation and system validation. Moreover, the paper presents results from initial performance tests performed during the first year and the experience gained from the special collaboration setup within the installation and operation project for the WPMS.

Wheel profile monitoring system (WPMS)

The Swedish railway system is well developed and utilises equipment for condition-based maintenance of the rolling stock and the track. To inspect the rolling stock there are wayside detector stations for the detection of hot boxes, hot/cold wheels, damaged wheels, overloaded cars, unbalanced loads, contact wire lift, and pantograph and wheel-rail forces.[10]

Figure 1 shows a diagram presenting wheel monitoring systems for the railway where wheel profile monitoring is included. The WPMS consists of four separate units (A, B, C and D), one on each side of each rail, see Figure 2.

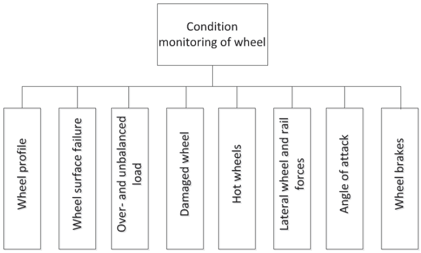

Figure 1: Condition monitoring of wheels for rolling stock.

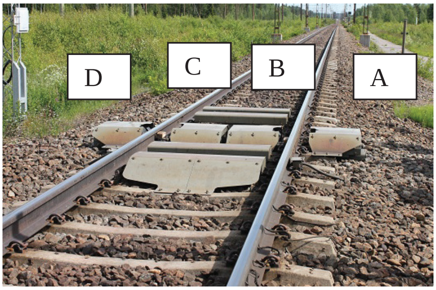

Figure 2: Wheel profile monitoring system located on the Iron Ore Line in northern Sweden.

These units contain a laser, a high-speed camera, and an electronic control system. When a train passes the units, the wheel triggers a sensor and the protection cover opens, the laser beam starts to shine, and then the camera takes pictures of the laser beam projected onto the surface of the passing wheels. These pictures are saved and an algorithm transfers the pictures of the wheel profiles to an xy-coordinate system. The coordinates can be shown using software and can be compared to the nominal wheel profile. This system can automatically measure and monitor the wagon wheel profiles at speeds up to 130 km/h.

The lifecycle of the WPMS

The present project involved a collaboration between the infrastructure manager and the main operator of the track. The infrastructure manager's commitment was to prepare the site with all the infrastructure needed for the installation. The operator's commitments were to purchase the WPMS and arrange and perform the installation of the measurement equipment together with the supplier. When the measurements started, the operator would be responsible for the spare parts and the infrastructure manager for the operation and maintenance of the equipment. See Figure 3 for the system lifecycle according to the V-model in EN-50126.[12]

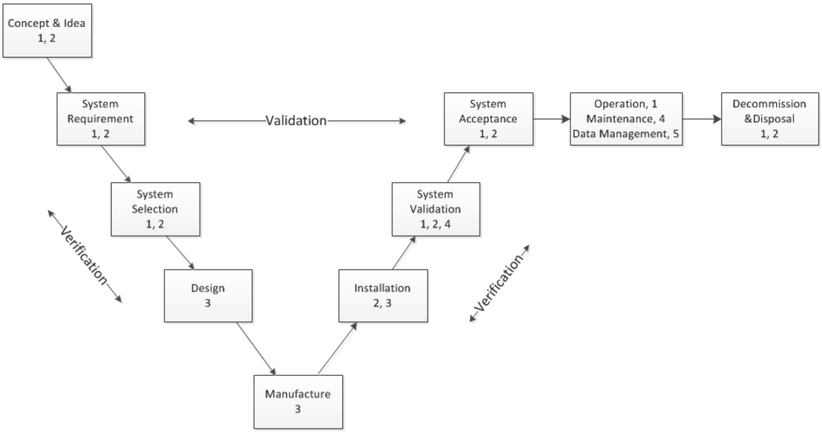

Figure 3: V-model representation of the lifecycle of a WPMS (adapted from EN-50126)
1-Infrastructure manager, 2-Train operator, 3-Supplier/Manufacturer, 4-Equipment maintenance company, 5-Data management organisation.

The whole system lifecycle consists of fourteen different stages, and the V-model used in this project is an adapted version of this, especially adjusted to fit this application. This paper will focus on the following steps: concept and idea, system requirement, system selection, installation and system validation. The other steps will be treated in another paper. The core team in the work performed in the different stages is the expert group, which consists of people from the infrastructure manager and the rolling stock operator, as well as a measurement expert from the railway sector. This group developed the selection criteria.

Concept and idea

"Concept and idea" is the first step in the lifecycle process in the EN-50126 standard, and in this step one starts to define what the basic concepts and ideas of the system are. Here the infrastructure manager and the rolling stock operator formulate the objectives of the project. The objectives come from the expert group and the company organisation and are set according to the company's maintenance goal. The infrastructure manager has the following maintenance goal: "Maintenance is carried out in order for traffic to be able to operate as the quality of service objectives imply, both now and in the future."[10]

The objectives were summarised as follows and they constitute the concepts and ideas of the WPMS:

- to gain more capacity for the busy Iron Ore Line, by decreasing the failure-driven capacity consumption,
- to find the maintenance limits for wheels in order to decrease the costs for the wheels and the rail,
- to investigate whether there are correlations between actual wheel profiles and different failures, for instance out-of-roundness and failures caused by high lateral wheel forces,
- to increase the effectiveness and efficiency in the railway system by using condition monitoring of wheel profiles.

These objectives are broken down into system requirements in the following section.

System requirements

This section describes the selection process for the WPMS.

Commercial WPMS

The first criterion was that only commercial WPMS were to be considered. It was deemed important to use a system that was already in operation, one of the advantages being that a large amount of operating information and references would be available. Spare parts would be available and an organisation for advice and support would already be in operation.

Suggestions for commercial WPMS could be found in a report by Brickle et al.,[5] where twelve systems for this purpose are presented, see Table 1. The aim of the report by Brickle et al. was to “identify and evaluate systems that monitor various features and aspects relating to wheel set condition, and to make recommendations for integrating these systems into a comprehensive condition monitoring regime”.

Table 1: Suppliers of wheel profile measurement systems that can be found on the open market.[5]

System	Company	System	Company
FactIS WPM	Lynxrail/TTCI	Wheel Profile Measurement Syst.	MRX Technologies
Treadview	Deltarail	Trackside Measurement System	Mer Mec
Wheelspec	ImageMap	Multirail Wheel Profile Diagnostics	Schenck Process
WheelCheck	Tecnogamma	Laser Measurement System	GHH Radsatz
Argus	Hegenscheidt MFD	WheelScan	KLD Labs
Model 2000 EVA	Talgo	Wheelview	Beenavision

General requirements

The following criteria were to be considered as the general requirements for this step of the evaluation process for the WPMS: system features, reporting capabilities, user-friendliness, availability, accuracy, performance, installation, deployment, speed requirements, maintenance and support. An investigation according to these criteria had already been conducted, resulting in the twelve different suppliers mentioned above.

Screening

By screening the candidate companies, the number of suppliers was reduced. In this step we sent a questionnaire to those companies whose existence we could establish. The screening criterion was that, if a company replied to the questionnaire that we had sent to them, then that company would be considered as a candidate supplier. If, on the other hand, no answer was received from a supplier, then that supplier would no longer be considered as a candidate supplier. After this screening five suppliers remained.

Special requirements

The special criteria set for the WPMS were the following: climate-resistance, measurement accuracy, photographing speed, vehicle identification, ease of calibration, maintainability and ease of installation. Some of these criteria have already been mentioned above.

Climate: The climate in northern Sweden is extreme and is characterised by cold winters, large quantities of snow, and snowstorms, but the summer can be fairly warm. The temperature can vary greatly for the same line; for example, for the stretch from Boden to Gällivare the temperature can vary by almost 70°C. That same section can have a maximum precipitation of 43 mm of rain on one day.[11] The average snow depth in the winter is usually around 60 cm, but there are large local variations. The WPMS must have a high level of reliability, especially during the winter, when the wear rate is considerably higher than during the summer.[4] The system has to work in extreme conditions, with a temperature range between +30°C and -40°C and with large quantities of snow.

Measurement accuracy: The accuracy must be as high as possible.

Photographing speed: The WPMS has to operate at line speed and photograph wheels moving at speeds in the range of 50-120 km/h, since the traffic speed is in this range.

Vehicle identification: The WPMS must be able to interact with the Automatic Vehicle Identification (AVI) system and to match data sent from the tag reader to the WPMS with wheels and wagons.

Calibration: The system must either be easy to calibrate or not need any calibration. It is an advantage if the system emits an alarm, through self-inspection, indicating when it is time for calibration of the equipment.

Maintainability: The system has to be easy to maintain and the time required for maintenance has to be as short as possible. Good maintenance support must be provided, with short delay.

Installation: Disturbance of the traffic cannot be accepted, either for preparation of the site or for installation. The installation has to take place in the empty slots in the timetable.

Summary: These main requirements listed above, together with the requirement of commercial availability, had to be met by the WPMS, and a survey was sent to each of the companies. Five suppliers were able to answer the survey, and these five remained in the evaluation (see the summary in Table 2).

Table 2: Performance of the five wheel profile monitoring systems left after screening.

Company	No. of systems in oper.	Min. speed [km/h]	Max. speed [km/h]	Radial accuracy +/- [mm]	Cold climate oper.	Calibration	Vehicle identificat.	Maintainability	Estimated installation time, approx. [hours]
A	12	5	120	1.5-2.0	Yes	No	Yes	Yes	No stop
B	12	0	40	0.2-0.5	No	Yes	Yes	Yes	4h stop
C	11	0	30	0.2-0.5	No	Yes	Yes	Yes	10h stop
E	5	0	130	0.25	Yes	Yes	Yes	Yes	No stop
F	7	0	130	0.5	Yes	Yes	Yes	Yes	No stop

The table above had enough precision for us to be able to select two systems for deeper scrutiny.

