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Evaluation of wayside condition monitoring technologies for condition-based maintenance of railway vehicles

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“Science is a wonderful thing if one does not have to earn one's living at it.”

Albert Einstein (1879-1955)

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Robert Lagnebäck

Luleå, March 2007

Abstract
Luossavaara-Kiirunavaara AB (LKAB) is an iron ore mining company in Sweden that strives to be one of the leading suppliers of iron ore products. In the chain from mining to end customers, transportation efficiency plays a mayor role in the outcome of the company's total financial result. The transportation of the ore from the LKAB mines in Kiruna and Malmberget is made by trains to the harbors in Narvik and Luleå. The railway transportations are made by LKAB subsidiaries Malmtrafik i Kiruna AB (MTAB) on the Swedish side and Malmtrafikk AS (MTAS) on the Norwegian side. The efficiency of the railway transportation is therefore a key function in the LKAB mining operations.

In a benchmarking, comparing the total operating efficiency, with other heavy haul railways around the world it became evident that the efficiency of the railway transportations at LKAB had potential for improvement. One of the factors with potential for improved efficiency was the maintenance strategy. There is an indication that a change from a time-based maintenance strategy to a condition-based maintenance strategy would increase the efficiency of the train operations. The purpose of this thesis is to study and analyze wayside condition monitoring equipment for railway vehicles, in order to support the implementation of a condition-based maintenance strategy.

To fulfill the stated purpose, five case studies, supported by a literature study, have been performed. The five case studies have been conducted to increase the knowledge of the abilities of available wayside condition monitoring equipment as a support for condition-based maintenance of railway vehicles. The literature study focused on railway operations around the world with a particular focus on the development, deployment and use of wayside condition monitoring equipment.

The literature study indicates that there is an increasing implementation and use of equipment for wayside condition monitoring of railway vehicles. Through the studies it has become evident that the direct interaction in the wheel and rail interface also creates a huge potential for savings on the infrastructure due to an implementation of wayside condition monitoring equipment for railway vehicles. The case studies highlight the need for different systems that complement each other by measuring different parameters. It is also important that the systems are integrated with existing systems and practices in order to exploit the potential benefits of the new technology. Furthermore, it is important to have a joint approach between both infrastructure owners and train operators in the deployment and use of wayside condition monitoring equipment, since the technology can support a condition-based maintenance strategy on both sides that could have a great impact on the efficiency of railway operations.

Keywords: Maintenance, Condition-based maintenance, Railway, Condition monitoring, Wayside, Railway vehicles

Summary in Swedish

Luossavaara-Kiirunavaara AB (LKAB) är ett Svenskt gruvbolag som bryter järnmalm. Man har som målsättning att bli en av de ledande leverantörerna i världen av järnmalmsprodukter. I kedjan från brytning till slutkund, spelar transporteffektivitet en avgörande roll i företagets totala ekonomiska resultat. Transporterna av malm från LKAB:s gruvor i Kiruna och Malmberget utförs med järnvägstransporter till utskeppningshamnar i Narvik och Luleå. Järnvägstransporterna utförs av LKAB:s dotterbolag Malmtrafik i Kiruna AB (MTAB) på den Svenska sidan och av Malmtrafikk AS (MTAS) på den Norska sidan. Järnvägs transporternas effektivitet är därför en nyckelfunktion i LKAB:s gruvbrytningsverksamhet.

I en benchmarkingstudie utförd på den totala effektiviteten av verksamheten hos gruvverksamheter med tunga järnvägstransporter runt om i världen blev det uppdagat att det finns en potential att förbättra effektiviteten hos LKAB:s järnvägstransporter. En av faktorerna som har potential att förbättra effektiviteten är underhållsstrategin. Det finns tydliga indikationer på att en förändring från ett förutbestämt underhåll till ett tillståndsbaserat underhåll skulle kunna öka järnvägstransporternas effektivitet. Syftet med denna licentiat avhandling är att utvärdera tekniska system som kan placeras vid spåret och användas som tillstånds övervakande utrustning för järnvägsfordon för att stödja en implementering av en tillståndsbaserad underhållsstrategi.