System selection

The evaluation was performed by an expert group comprising personnel from the infrastructure manager and the operator, together with a railway consultant. The most important requirements were high measurement speed and an easy installation of the equipment which did not entail any disturbances of the traffic. Of course, the system had to be able to survive and work properly in the cold climate concerned, but this was impossible to verify, other than by checking how many systems each supplier had in operation in a cold climate. This assessment of the systems was qualitative and not quantitative.

The most important features of the WPMS, as mentioned above, included good speed performance and climate-resistance and only three systems possessed these features, namely systems A, E and F. The requirement for measurement accuracy was set as “the highest possible accuracy” and, since one of these three systems had a significantly lower accuracy, two systems remained and both showed the same performance in this respect, namely system E and F. The next step was to invite the competing companies supplying these two systems to provide more detailed technical information and discuss business issues. After individual meetings with each supplier, one was found to meet our requirements more adequately and system F was selected.

Installation and validation

The selection process ended with the conclusion that one supplier fulfilled the requirements in the most preferable way. This supplier was awarded the contract to deliver the WPMS.

Preparation and installation

The installation of the WPMS was carried out in the autumn of 2011 by the supplier, and before the installation, the site was prepared by the infrastructure manager. The Investment Department of Trafikverket was responsible for organising the preparation of the site, and the actual work involved was carried out by contractors.

Performance test

The performance test consisted of two parts, a test of the measurement accuracy of the system and a test of the winter performance. The measurement accuracy test involved the comparison of measures from the measurement station with measures obtained with handheld measurement equipment. The purpose of the winter performance test was to investigate how the system survived a winter climate, by determining the number of faults that were due to the cold and the number of useful measurements in conditions characterised by snow and cold.

Measurement accuracy

When the test of the measurement accuracy of the equipment was passed, the supplier would receive the whole payment for the system. This performance test was carried out on thirty-two wheels and four different wagons moving through the site in November 2011. Then sixteen of these wheelsets (on wagon 4011, 4012, 4019 and 4020) were measured manually with a MiniProf instrument and the results were compared with the pictures generated from the measurement equipment. Figure 9 shows the profile of one wagon and one locomotive wheel of the iron ore train taken with the WPMS. The measurement parameters were the flange height, flange thickness and flange slope. The tread hollow wear was not presented since the measured value was zero in most of the cases.

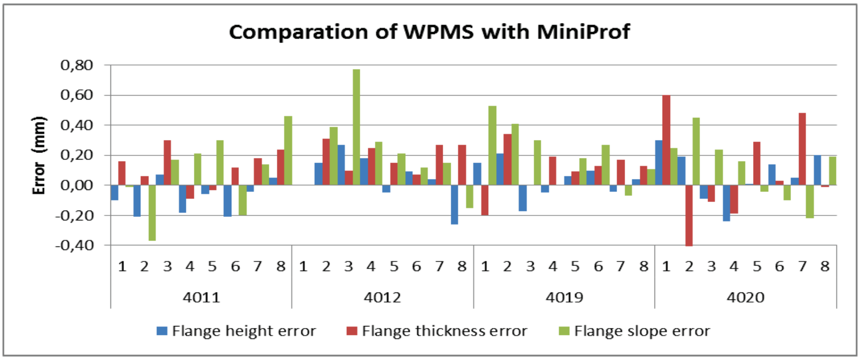

Figure 4: The errors of all the wagons and wheels that were measured, 4011-4020 are the wagon numbers and 1-8 are the wheel numbers.

The measurement of the wheels was performed in random places on the wheel, which means that the WPMS and the MiniProf instrument did not use the same measurement points. The compared measurements made by the WPMS and the MiniProf instrument showed good agreement with each other; see Figure 4 for measurement data. Some measurement parameters show a large deviation, for instance wagon 4020 and wheel 3 have a deviation for the flange slope of 0.77 mm. Wheel 1 on wagon 4012 was excluded due to a problem performing the measurements with the MiniProf instrument.

A boxplot diagram shows that these measurements have a different behaviour, the flange height is closer to zero and has a smaller spread compared to the others. The flange slope has the largest spread and all the measurements have a positive weight, see Figure 5. The reason why the flange thickness has a large spread can be the combination of two cameras (camera A and B see Figure 2) used when capturing the flange thickness. The reason why the flange slope has a spread in the plot can be the fact that the measurement reference of the slope has an accuracy problem or the fact that there is one large difference in the wheel circumference.

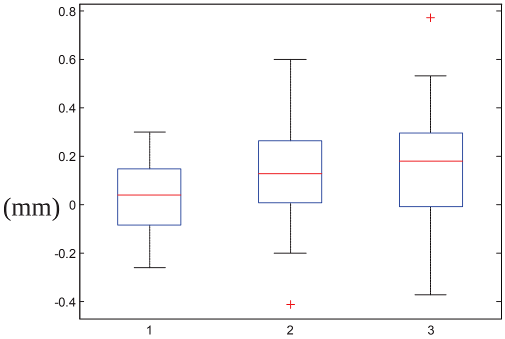

Figure 5: Boxplot of the measurement errors for the flange height (1), flange thickness (2) and flange slope (3).

Table 3 shows the mean and standard deviations for all the measurements except those for wheel 1 in wagon 4012, which were wrong due to the problem with the MiniProf measurements. The grouping information obtained using the Tukey method shows that the flange height error belongs to group A, the flange thickness error belongs to group A and B, and the flange slope error belongs to group B. This can be interpreted to mean that the flange height error and flange slope error do not have the same behaviour, which is consistent with Figure 5. The Anderson-Darling goodness-of-fit test shows that all these three measurements belong to a normal distribution.

Table 3: Performance test of the wheel profile measurement system – accuracy of the system compared to that of the MiniProf handheld measurement tool.

Statistics	Measurement error		
	Flange height	Flange thickness	Flange slope
Mean (mm)	0.02	0.13	0.17
SD (mm)	0.15	0.20	0.07

A wheel profile is not constant around the whole wheel; there is an average variation of 0.131 mm for the flange height (affecting the circumference) and of 0.145 mm for the flange thickness.[13] The accuracy of the MiniProf measurement equipment is ±10 µm.[14] These variations and the accuracy of the measurement equipment have to be taken into account, see Table 4.

Table 4: Performance test including the variation of the circumference of the wheel -accuracy of the system compared to that of the MiniProf handheld measurement tool.

Statistics	Measurement error		
	Flange height	Flange thickness	Flange slope
Mean (mm)	0.151	0.275	0.315

Winter performance

The winter performance test was divided into two blocks, of which the first concerned the measurement reliability and the second the system reliability. The measurement reliability for the winter season depended to a great extent on the snow smoke and the snow on the equipment. The system reliability depended more on whether the equipment worked in a cold climate and whether the components were damaged or degraded due to the extreme conditions.

Measurement reliability: For the winter month of April, around 45% of the data were useful, while the rest of the data were not usable, since the WPMS was not able to take pictures of the wheels. This can be compared to the month of May, when 90% of the data were useful, see Figure 6.

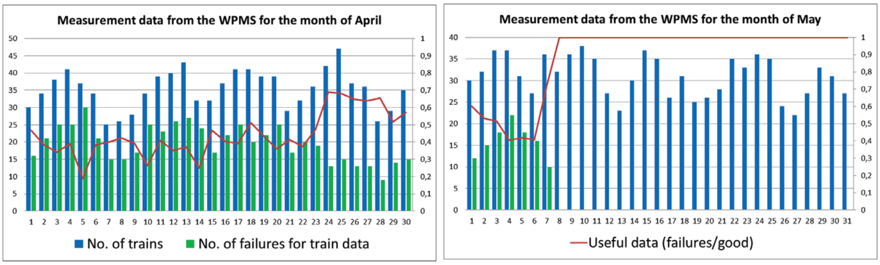

Figure 6: Measurement data from the WPMS for the months of April and May for the first year (2012).

The reason for this big difference may be snow smoke under the passing train and the system thus having problems photographing the wheel profile. There are two main reasons for the amount of missing data, the first reason being snowfall and snow blowing up due to passing trains, the second being failures of the measurement system due to mechanical and software problems. In this connection one can mention the fact that the last heavy snowfall for this season was on 4th-5th May, during which period there was a low percentage of useful data.

The failures in the system during this period concerned an axle sensor, which malfunctioned until 8th May, and problems with the communication between the camera and the computer which were remedied on 5th May. After that the snow melted away, the failures ended and the information from the system was useful, see Figure 4 after 8th May.

Figure 7a-b show two trains from the same day with different process rates; one train has a process rate of 97% and the other has a process rate of 6%.

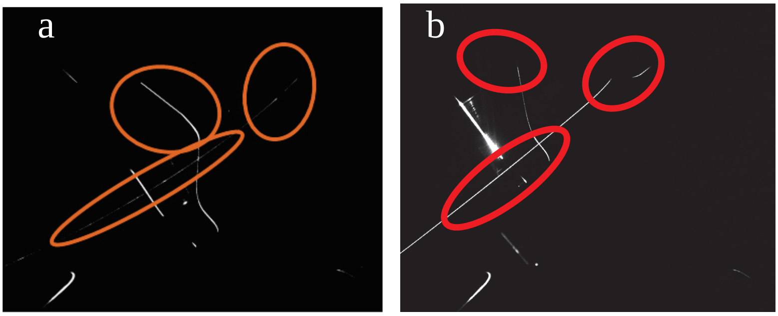

Figure 7: Picture from camera A with two different trains' different process rates on the same day. a) Iron ore train with a process rate of 97%, train no 26500 from 9/11/2013 – 19:14:48. b) Iron ore train with a process rate of 6%, train no 26494 from 9/11/2013 – 16:39:41.

The low process rate for some trains can be attributed to at least two reasons. The first can be the hunting motion of the train, resulting in the wheel drifting too much to the one side and the laser beam being projected onto a wrong position, with too small a spread of the laser, or in the flange shadowing a part of the laser beam. A comparison of Figure 7a and Figure 7b shows that the laser beam in the rotation direction is different. In Figure 6a the laser beam is on the wheel tread and in Figure 7b the laser beam is on the wheel flange root. The second reason for a low process rate can be the velocity of the passing train, since trains with a lower velocity than 40 km/h show a process rate under 40%. The reason for this is that there is no adaptive algorithm that takes into account the time between passing the sensor and taking a picture of the wheel profile. If the speed of the train is too low, the wheel is in the wrong position and this gives a wrong picture or no picture at all.

System reliability: At the beginning of the system's operation, there were problems with the router and the residual current switch. During the winter the system encountered problems with a failed sensor. The wheels piled up ice and snow on top of the sensor, and after a while the sensor broke due to the wheel load; the broken sensor is shown in Figure 8. This sensor triggers the start of the WPMS and is an important part of the system.

Figure 8: Failed sensor belonging to the wheel profile monitoring system (photo by Dan Larsson).

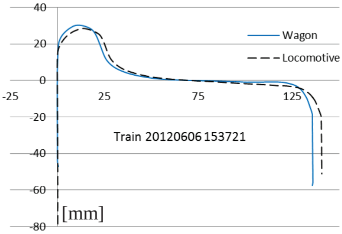

Figure 9: Measurement data from WPMS, wheel profiles of one wheel of the iron ore train. Wagon shown by the solid line and locomotive by the dashed line.

Moreover, a short circuit in one of the rail heaters caused problems for the traffic and it took several days to detect this failure (for failures see Table 5). The router was replaced with another one, the residual current switch was removed, and these problems were thereby solved. The problem of the sensor breaking due to the snow and ice load could be eliminated by placing heaters close to the sensor to keep out snow and ice. The problem with the short circuit was fixed with an insulating distance between the heater and the rail.

Table 5: Problems during the installation and almost two years of operation for the WPMS.

Problem	Component	Reason	Improvement
No connection	Router	Faulty router	New router
Current turned off	Residual current switch (RCS)	Humidity	Removal of the RCS
Short circuit	Heater	Humidity/cold	Insulating distance
Failed	Axle detector	Ice and snow	Heater/new type of detector
Failed	Current converter for one laser	Unknown	No improvement

The system acceptance is a commercial issue and cannot be presented in this report.

Discussion

This form of cooperation between the infrastructure manager and the rolling stock operator gives the possibility of sharing the risk and the cost involved when new technology is implemented and evaluated in the field. Moreover, both parties derive the same advantages from the investment without competition for data and information. Furthermore, both parties have the same incentive to enhance the capacity of the Iron Ore Line, through improving the maintenance quality of the rolling stock and the track assets to meet the demands of the future.

The WPMS has already provided great benefit by triggering alarms indicating wheels that have exceeded the permissible range and has already enhanced the capacity on the track. The reliability of the winter performance was adequate for this equipment. Snow and other running-in problems were reasons for incomplete measurements during the first winter. Hopefully the improvements made in the system will increase the reliability of the WPMS during the coming winter season.

The work presented will lead to the implementation of additional activities and research:

- Integration of the information from the WPMS in the computerised maintenance management system (CMMS). (This integration has already been started by the operator.)
- More research is needed to design models for interpreting and predicting the results from wheel profile monitoring, as a foundation for maintenance decisions.
- Research should be conducted to determine the number of bad wheels running on the track and what benefits the infrastructure manager can gain in terms of capacity enhancement and cost reduction if this number can be minimised.
- Further research should focus on the economic threshold for rolling stock wheels to extend the useful service life of railway assets.
- Further research should be conducted to investigate how this system can work together with already existing systems for monitoring rolling stock.
- Further research should be performed to investigate whether the wheel-rail interface optimum is dependent on the wheel and rail profile and whether there is a degradation model for the rail that represents this condition.

Suggestions for capacity enhancement when the WPMS is in use are as follows:

- Wheel maintenance should be planned better through the monitoring of wheel profiles.
- Bad wheels should be selected for removal from the railway.

Conclusions

There is a great variety of wayside condition monitoring equipment in use on railways. This paper shows that the lifecycle approach from EN-50126 can be used to introduce new condition monitoring systems which suit railway applications and which also function in extreme climates. The paper presents the deployment of the important steps in the lifecycle approach: concept and idea, system requirement, system selection, installation and system validation.

The accuracy of the laser wheel profile measurement system compared to the MiniProf measurement equipment corresponded to a deviation under 0.2 mm for the flange height, 0.3 mm for the flange thickness and 0.32 mm for the flange slope, when the test included the variation of the circumference.[13] This accuracy is probably good enough to make it possible to use the wheel profiles to plan the maintenance process.

The goodness-of-fit test shows that all three measurements (of the flange height error, flange thickness error and flange slope error) belong to a normal distribution, and that the flange height error and flange slope error do not have the same behaviour.

The speed of the train influences the process rate in such a way that speeds under 40 km/h have low process rates.

The measurements' reliability for the month of April 2012 was around 45%, basically due to failures of system components. The reliability increased to around 100% when the snow melted, as shown by the data at the end of May 2012.

The system reliability was disturbed by problems and failures in components such as the router, the residual current switch, the heater for removing snow, the axle counter and the current converter for the laser.

The infrastructure manager and the rolling stock operator both have potential benefits to reap from the newly installed WPMS. The new maintenance principles and concepts resulting from the information obtained from the equipment are as follows:

- the introduction of a proactive type of inspections of rolling stock in the Swedish railway network;
- a better status check of the wheels for the rolling stock fleet;
- less expensive and time-consuming manual inspection of wheels;
- information for the maintenance organisation for planning the re-profiling of wheels;
- use of the information obtained to develop maintenance principles for wheels;
- probably higher safety on the track;
- in the long run, less capacity consumption due to wheel failures.

Acknowledgments

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Paper II

A study of railway wheel profile parameters used as indicators of an increased risk of wheel defects

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Abstract

The capacity demands on the railways will increase in the future, as well as the demands for a robust and available system. The availability of the railway system is dependent on the condition of the infrastructure and the rolling stock. To inspect the rolling stock and to prevent damage to the track due to faulty wheels, infrastructure managers normally install wayside monitoring systems along the track. Such systems indicate, for example, wheels that fall outside the defined safety limits and have to be removed from service to prevent further damage to the track. Due to the nature of many wayside monitoring systems, which only monitor vehicles at definite points along the track, damage may be induced on the track prior to fault detection at the location of the system. Such damage can entail capacity-consuming speed reductions and manual track inspections before the track can be opened for traffic again. The number of wheel defects must therefore be kept to a minimum. In this paper wheel profile parameters measured by a wayside wheel profile measurement system, installed along the Swedish Iron Ore Line, are examined and related to warning and alarm indications from a wheel defect detector installed on the same line. The study shows that an increased wheel wear, detectable by changes in the wheel profile parameters could be used to reduce the risk of capacity-consuming wheel defect failure events and its reactive measures.

Keywords
Condition monitoring, wheel profile, wheel impact detector, wheel defect detector, laser scanning, wheel maintenance

1 Introduction

According to a White Paper issued by the EU Commission, the railways need to increase their efficiency and their share of the transport sector, improve their competitiveness, and decrease greenhouse gas emissions. The capacity demands on the railways will therefore increase in the future, as well as the demands for a robust and available system. The demands for increasing traffic will reduce the time for train-free periods, which will reduce the available time for support processes such as maintenance actions on the infrastructure.

To ensure a certain level of availability with increasing traffic, optimal maintenance policies and plans must be implemented. These plans have to include different stakeholders, since the railway branch often has a multi-stakeholder structure with identifiable boundaries between the stakeholders.

Due to the inherent characteristics of the capacity of a railway system, the failure-driven capacity-consuming events within a railway network should be kept to a minimum. This can be achieved by the use of appropriate existing and new condition monitoring systems, which can detect and predict failure events at an early stage.

Condition monitoring systems will decrease the operational risk, enhance performance and in the long run contribute to cost reduction. In the Swedish railway network, wayside equipment for rolling stock monitoring was first installed and put in use in 1996 and today there are 190 wayside inspection devices along the railway network. There are wayside inspection systems for the detection of hot boxes, hot/cold wheels, damaged wheels, overloaded cars, unbalanced loads, contact wire lift, pantograph condition and wheel-rail forces[1].

From the perspective of the infrastructure manager, maintaining the wheels in good condition and minimizing the number of wheel defects are important to prevent accelerated deterioration of the infrastructure which decreases its life length.

Wheel defects failure modes mostly have operational consequent since it constitutes capacity-consuming reactive measures to isolate and assess the extent of damage on the infrastructure. When a wheel defect is detected, time-consuming inspection of the track and sometimes maintenance actions are needed. Even though no maintenance actions are performed, these events limit the traffic since the speed is reduced along the track section concerned until the inspection has been carried out. In most cases this inspection is manual, and the length of the track section to be inspected depends on the extent of the damage and the prevailing temperature, and is decided by the traffic control centre[2]. Therefore, from a capacity perspective, it is important to reduce the amount of faulty wheels in a preventive way. Wheel defects can be classified into different failure categories based on the associated root causes and failure mehanism, see Figure 1.