För att uppnå det utsatta syftet har fem fallstudier, samt en litteratur studie genomförts. De fem fallstudierna har utförts för att öka kunskapen om egenskaperna hos tillgänglig tillståndsövervakande utrustning för placering vid spåret som stöd för tillståndsbaserat underhåll av järnvägsfordon. Litteraturstudien har fokuserats på järnvägsverksamheter i runt om i världen med speciellt fokus på utveckling, utplacering och användande av spårbunden tillståndsövervakningsutrustning .

Litteraturstudien indikerar att det pågår en ökande implementering och användning av tillståndsövervakande utrustning för järnvägsfordon. Genom studierna har det framkommit att den direkta interaktionen mellan hjul och räl också skapar en stor potential för besparingar på infrastrukturen med hjälp av en implementering av spårbunden tillståndsövervakande utrustning för järnvägsfordonen.

Case studierna belyser nödvändigheten av att ha olika system som kan komplettera varandra genom att mäta olika parametrar. Det är också viktigt att systemen är integrerade med existerande system och metoder för att uppnå de potentiella fördelarna med den nya teknologin. Det är dessutom viktigt att ha ett gemensamt tillvägagångssätt mellan både infrastrukturägare och tågoperatörer i implementeringen och användandet av spårbunden tillståndsövervakande utrustning, eftersom teknologin kan stödja en tillståndsbaserad underhålls strategi för båda sidor, vilket kan ha stor positiv inverkan på järnvägsdriftens effektivitet.

Nyckelord: Underhåll, Tillståndsbaserat underhåll, Järnväg, Tillståndsövervakning, Spårbunden, Järnvägsfordon

Table of contents

1 Introduction and background

The railway was one of the key factors in the industrial revolution and development of the modern industrial societies of the world. The need of good transportation possibilities for both freight and passengers is a key function in modern society. The railway is still an effective transportation solution for transporting both small and large quantities over both short and long distances. It is even argued that the railways alone had the largest impact of all innovations in initiating economic growth providing the people in industrial societies with higher living standards. (Rostow, 1962; Mckillop and Pearon, 1997)

The railway has a long history and the Swedish railway celebrated 150 years in 2006. In the northern parts of Sweden, the iron ore line has played an important role in the development of the societies surrounding the railway. The iron ore line, see Figure 1, is part of the Swedish railway system. The railway line is a key function in LKAB's logistics solution for transporting iron ore from their mines to the end customer. The Iron Ore Line is 536 kilometres long and runs from Narvik in Norway, through the mine locations in Kiruna and Malmberget to its final destination in Luleå. Rail traffic on the iron ore railway in Sweden is managed by Malmtrafik i Kiruna AB (MTAB), which is a subsidiary of Luossavaara-Kiirunavaara AB (LKAB). The railway is operated by Malmtrafikk AS (MTAS) on the Norwegian side.

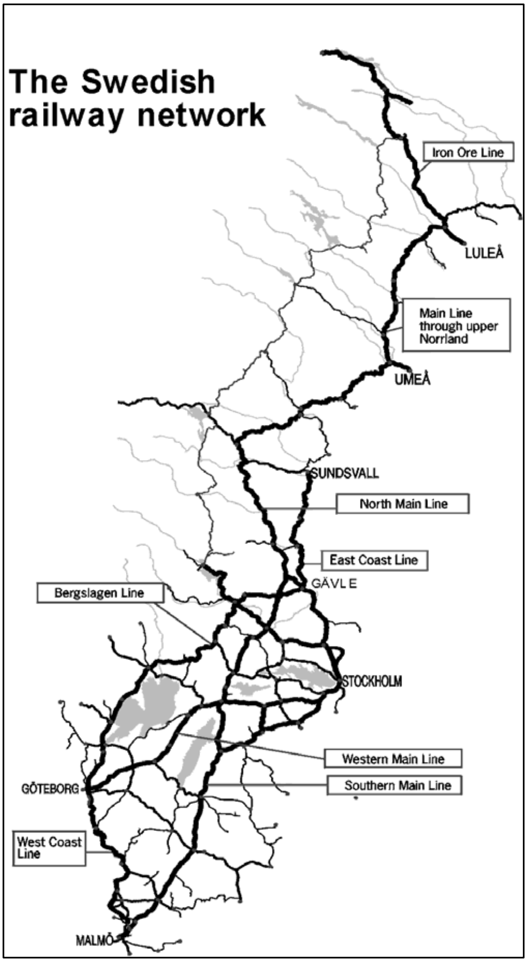


Figure 1. The Swedish railway network, 11 000 km of length.. Banverket, the Swedish National Rail Administration, acts as the primary infrastructure owner while several independent operators are running the traffic. Iron ore line in the north.

The railway infrastructure is managed by the Swedish National Rail Administration (Banverket) on the Swedish side and by the Norwegian National Rail Administration (Jernbaneverket) on the Norwegian side. (LKAB, 2007)

The purpose of the railway is to transport the finished products from the different ore processing plants to customers by rail to the shipping ports at Narvik and Luleå. The ore products are then transported further by ship to international customers, both to customers in Finland and other countries around the Baltic, and also to customers in continental Europe and the rest of the world. (LKAB, 2007)

The products from Malmberget are transported mainly to Luleå for direct delivery to SSAB in Luleå or for further delivery to SSAB in Oxelösund, see Figure 2. Five or six trains make the 220 km, five to six hour journey daily from Malmberget to Luleå. Most products from Kiruna and Svappavaara are transported to Narvik, for further delivery. Eleven to thirteen daily trains make the 170 km run between Kiruna and Narvik. The trip takes about four hours. (LKAB, 2007)

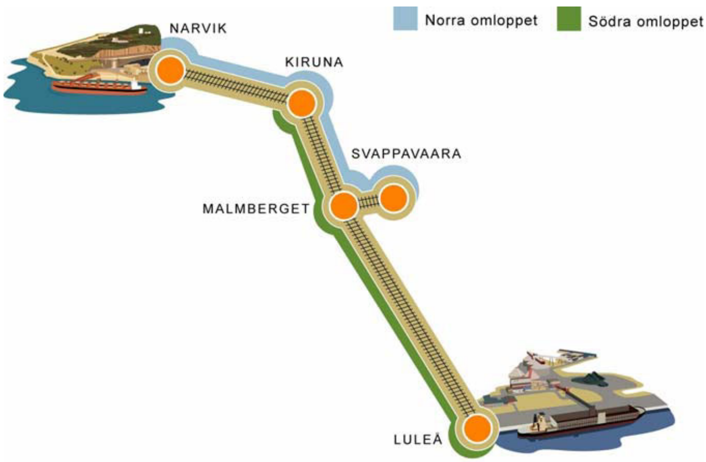


Figure 2. The Iron Ore Railway from Narvik to Luleå. (LKAB, 2007)

Luossavaara-Kiirunavaara AB uses its own locomotives and ore cars. The rolling stock includes both regular-traffic, like the IORE locomotive, and terminal locomotives and also various types of different ore cars. The ore cars that are currently in operation carry a payload of between 80 and 100 tonnes. MTAB has a mine-to-harbour freight capacity of more than 23 million tonnes per year. This corresponds to about 7000 fully loaded ore trains per year. The Swedish railway operations are controlled from an ore transport center in Kiruna. Rail operations in Norway are controlled by, Malmtrafikk AS (MTAS), which has its own organization in Norway. (LKAB, 2007)

LKAB hopes to lower the operation cost of the railway transports and wants to achieve a reduction in the freight costs through the ongoing upgrade of both infrastructure and vehicles to 30-tonne axle load, as well as through the possibility of hauling longer trains when the train sets are increased from 52 to 68 cars. (LKAB, 2007)

A benchmarking (Nordmark, 2004) was made during 2003 between heavy haul transportation railways in Sweden, Australia, Brazil and South Africa. This report showed that there is a difference between LKAB/MTAB and the best heavy haul companies in the report. One of these differences concerned the total cost of the freight in dollar per tonnage transported. LKAB has a higher total freight cost than its competitors.