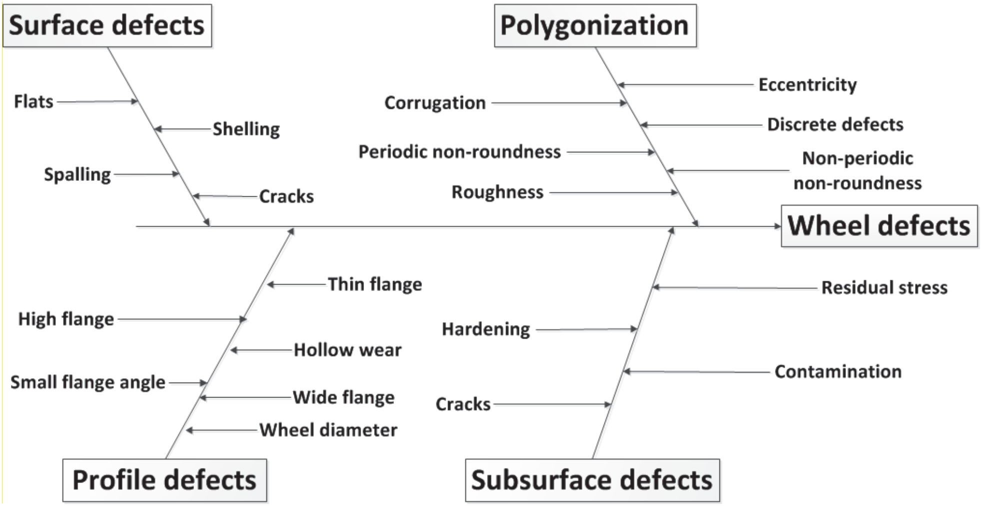

Figure 1: Wheel defects divided into four groups: surface defects, polygonization, profile defects and subsurface defects[3,4].

This paper presents a study of railway wheel profile parameters used as indications of an increased risk of warning and alarm from wheel defect detectors. The aim of the study has been to reduce the risk of capacity-consuming failure as a result of wheel defects and track deterioration. The following two sections describe the wheel defect detector and the wheel profile measurement system used in this study. These sections are followed by a description of the data collection procedure, analysis method and results. The paper ends with concluding remarks and discussions about important aspects of the study.

2 Wheel defect detector

The purpose of the wheel defect detector (WDD) is to minimize further damage to the infrastructure due to out-of-round wheels[5]. A wheel defect detector uses strain gauges, accelerometers or optical sensors to measure the wheels of passing trains[6]. Figure 2 shows a wheel defect detector installed on the Swedish Iron Ore Line.

Figure 2: Wheel defect detector installed along the Iron Ore Line in the northernmost part of Sweden.

This wheel defect detector measures the forces from the wheel. In Figure 3 the different loading scenario is shown in the event of wheel defect: this include the static train load and dynamic load from wheel defect which give rise to force peak[7].

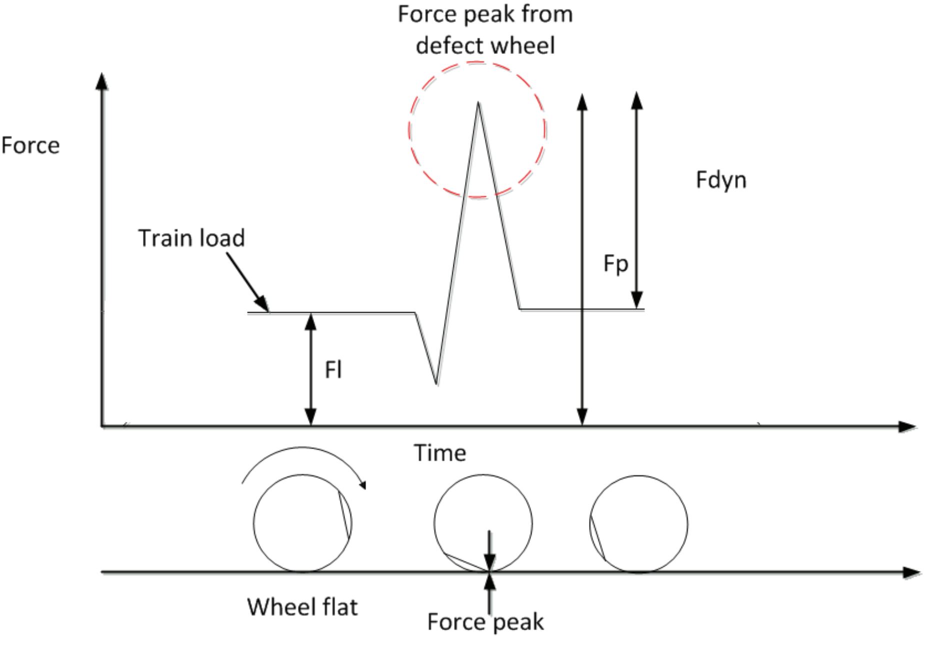

Figure 3: Hypothetical description of the force load of a wheel defect[7].

The definitions of the forces are as follows: Fp is the force peak, Fdyn is the dynamic supplement, Fl is the wheel load from the train, and R is the ratio between Fp and Fl, see Formula 1.

$$Ratio\,(R) = \frac{Fp}{Fl} \tag{1}$$

The normal alarm and warning limits for these forces are as follows: 240-425 kN for the force peak, 155-240 kN for the dynamic supplement, and 3.7-4.2 for the force ratio; these values depend on the train type and speed[8]. In the Swedish railway network the wheel-rail vertical contact forces detected by the wheel defect detector are used to diagnose the status of the wheel conditions of the rolling stock. A three-stage classification of the wheel is used where high forces generate an alarm and medium forces generate a warning, see Table 1.

Table 1: Wheel defect detector warning (W) and alarm (A) limits for different vehicle types (sucrose Trafikverket).

Types of W & A	Vehicle	Warning	Alarm
Peak (kN)	Cargo car		350
	Pass. car		350
	Loco.		425
Dynamic suppl. (kN)	Cargo car	160	
	Pass. car	155	
	Loco.	240	
Ratio (dimensionless)	Cargo car	4.2	
	Pass car	4.2	
	Loco.	3.7	

Wheel failures are not always easy to detect visually. Only half of all the wheels with a force peak over 400 kN have visual indications of unacceptable damage[3]. An indication of increased force values from the wheel defect detector can be due to an out-of-round wheel. An out-of-round (OOR) wheel is a wheel with some kind of deformation on the surface, and this deformation can have a large number of shapes and different root causes. This wheel defect causes dynamic forces which can cause damage to the rolling stock and the track. The development of irregularities on the wheels depends on the dynamics of the rolling stock and the track system[3,9].
The classification of out-of-roundness defects can be made as follows: defects due to eccentricity, discrete defects, corrugation defects, periodic non-roundness, non-periodic non-roundness, roughness, flats, spalling and shelling[3]. These defects can also be divided into two main types: Type A – tread defects initiated and Type B – polygonization[4].

Wheel flats can be considered as discrete out-of-roundness defects. A wheel flat is a flat part of the wheel which can have different root causes, e.g. locking brakes, brakes in bad condition, frozen brakes, and bad adhesion between the wheel and rail, for instance due to leaves on the rail. A wheel flat is classed as a Type A out-of-roundness defect[4]. The approximate length of a flat which would generate an alarm is around 60 mm[8]. It is common for cracks to appear at the position of a wheel flat created by a sliding wheel. Research has shown that almost 66% of all wheels have detectable cracks after sliding[10].

3 Wheel profile measurement system

In the year 2011 the first wheel profile measurement system was installed in Sweden, along the Iron Ore Line, see Figure 4. The iron ore transport operator uses the wheel profile measurement system to detect wheels which fall outside the safety and maintenance limits. The Iron Ore Line is located in the northernmost part of Sweden and is the only iron ore line in Europe; this is a single track with a length of 473 km and an axle load of 30 tonnes. The line is one of the busiest lines in Sweden and, due to future increases in the volume of iron ore being transported, there is a risk of the line falling short of the capacity/service quality demand. The Iron Ore Line has the largest predicted traffic increase compared to all the other railway lines in Sweden, with a predicted growth of 136% between 2006 and 2050 due to the expansion of the mining industry in the north of Sweden[11].

The wheel profile measurement system installed on this line consists of four units with lasers and high-speed cameras; for more details see ref 12. Beena Vision[1]. Pictures of the wheel tread taken with a projected laser beam are transformed into wheel profiles in an xy-coordinate system.

Figure 4: Wheel profile measurement unit installed in the southern part of the Iron Ore Line.

The measured profile can then be analysed with respect to a nominal wheel profile and different wheel profile measures. Figure 5 shows an example of a measured wheel profile plotted together with an original wheel profile shape. The installed wheel profile measurement equipment extracts the following parameters from the

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[1] http://www.beenavision.com/products_wheelview.html

wheel profiles: the flange height (Sh), flange width (Sd), flange slope (qR), tread hollowing and (Th)[12]. Table 2 shows the safety limits for the flange thickness, the flange angle and the tread hollowing.

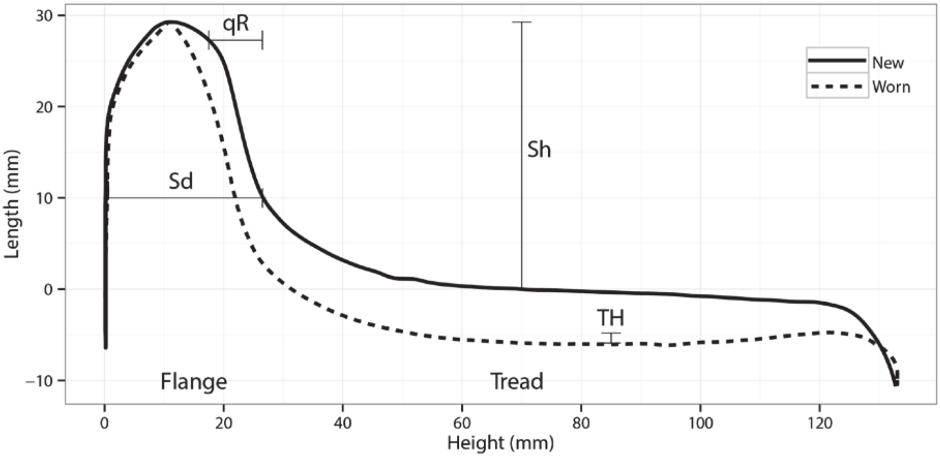

Figure 5: Original and worn wheel profiles measured by the wheel profile measurement system. The wheel profile parameters are illustrated in the figure. Sh: flange height, Sd: flange thickness, qR: flange slope, and Th: tread hollowing.