Another difference between LKAB/MTAB and the best companies in the benchmarking was the applied maintenance activities. The leading heavy haul railways are working with condition-based maintenance both in terms of rail and vehicles, while LKAB/MTAB still base their maintenance plan mainly on the distance traveled by the vehicles while Banverket mainly uses the amount of weight transported on the rail as their input for the maintenance activities.

In the past, maintenance activities have in general most often been conducted when a fault has occurred to repair the system (Kelly, 1989; Moubray, 1991). With experience and increasing knowledge of technical systems, maintenance activities have evolved towards a more preventive approach based on time intervals as the knowledge about the degradation of the systems and components have increased (White, 1973; Moubray, 1991). These maintenance time intervals are based on, for example, usage time, distance or the amount of operations the systems have been exposed to.
In the railway industry the maintenance intervals are often traditionally based on time or mileage, and these intervals are often based on earlier experience or on the supplier’s specification. This method of maintenance can further improve, if the variations in wear can be anticipated.

MTAB has developed its maintenance from the earlier time-based intervals to distance-based intervals with fixed maintenance procedures, based on a transponder system called Automatic Truck Identification (ATI), an identification system with radio link that is used to calculate the distance travelled by each individual ore car. MTAB is continually working with the development of their maintenance strategy to meet the new and higher demands on the operation.

However, with higher demands on availability and reliability from technical systems, the next step in the evolution of maintenance has led to a preventive approach of condition-based maintenance. This is due to the fact that the ability to follow the actual condition of the system makes it is possible to utilize it more effectively, since maintenance activities can be planned in advance in a more precise way and the operations of the system can be planned accordingly. (Kelly, 1989)

LKAB, and the Swedish National Rail Administration (Banverket), in cooperation with Luleå University of Technology (LTU) are looking into ways of improving the maintenance activities and with that the performance of the transportation system. LKAB has the goal of having one of the most efficient heavy haul transportation railways in the world to contribute to its long-term development as one of the leading iron ore companies in the world.

Condition-based maintenance is an approach applied to improve both safety and reliability as well as decreasing cost of operation and the need of support during the useful life of a technical system. (Mobley, 1990; Becker et al., 1998; Söderholm, 2005)

Maintenance based on actual condition would be more economical. To achieve the goal of bringing the railway industry from time/mileage-based maintenance to a more condition-based maintenance, there have to be ways to monitor the condition and from that be able to predict the remaining life length of the item. Hence, the condition-based maintenance strategy needs ways of measuring the condition of the system so that the user is able to take correct maintenance decisions. Furthermore, to be able to conduct condition-based maintenance, analyses and trending of the collected measurements have to be made (Rao, 1996). Therefore, it is important to have both a system and a good organization for handling the collected data, so that appropriate maintenance activities are done thus creating continuous improvement in operation. (Liyange and Kumar, 2003; Söderholm, 2005; Parida, 2006)

Some condition monitoring could be said to have been used even historically, since operators of systems have used their experience and senses such as smell, taste, hearing and vision to monitor the condition of the system. Manual inspections are still a very useful way to monitor a system, but as the systems get increasingly complex the need for objective and reliable methods of condition monitoring increases. Condition monitoring is a growing field in industry and also in some ways in medical areas of human health monitoring. The technologies for condition monitoring in industry include vibration measurements, oil analyses, infrared thermography, laser systems and ultrasonic, just to mention a few. (Rao, 1996)

With advancements in condition monitoring technologies, the condition-based maintenance strategy has become a powerful means to reduce the cost of system operation and maintenance. This trend is clearly visible also in the railway sector (Lagnebäck, 2004). Track owners are implementing advanced technology and systems to monitor the condition of the track, which often consumes the biggest part of the infrastructure maintenance budget (Espling, 2004). For the train operator, wheel maintenance is a big part of the rolling stock maintenance budget (Åhrén, 2002). In many cases (as in Sweden) the track and vehicles are owned by different companies, resulting in possible sub-optimization of the wheel or rail maintenance operation (Granström, 2005). Hence a combined maintenance approach can be an effective approach in the optimization of both wheel and rail maintenance efforts to find the best economic solution for both parties. The increased benefits on either side can then be divided and regulated so that both parties benefit from this cooperation (Espling and Olsson, 2003; Espling, 2004; Larsson, 2004; Granström, 2005). One such example is the application of differentiated freight charges depending on the condition of the vehicles. It is therefore important to develop both strategies and the organizations so that they are able to use the information in the best interest of both the rail and vehicle owners. Finding a balance is a concern within the Swedish railway industry that is consists of different stakeholders: several train operators and one major track owner.

To control the condition of vehicles and track, condition monitoring tools, in combination with cost prediction models, can be used to decide the maintenance strategy that minimizes the total cost of maintenance. (Larsson, 2004)

One of the challenges with implementing condition monitoring is to find the right measurement technologies, since reliable and valid measurements are a necessity for an effective condition monitoring approach (Rao, 1996). There is the question of finding relevant and correct parameters that can be measured to provide the most relevant measuring data, because the measurement data must then be transformed into relevant and understandable information that can then be used as decision support in the maintenance management process. These are some of the corner stones that are needed to be able to arrive at a condition-based maintenance strategy.

Today there are many commercial products for condition monitoring on railway vehicles (Lagnebäck, 2004). Many of these products are wayside monitoring systems and not directly mounted on the vehicles. In many cases, it would not be economical to monitor the condition of every component on a vehicle. One reason is that the cost of monitoring could be more costly than handling the faults if they occur, as is the case with non-critical components that will not affect the immediate ability to perform the task at hand. Another reason is the increasing risk of creating false alarms due to increased system complexity with the increasing amount of sensor technology (Söderholm, 2005).

Even though there has been much development from the first steam locomotives up to today's high-speed trains and heavy haul transportations with large axle loads, the use of steel wheels on steel rail is still the key function in most railway systems (IHHA, 2001). This highlights the interface between the wheel and the rail as a focus area for the functionality of the railway system. Most of the condition-monitoring systems for railway vehicles are therefore focused on the wheel and bogies. The wheel/rail interface is the one of the most important parameters in the vehicles' condition. This is where most of the cost for maintenance on both railway vehicles and infrastructure occurs (Kumar, 2006). It is also important to monitor this condition to avoid accidents, as a derailment is very costly and may cause injuries (Holmgren, 2006).

1.1 *The research area illustrated in its broader context*

To pinpoint the area of this research in the context of the overall objectives described in the introduction and to highlight the potential benefits with achieving the goals of a condition-based maintenance strategy, see illustration in Figure 3.