Table 2: Limits for wheel profile measurements

Limits	Sh	Sd	qR	Hw
Safety	36	22	6.5	2
Maintenance	34	22.5	7	1.5

4 Data collection and analysis method

During one month (April 2013) a number of trains operating along the Swedish Iron Ore line and representing mixed traffic were studied. A total of 28 train sets, including a total of 6,933 wheels, were analysed during this period. Data from the installed wheel profile measurement equipment were extracted and sent to a specially designed e-maintenance lab[2] where the wheel profiles data were stored together with the corresponding wheel profile parameters described in previous sections. The different wheel profiles were then categorised into two groups using information from the wheel defect detectors installed on the Iron Ore Line. The first group contain the profiles of wheels that did not trigger any alarm or warning indication from the wheel defect detector system. The second group contain the profiles of wheels that generated a warning or alarm. The information from the wheel defect detector was manually extracted from databases connected to the system.

For each group the wheel profile parameters were plotted in diagrams visualising the distribution of each parameter. Each parameter was plotted in a graph illustrating the difference between the distributions for wheels with no defect indications and wheels with indications of alarms/warnings.

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[2] www.ltu.se

5 Results and discussion

Out of the 6,933 wheels measured in this study, the wheel defect detector indicated warning/alarm for 31 wheels (29 warnings and 2 alarms marked with black dots in the result figures). The remaining 6,902 wheels were classified as healthy wheels with neither alarm nor warning indication. Figures 6-9 show the parameter values plotted for all the wheel passages during the complete measurement period. The upper graphs illustrate the healthy wheels and the lower graphs the wheels with an alarm/warning indication.

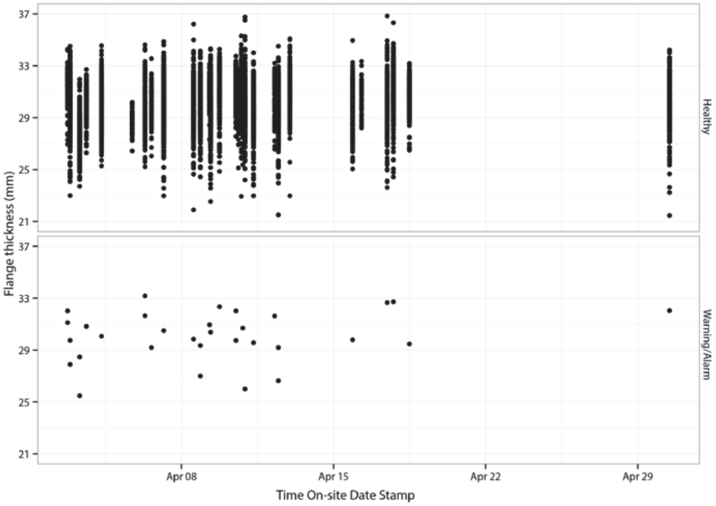

Figure 6: Parameter value Sd plotted for all the wheel passages during the measurement period. The upper graph illustrates the healthy wheels and the lower graph the wheels with an alarm/warning indication.

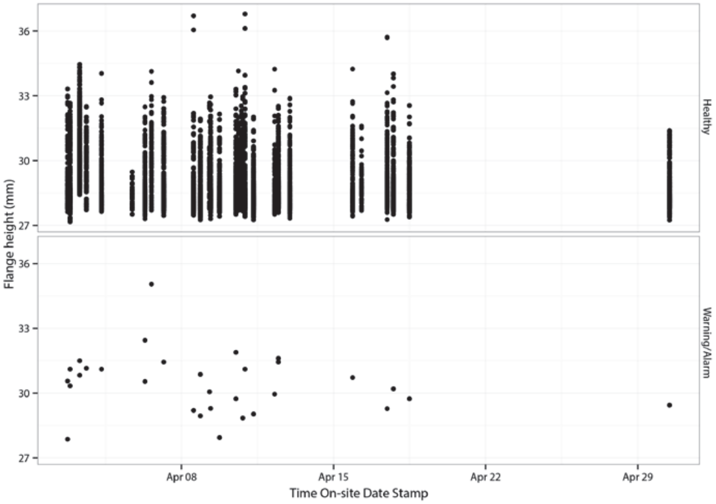

Figure 7: Parameter value Sh plotted for all the wheel passages during the measurement period. The upper graph illustrates the healthy wheels and the lower graph the wheels with an alarm/warning indication.

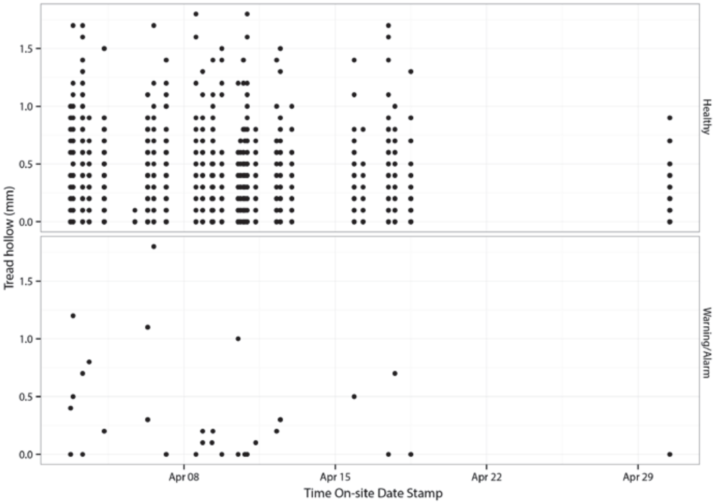

Figure 8: Parameter value Th plotted for all the wheel passages during the measurement period. The upper graph illustrates the healthy wheels and the lower graph the wheels with an alarm/warning indication.

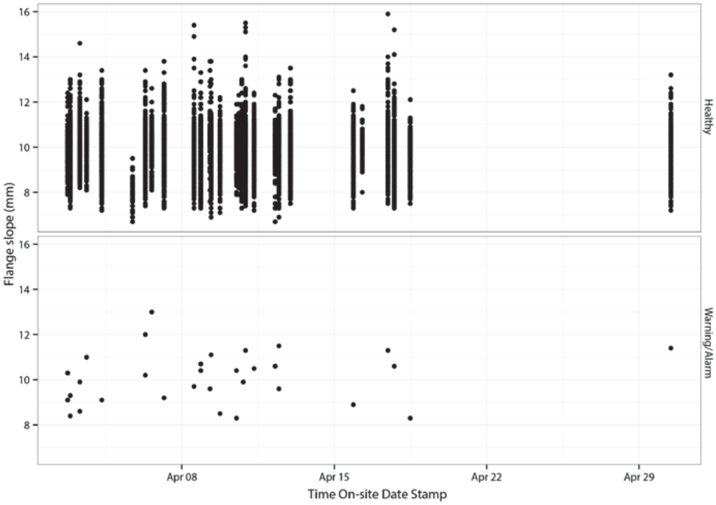

Figure 9: Parameter value qR plotted for all the wheel passages during the measurement period. The upper graph illustrates the healthy wheels and the lower graph the wheels with an alarm/warning indication.

In Figure 10 the flange thickness distribution is plotted for the two wheel categories. Going from a large flange thickness in the direction of a thinner flange, the distributions for the two groups follow each other for a while. However, below a thickness of 30 mm, the distribution for the wheels with warnings and alarms differs from that for the healthy wheels. By examining the plotted Sd-distributions, an indication of a reduction in the amount of profiles in the span 27.5-29 mm and an increase in the span 24-27.5 mm can be seen. An increased amount of profiles with a thinner flange is consistent with wheels exposed to a larger amount of wear and usage, which is also consistent with an increased risk of the occurrence of wheel defects.

In Figure 11 the flange height distribution is plotted in the same way as the flange thickness distribution was plotted in the previous figure. By examining Figure 11, a big difference can be detected regarding the shapes of the distribution curves for the two wheel categories. Wheels with warning and alarm indications show a higher density for larger values with a peak in the distribution around 31 mm, while the distribution for the healthy wheels shows a peak at 28 mm. Studying the flange slope distribution plotted in Figure 12, one can see that the distribution for the healthy wheels indicates a peak value around 10 mm. The distribution for the wheels with warnings and alarms shows a decreased density in this region and an increased density around 12 mm. The behaviour of the flange height and flange slope is also consistent with an increased wear and usage and hence an increased risk of wheel defect indications. Figure 13 shows the plotted distribution of the tread hollow wear, which also indicates an increased risk of wheel defect indications with an increased value of the tread hollowing.

The wheel profile measurement system only measures the profile at a discrete point along the circumference. Therefore, the profile variation must be taken into account when analysing the profile measurement results. In a study published by Fröhling[13], there is an average variation of 0.131 mm for the flange height, 0.145 mm for the flange thickness and 0.087 mm for the hollow wear. This variation is approximately one tenth of a millimetre and does not affect the results in this study in a significant way. The accuracy of the measurement equipment is also a factor that must be considered when analysing the results. In a performance test study of for this equipment published by Asplund[12], there is an average variation of 0.02 mm for the flange height, 0.13 mm for the flange thickness and 0.17 mm for the flange slope this compared to measurement done by MiniProf. The accuracy of the wheel profile measurement system used in this study is under 0.2 mm which also represents a deviation which can be considered as small in relation to the results presented.

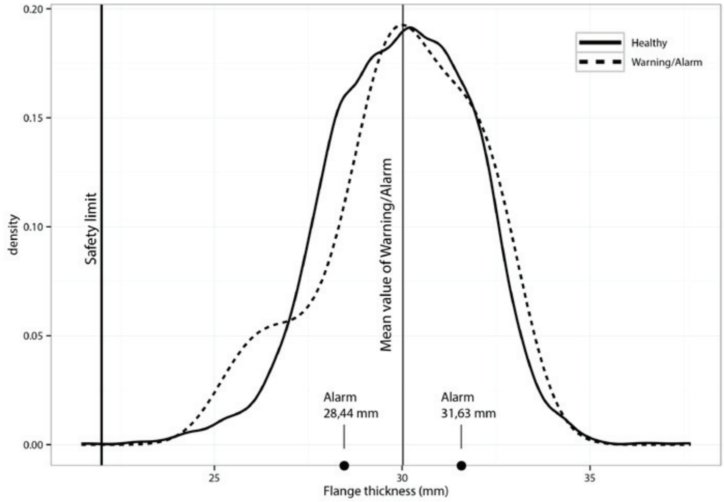

Figure 10: Flange thickness (Sd) distribution plotted for healthy wheels and wheels with a defect indication. Values for the two wheels with alarm indication are marked with black dots and mean value of warnings and alarms is 30.02 mm.