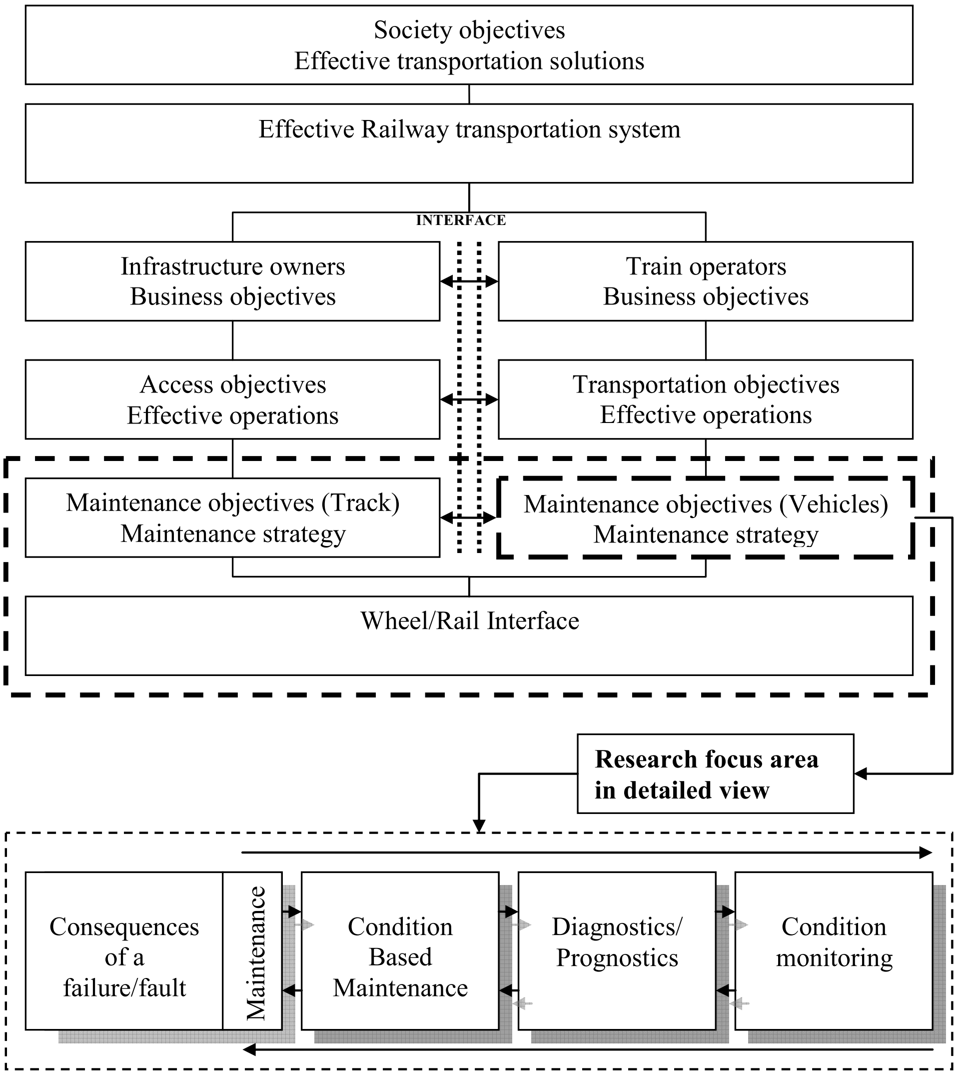


Figure 3. The research area: focusing on condition monitoring for railway vehicles to be able to implement a condition-based maintenance strategy for vehicles. The goal is also to find an approach for supporting the total **INTERFACE** between Infrastructure owners and Train operators to facilitate continuous improvements and the development of a more effective transportation solution.

The focus of the research is to evaluate the possibilities of using condition monitoring to implement a condition-based maintenance strategy for vehicles and also to find an approach for supporting the total interface between infrastructure owners and train operators. With a joint approach of developing and maintaining an effective transportation system there is a huge possibility for the railway to achieve continuous improvements with the help of a condition-based maintenance strategy and in this way create a more effective transportation solution.

1.2 Purpose of the thesis

The purpose of this thesis is to study and analyze wayside condition monitoring equipment for railway vehicles, in order to support the implementation of a condition-based maintenance strategy.

1.3 Research questions

1. How can the condition and performance of a railway vehicle be monitored by wayside condition monitoring technologies?

2. What kind of information can be extracted from the achieved measurements from wayside condition monitoring technologies?

3. What are the possible benefits of applying wayside condition monitoring technologies for condition-based maintenance of railway vehicles?

1.4 Goal

The goal is to collect and compile information that contributes to knowledge, which supports and facilitates an implementation of a condition-based maintenance strategy for train operators that also can be beneficial for the infrastructure owner.

1.5 Delimitations

There are three main delimitations made in this study.

Firstly, the research is not aiming at creating new technologies, but looking at ways to use those already available. The appropriate technologies exist and the problem is most often to find the appropriate technical solution from among these.

Secondly, the decision to evaluate wayside technologies for condition monitoring has been taken since the cost of putting condition monitoring equipment on every car will be high. Also due to the rough condition that many cars are operating in, the equipment would be exposed to very harsh treatment.

Thirdly, the studies will mainly focus on technologies for monitoring the interface between the wheel and rail, since the main cost of maintenance of cars is connected to the wheels and bogies.