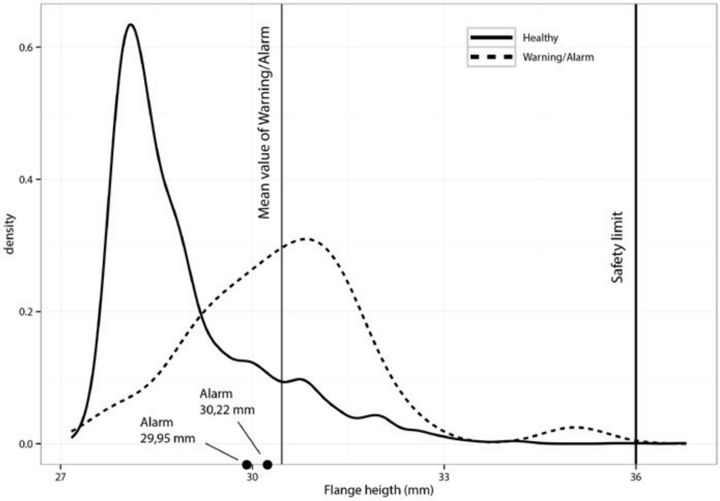

Figure 11: Flange height (Sh) distribution plotted for healthy wheels and wheels with a defect indication. Values for the two wheels with alarm indication are marked with black dots and mean value of both warnings and alarms is 30.46 mm.

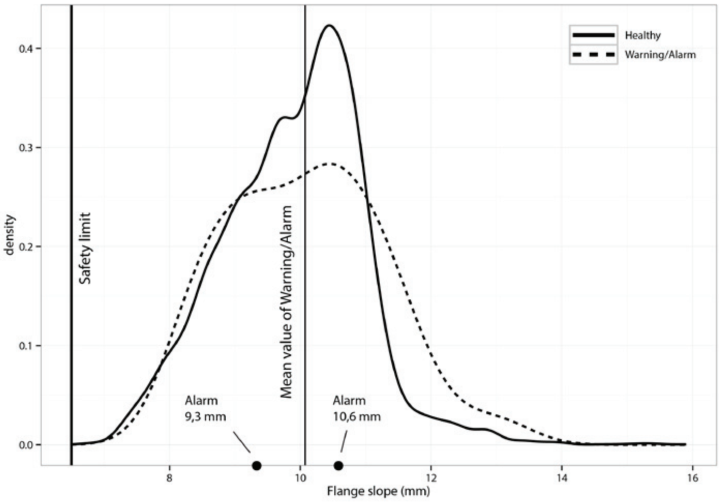

Figure 12: Flange slope (qR) distribution plotted for healthy wheels and wheels with a defect indication. Values for the two wheels with alarm indication are marked with black dots and mean value of both warnings and alarms is 10.07 mm.

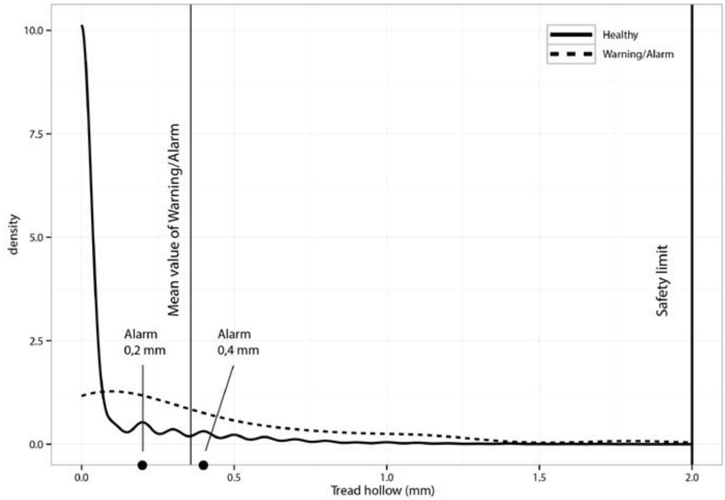

Figure 13: Tread hollowing (Th) distribution plotted for healthy wheels and wheels with a defect indication. Values for the two wheels with alarm indication are marked with black dots and mean value of both warnings and alarms is 0.36 mm.

6 Conclusions

The distribution of all the examined parameters of the wheel profile measurement system, Sd, Sh, qR and Th, showed a behaviour consistent with an increased wear and usage in the distribution plots for the wheels with alarm and warning indications. An increased flange height (Sh) shows the most conclusive relationship in the distribution plot to an increased risk of wheel defect indications compared to the other wheel profile parameters examined. The results indicate that, if one sets the wheel maintenance limit to a flange height of 30.46 mm instead of 34 mm, more than half of the wheel defect warnings can be removedand resulting capacity consuming reactive measures avoided. . This conclusion must, however, be analysed in greater detail in a research study where the total amount of examined wheels is increased. The different trains studied should be grouped into categories with respect to their load and operator, and the warnings and alarms should be divided into separate groups or analysed on a parameter level using the following wheel defect detector parameters: the force peak (Fp), dynamic force (Fdyn) and force ratio (R). Furthermore, it can also be inferred that aggregating the information in the individual wheel profile parameter using a composite indicator will give an appreciated indication of wheel defects. In future work, the reduction in the wheel defects achieved by using the wheel profile parameters as indicators of an increased risk of wheel defects will be ascertained and quantified in terms of its cost implication. A life-cycle-cost analysis, considering the consequential increase in wheel maintenance cost and benefits from reduction in the wheel defect indications will be done.

7 Acknowledgements

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Paper III

Inspection of railway turnouts using camera

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Abstract

The railway turnout is an essential component in a railway system, used to divert traffic along different tracks. A turnout includes a number of different parts, including the switch blade, frog, point machine, switch roller, soleplate, check rail, wing rail, drive rods, control rods and other bars. These parts must be kept in good condition, meeting functional and safety requirements. Failing to comply will result in a reduction of the network's capacity with economic consequences. Not honouring the safety limits could result in severe accidents, including derailment, causing human casualties. By performing the right type of inspection and/or maintenance at the right time, these unwanted events can be reduced. To determine if and when a maintenance action should be performed, the condition of the turnout must be established, usually by manual inspections or with measurement vehicles. The drawback is the discrete nature of these inspection events. Failure modes with development times shorter than the inspection interval could result in a malfunction of the unit. An on-line measurement system would be able to deal with these failure events and initiate correct maintenance actions at an earlier stage. With an on-line system, remotely located turnouts could be inspected without on-site personnel. Capacity consuming failures of turnouts with a strategic location or with bottleneck characteristics could also be corrected before they affect traffic. This paper describes a feasibility study of a camera based inspection system for turnouts and discusses the effect the method could have on system reliability and capacity.

1 Introduction

The railway has many advantages, including the ability to transport people and cargo in an effective, efficient, environmentally friendly and safe way. Its disadvantages include constraints in flexibility and a large demand for resources, for instance, in operation and maintenance. The railway turnout is an essential component of a railway system. Turnouts increase flexibility by diverting traffic, but they need many resources to work properly. In addition, attaining good track flexibility requires a large number of turnouts; for example, the Swedish railway network has 10799 turnouts on a track length of 12000 km. A turnout consists of many different parts. Because of their complexity and because they have a high safety and economic impact on the railway infrastructure, turnouts require careful monitoring.

The inspections of turnouts can be divided into four types; simple visual inspection, detailed visual inspection, measured inspection and non-destructive testing. Actions resulting from the inspection reports or failures include adjustments, lubrications, cleaning/rinsing, functional checks, repair, replacement, grinding and tamping [1].

Of all infrastructure-caused train delays in the Swedish network from 2004 to 2006, 17% were attributed to turnouts [2]. The failure of an individual turnout can cause problems for the railway, including costs and lost train operation. The turnouts (switches and crossings) account for about 13% of the yearly maintenance budget for the Swedish railway infrastructure and cause many delays, as mentioned above. The maintenance costs depend on the traffic load, the type of traffic and type of turnout. The degradation of the turnout has a significant relation to the load [3]. The highest maintenance costs are for turnouts on the iron ore track in the northern part of Sweden; this cost is due to the higher axel load and the more extreme climate, including cold weather and snow during the winter [4].

The turnout fleet in Sweden is old; many turnouts have already passed their technical life length and many more will do so in the next ten years [5]. Therefore, we can expect higher maintenance costs, combined with increased traffic disturbances in the near future. This calls for more inspections and better condition monitoring of the turnouts. A camera could facilitate maintenance inspections, thus enhancing the track capacity and saving maintenance costs. Manual inspections are expensive and in many cases impossible due to high capacity demands for the track; in any event, the trend is towards fewer human inventions on the track. There are also turnouts in inaccessible terrain where the only access is by the track; problems in these areas can lead to a large loss in the capacity of service.

Condition monitoring can be categorized into analysis, process monitoring, performance monitoring, functional testing and inspection [6]. This paper discusses camera inspection of turnouts and what can be measured using a camera. The current methods for inspecting turnouts are the following: geometry cars, continuous monitoring using sensors, mechatronic systems, measuring instruments and ultrasonic tests [7].

Much work has been done on the condition monitoring of railway turnouts. Many papers discuss the application of tools, such as machine vision algorithms and a filter approach, to improve the performance of turnouts [8, 9, 10]. A vehicle has also been developed to inspect turnouts; it has been used in field tests in US and UK to determine the wear of turnouts [11]. Cost benefits have been studied using condition monitoring equipment and LCC calculations in a real case study; the approach includes the penalty costs and maintenance savings [12]. There is also on-going work to develop trolleys to inspect turnouts using lasers [13].