2 Research methodology

In this chapter the research problem and its background sets the scene for the choices of research methodologies.

2.1 Describing the research area

There is a constant need in the railway industry for continuous technical developments and improvements to reduce transportation costs. In a heavy haul rail transportation system the wheel/rail interface maintenance cost can be up to 50% of the total cost (Banverket, 1997). Heavy haul railway operators are constantly looking for improvements in their operation and maintenance of their assets. One way to identify such improvements is to benchmark their maintenance and operation activities with other heavy haul operators around the world. As the result of such a benchmarking between different heavy haul railways (see Chapter 1) where LKAB was one of the companies, the need to initiate research came to light. There are possibilities for improvement in the heavy haul railway transportation system with implementation of condition-based maintenance (CBM) on railway vehicles at LKAB/MTAB. This area of focus was chosen due to the fact that the leading companies in the benchmarking have worked with the implementation of this maintenance strategy for several years and during this time have seen a positive effect in the increase of the life length for both rails and wheels.

The questions and issues that are raised when implementing condition based maintenance in a process concern the methods and strategies to be used and also the technical demands upon supporting systems for these methods and strategies. The initial research work was set to focus on the condition monitoring part that is a critical requirement for a good overview of the actual condition, which can provide for a good decision support.

2.2 Research purpose

The purpose of this thesis is to study and analyze wayside condition monitoring equipment for railway vehicles, in order to support the implementation of a condition-based maintenance strategy.

2.3 *Research approach*

There are different ways to approach the research area. The research approach can be divided into deduction and induction (Alvesson and Sköldberg, 1994). The deductive approach strives to generate testable statements, based on theory. The inductive approach is based on empirical work and conclusions are formulated based on experiences from the performed studies.

From theoretical deductive work, mainly literature research, the area was narrowed down to the need for condition monitoring technology. From that the empirical inductive work was initiated with case studies of technical systems that could be useful for a condition-based maintenance process, see Figure 4.

The conducted research process is illustrated in Figure 4.

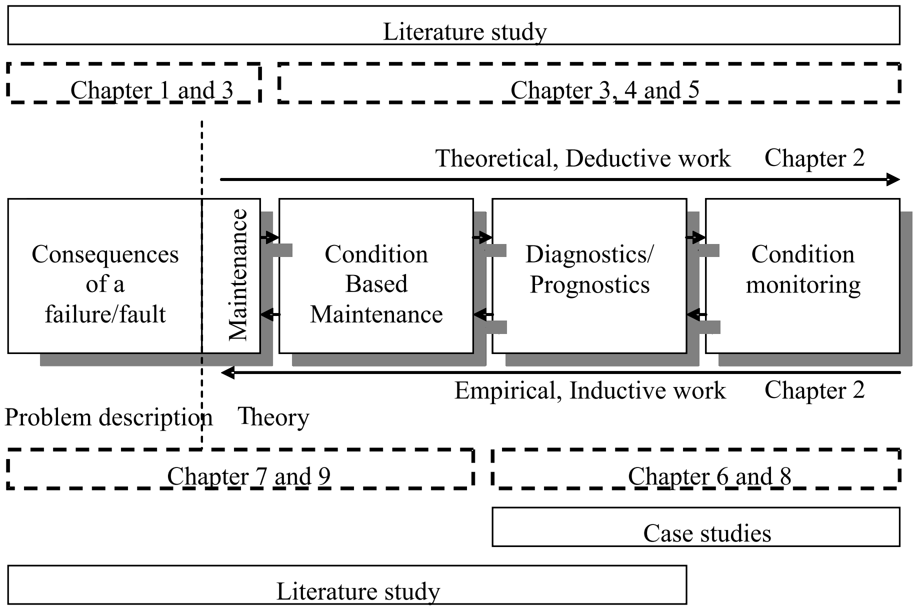


Figure 4. The applied research process during the thesis work.

The research may be divided into either a qualitative or quantitative approach. Generally quantitative information is described by numbers and qualitative information described by words (Eriksson and Widersheim-Paul, 1997).