Based on the review done by the author, well-structured decision support model, for defining condition monitoring parameters, is yet to be developed or adapted for the railway sector, though their exist similar decision support models in other sectors [6]. Maintenance decisions support model and how to deal with failure consequences can be found for instance, in ref [14] and [15]. These discussed how to choose the right maintenance actions based on failure consequences and the right maintenance strategy for an item. These articles addressed the following questions: can the item be condition monitored? Are these cost effective and can these improve the effects of maintenance? However, not how this can be done, how to find the critical measures and how to be certain that all critical failure modes will be included and documented in a systematic way. Furthermore, the demand for high safety within the railway branch requires that risk assessment should be well defined and well developed, which has not yet been adequately presented in a decision support model.

Camera vision systems are already used to monitor the couplings between wagons and to inspect rolling stock by taking pictures of, for instance, the springs and brakes [16]. However, the literature does not mention the criteria for choosing which turnouts should be inspected with a camera vision system, or how camera inspections can decrease risk and increase track capacity.

This paper presents a feasibility study of using a camera inspection for railway turnouts and offers an adapted decision support model for choosing appropriate inspection tasks. This model work flow includes the following steps; analysis and selection of critical equipment, risk management, analysis of types of condition monitoring activities, and assessment and decision-making [6]. This paper shows what degrades turnouts and discusses the potential for using Failure Mode and Effect Analysis (FMEA) to define the inspection tasks for turnouts. It ends with a discussion and proposal for future work.

2 Defining work flow

This section begins with a breakdown of a turnout’s characteristics; it then discusses turnout degradation and the function of a turnout on three levels. It shows the work flow and the use of FMEA to determine what measures can be extracted by a camera.

2.1 Turnout characteristics

Before determining if a camera can be helpful, it may be useful to define a turnout and its subsystems as well as its functions and typical causes of degradation. The breakdown of a turnout includes 14 different sections; see Fig. 2a, [17].

The next step is to define the function at each level: level 0, level 1 and level 2. The level 0 function is to “allow vehicles to run along varying routes” and level 1 function is to “support movements of train” and “direct path of train according to signalling commands”. This function can breakdown into more detailed levels; see INNOTRACK [18].

Factors influencing degradation at each level are design, manufacturing, maintenance and operation. All have sub-causes that influence degradation as well. Fig. 1 provides a fishbone (effect-cause) diagram of the degradation of a turnout.

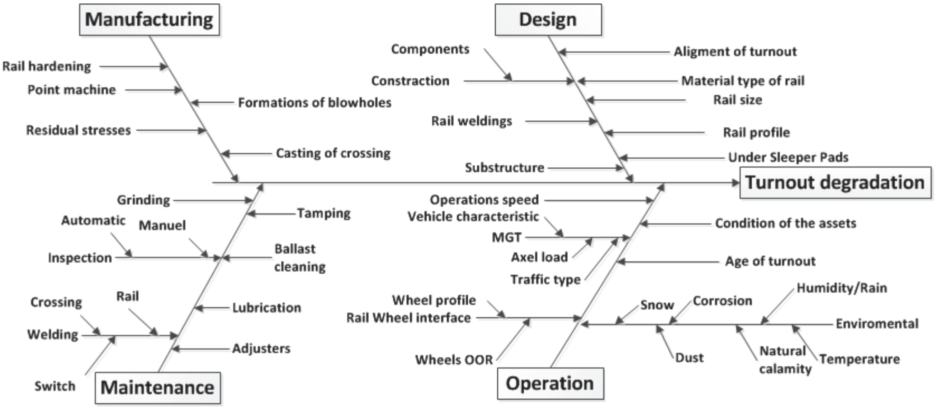


Fig. 1: Fishbone diagram of a turnout with typical causes of degradation, considering four main areas; manufacturing, design, maintenance and operation.

2.2 The decision support model

The first step in this paper is to consider the feasibility of performing maintenance inspections with a camera and to ask whether this can reduce failures and increase capacity. The next step is to define the work-flow process used to select and evaluate a method of condition monitoring. To find the parameters for a turnout and to determine the most appropriate inspection tools, it uses an adapted workflow [6]. The four steps are shown in a flowchart in Fig. 2b. The difference between the decisions support model by ref 6 and the proposed one are: The proposed model consider risk assessment (step 2), generates a list for all failure modes with an acceptable risk and bring back the unacceptable risks by new technology and innovations to the step 1, selection and analysis of equipment and systems. This step covers all failures that will be excluded due to low risk by documentations. No other decision support model takes care of all failure modes in this way.

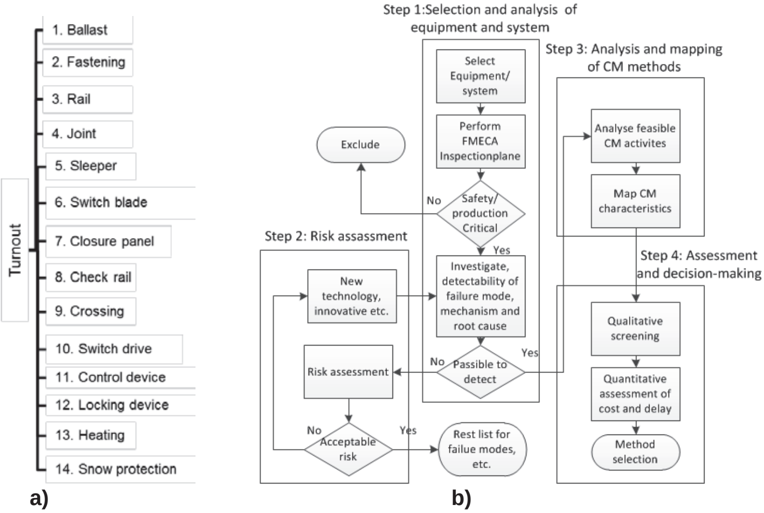


Fig. 2: a) Breakdown of turnout according to BVS811, [17]. b) The decision support model.

This flowchart is adapted to find the inspection tasks; the steps are as follows:

Step 1: **Selection and analysis of critical equipment or systems:** This step starts by selecting the system to be analysed, in this case, the turnout. Then a Failure Mode and Effect Analysis (FMEA) is performed to determine what must be monitored and how this can affect the maintenance of the system. This stage requires the information above, namely, the breakdown, functions, and degradation of a turnout, so that the investigation of the detectability of failure modes, mechanisms and root causes can take place. All detectable failure modes can be moved to step 3; the others must be given a risk assessment (step 2). More details of FMEA are presented below.

Step 2: **Risk assessment**: This step considers the risk of the failure modes that cannot be inspected or do not require inspection. If the risks are not acceptable, step 1 is performed again. Because of new technology and innovations, it is important to update the analysis continually.

Step 3: **Analysis and mapping condition monitoring methods:** This stage finds and evaluates the type of inspection activities for the different levels, failure modes, failure mechanisms and root causes. It studies the feasibility of inspections, finds the characteristics of inspections and selects the most promising inspection methods.

Step 4: **Assessment and decision-making**: The qualitative evaluation/screening and ranking of the inspections' monitoring tasks begins here. The next step is quantitative evaluation, followed by cost analysis. The last step compares the camera inspection to a baseline, allowing the benefits of the camera inspection to be evaluated.

2.3 Failure Mode and Effect Analyse (FMEA)

FMEA is a key tool to determine inspection tasks and define system improvements. It was developed for the aerospace industry to improve reliability and safety, but is also used in the chemical and automotive industries to improve safety and product quality as well as production capabilities [19]. There are many other benefits of FMEA, including identifying risks at an early stage, preserving product knowledge, reducing field failures, identifying potential failure modes and effects, rating the severity of the effects, identifying robust design and operation, improving the likelihood of detecting failures early, helping to find diagnostic procedures, prioritising design improvement, finding and identifying the critical characteristics, analysing the service, helping prevent errors, helping to find corrective actions, providing product or process documents [20].

Despite the many benefits, using FMEA requires a great deal of effort from many people with different experience and knowledge. Since this tool was developed for industry applications and the railway has other characteristics, the process must be modified to fit the railway [19]. Railway systems include signalling, track, substructure, power distribution; in addition, the track system has many sub-systems, such as turnouts, track fastenings, joints and ballast. This means not all possible failure modes can be found; moreover, many systems are huge.

This paper applies a large-scale distribution process, whereby the most frequent failure modes are used for the analysis [22]. The FMEA workflow is divided into four main stages: establishing the rules, planning the work and scheduling the time; performing the FMEA in a worksheet, diagrams and fault trees; putting together the information, analysing it and making recommendations; and finally, updating the FMEA when something in the system is updated or developed [23].

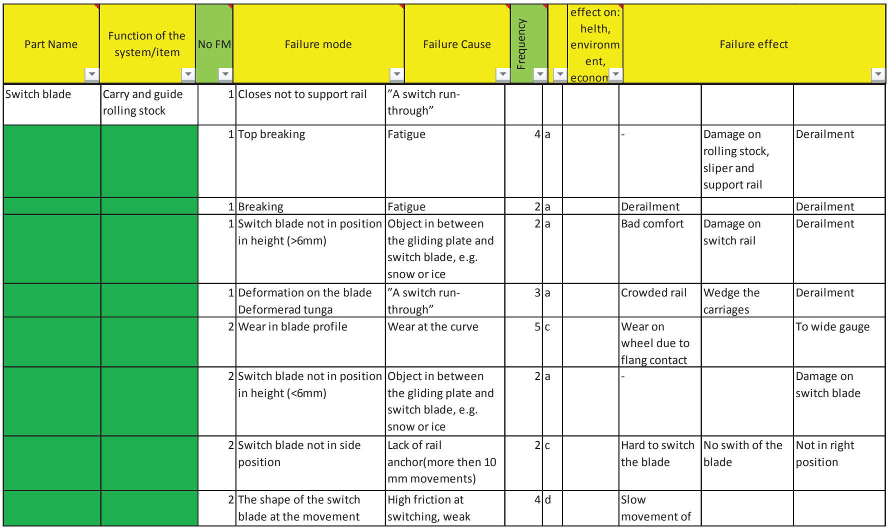
2.3.1 Establish rules and plan the work

To establish the rules, the following standards were used: SS-EN, SAE and MIL-STD, [23, 24, 25]. The system boundaries were defined from the stock front joint to the stock rail joint, including the ballast. The turnout used in the FMEA case study is located in the southern part of Sweden on the track section 815(north of Hässleholm); this turnout has around 10 MBT/year. Before beginning the analysis, it is important to know the following: all problems are not the same; the customer must be known; the function most be known; and the work must be preventive in its orientation [20].

2.3.2 *Perform FMEA in a worksheet*

In this step, a FMEA was performed with people from the Swedish Transport Administration and Lulea University of Technology. A worksheet was adapted for this purpose, based on the SAE standard [24]. Table 1 shows a portion of the performed FMEA, considering an EV-UIC60-760-1:15 turnout for one component, the switch blade. For more details how to work with the worksheet, see SEA standard [24].

Table 1 FMEA of a turnout EV-UIC60-760 1:15 for the switch rail.



Part Name	Function of the system/item	No FM	Failure mode	Failure Cause	Frequency		effect on: helth, environment, econom	Failure effect		
Switch blade	Carry and guide rolling stock	1	Closes not to support rail	”A switch run-through”						
		1	Top breaking	Fatigue	4	a		-	Damage on rolling stock, sliper and support rail	Derailment
		1	Breaking	Fatigue	2	a		Derailment		Derailment
		1	Switch blade not in position in height (>6mm)	Object in between the gliding plate and switch blade, e.g. snow or ice	2	a		Bad comfort	Damage on switch rail	Derailment
		1	Deformation on the blade Deformerad tunga	”A switch run-through”	3	a		Crowded rail	Wedge the carriages	Derailment
		2	Wear in blade profile	Wear at the curve	5	c		Wear on wheel due to flang contact		To wide gauge
		2	Switch blade not in position in height (<6mm)	Object in between the gliding plate and switch blade, e.g. snow or ice	2	a		-		Damage on switch blade
		2	Switch blade not in side position	Lack of rail anchor(more then 10 mm movements)	2	c		Hard to switch the blade	No swith of the blade	Not in right position
		2	The shape of the switch blade at the movement	High friction at switching, weak	4	d		Slow movement of		

2.3.3 *Gather information, analyse it and make recommendations*

This was a necessary step, as it proposed parameters to measure using the camera. At this point, FMEA was ready; all information had been gathered and used to detect the most critical failure modes.

2.3.4 *Update FMEA when something in the system is updated or developed*

Since FMEA is a living document that can be used in all stages, from the development phase to the service phase, it should be updated every time something changes in the system to ensure that stakeholders will gain from the system’s improved reliability and quality. The Transport Administration takes care of the final FMEA to develop the maintenance routines of the turnout.

3 Case study

The data in this case study come from turnouts in the centre of Stockholm, on track section 401, and were gathered in 2011; see track layout in Fig. 3. This is a strategically important and busy track section with a great deal of passenger traffic. Therefore, a small improvement in this section will provide large gains for local traffic (and global traffic as well) and enhance track capacity.

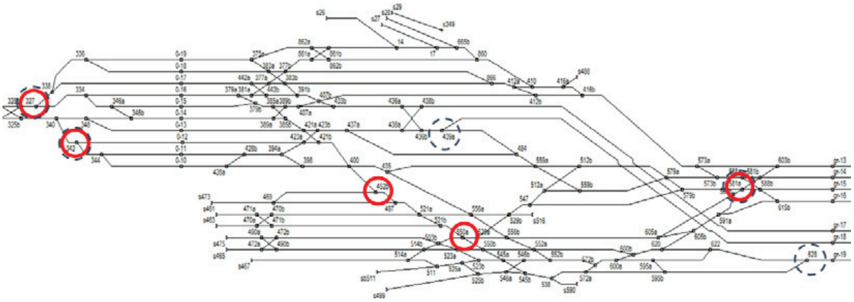
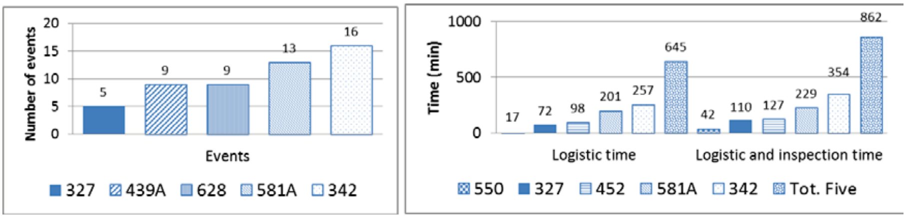


Fig. 3: Track layout from Stockholm city track section 401; red circles are turnouts with the largest amount of downtime due to maintenance action "check" and dashed circles are turnouts with the largest number of maintenance events during 2011.

The data show a total of 183 corrective maintenance actions; the five turnouts with the largest amount of corrective maintenance actions are shown in Fig. 4a; turnout 342, followed by turnout 581A, shows the largest number of disruptions. When we look at the maintenance action "check" for five turnouts and add up the total downtime due to logistics and inspection times, we get 862 minutes, with a logistics time of 645 minutes; see picture 4b. Turnout 342 leads in downtime, followed by turnout 581A.



a) **b)**

Fig. 4: a) Number of corrective maintenance actions for all turnouts in track section 401 for 2011 with all maintenance actions. b) The downtime of five turnouts on track section 401 for 2011 when maintenance action is "check".

The total train delay for all events is 19 minutes. The downtime could be reduced if the "check" were done by camera inspection, thus enhancing the capacity of the line. All together, 21 of 327 turnouts performed the action "check" on this particular track section. Table 2 shows the information for the turnouts with the most downtime due to the maintenance action "check".

Table 2: Turnouts with the largest amount of downtime due to maintenance action "check"

Turnout	Type	Instalations year	Inspection class	Max speed diverging track	Radius	Rail type
327	ST	2006	3	80	760	60
342	ST	2008	3	50	300	60
452b	ST	1985	2	40	190	50
550a	DT	1986	2	40	-	50
581a	DT	1985	3	40	-	50

4 Camera Inspection of a turnout

The camera inspection is done with a standard web-based camera, with a resolution of 1600x1200 pixels, built into a plastic housing to protect the equipment. The weight of the prototype is approximate 3 kg including the Internet access unit and batteries. A picture of the camera kit and a picture taken by the camera are shown in Fig. 5a-b.

a) *b)*

Fig. 5: a) Camera kit for this test. b) Picture from the camera of a test installation. (Damill AB)

Batteries are just for test purposes and will be replaced by a continuous power supply in future versions. The camera operates for 6 hours without changing batteries. Unlike other wayside based vision systems, this system is mounted above the overhead line to get a fully symmetric bird's eye view of the turnout. Such an arrangement makes it possible to inspect both rails and blades and also to make geometric calculations, possibly reducing some of the manual inspections listed in section 3. The test system has been developed by the Swedish engineering company Damill AB.

5 Results and discussion

Usually no well-structured decisions support model is used for finding condition monitoring measures within the railway sector. Decision support model presents some advantages when implemented: finding critical parameters, high performance of condition monitoring, good control and documentation, obtain as high safety level as possible with the condition monitoring. This article has presented a useful model which can be adapted in specific cases in the railway sector. Furthermore this paper shows that this model is practical since it has been demonstrated for the acquisition of the camera monitoring system for turnout. This can be adapted for defining condition monitoring for different items, parts, subsystems and systems.

The decision support model can be used to find and define measures for different items and systems. The analysis shows that FMEA plays an important role in defining the system, what can be inspected and potential gains resulting from the action. The case study suggests that many turnouts have a large number of events; maintenance "checks" are common and cause a great deal of downtime while they are being performed. In addition, some turnouts are simply "bad actors"; this needs more research. The camera inspection system works and produces good quality pictures, but the resolution could be improved to capture finer details if required. Other functions could be implemented to improve the camera inspection system, like different types of illuminations, lasers or infra-red light, to generate, e.g., 3-D measures of different contours.

As expected, the test revealed that installing the camera above the overhead line has certain advantages. All parts are clearly visible, including both rail head gauge corners and blades. As the camera view is perpendicular to ground level, calculation of track gauge dimension can be made from the image if light conditions are good. However, because the high mounting position above the overhead line requires zooming capability, the camera resolution should be at least 2000 pixels in its main direction; this excludes most web cameras. In addition, because the camera housing should be tiltable, the mounting of the camera can be quite expensive if no catenary mast is present in the desired position.

Using camera inspections for turnouts could enhance the capacity on the track; for instance, if an object falls from a passing train and blocks the blade, there is no way to know this before trying to switch the turnout and then noticing that the blade will not go into position. With camera monitoring, this will be noticed before switching the blade, thus providing more reaction time. In other words, an advantage of camera inspection of a turnout is faster diagnostics and better knowledge of the failure before entering the site. This earlier and better knowledge can reduce the maintenance logistics time and save money (for both contractors and infrastructure managers) and enhance track capacity. Camera inspections should be used on the most critical turnouts, like those on busy lines or those placed far away, with poor maintainability capability. The ability to note trends and make predictions will also increase, improving maintenance planning and enhancing track capacity.

6 Conclusions

This process can be used to define condition monitoring measurements for all kinds of systems and items within these systems on a railway. It can also be used more widely to find appropriate condition monitoring parameters or measurements in other systems. FMEA plays an important role in finding weak spots and improving the performance of a system or item within the system. In this work, five turnouts are shown to gain from camera inspections using the prototype described above. In short, using camera inspections can enhance the capacity of track section 401.

7 Acknowledgement

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