The research process in the thesis was initiated by the goal of decreasing the consequences of failures and faults on the vehicles using the railway track, as this will affect the whole railway transportation system.

The research approach in this thesis is mainly qualitative, but also supported by a quantitative approach. The qualitative approach aims at identifying problem areas and technologies for assessing them.

Furthermore, the qualitative approach also aims at describing the current status of available technologies used for wayside condition monitoring of railway vehicles and the current use of them.

A quantitative approach is applied to evaluate the reliability and validity of measurement data generated by some of the different available technologies used for wayside condition monitoring. Furthermore, this approach is also used to evaluate the usefulness of the data as decision support for condition-based maintenance.

Maintenance was set as the focus area for the possibilities of solutions to come to terms with the consequences of failures and faults. The focus inside the area of maintenance was the possibilities created by the condition-based maintenance process.

2.4 Research strategy

The choice of research strategy depends on what kind of information the researcher is looking for due to the purpose of the study (Yin, 2003). One must be aware of the strengths and weaknesses of each research strategy. Generally three conditions determine the choice of research strategy, namely: type of research questions, the researchers' control of behavioral events and the degree of focus on contemporary events (Yin, 2003). Yin (2003) suggests that different research strategies may be divided into: experiment, survey, archival analysis, history and case studies, see Table 1.

Strategy	Research Questions	Requires Control of Behavioral Events	Focus on Contemporary Events
Experiment	How, Why	Yes	Yes
Survey	Who, What, Where, How Many, How Much	No	Yes
Archival Analysis	Who, What, Where, How Many, How Much	No	Yes or No
History	How, Why	No	No
Case Study	How, Why	No	Yes

Table 1. Selection of research strategies depending on research situation (Yin, 2003).

2.5 Applied research strategy

The research purpose of this thesis is focused by three research questions, namely:

1. How can the condition and performance of a railway vehicle be monitored by wayside condition monitoring technologies?

2. What kind of information can be extracted from the achieved measurements from wayside condition monitoring technologies?

3. What are the possible benefits of applying wayside condition monitoring technologies for condition-based maintenance of railway vehicles?

The three research questions are of the "how" and "what" type. In Table 1 the strengths and weaknesses of different research strategies are presented. According to Yin (2003), there is more than one appropriate research strategy to answer research questions of the "how" and "what" type, namely: experiment, survey, history and case studies. However, some require control over behavioral events. Experiments are excluded due to the inability to control behavioral events in the conducted research. Hence, case studies are an appropriate research strategy that does not require control over behavioral events. This is the motive for choosing case studies as the main research strategy. A literature study was also performed to support the case studies. The motive for performing a supporting iterature study was to identify current condition monitoring methods and technologies used in condition-based maintenance.

2.6 Data collection

There are different ways of collecting qualitative data, such as by: documentation, archival records, interviews or observations (Yin, 2003).

2.7 Applied data collection

In this section the applied data collection methods in the literature study as well as the case studies are described.

2.7.1 Literature study

Qualitative data was collected from the National Swedish Library Data System. It contains titles representing the contents of predominantly research libraries, which include foreign literature. Mainly books were identified through this search.

A number of databases have been used to search for research papers, such as proceedings and scientific articles. The search included Compendex, Emerald and Elsevier Science Direct, from these searches a number of relevant articles were identified, for example Cline et al. (1988); Newman et al. (1990).

To support the search in the databases, some keywords relevant for the research area were pinpointed. The keywords were used alone and in different combinations with each other.

The keywords used were: Condition Monitoring, Railway Vehicles, Detectors, Condition-Based Maintenance, Wayside, Wheel/Rail Interface, and Maintenance Strategy

The compiled knowledge of the literature study is mainly presented in chapters 1 to 5. It is also used as a base in the discussions in chapter 7 and in the further research suggested in chapter 9.

2.7.2 Case studies

Quantitative data were collected by measurements made in cooperation with vendors of different wayside monitoring systems. Data recorded from the wayside monitoring systems were exported to Microsoft Excel files. The data was displayed graphically and comparisons were made between the different wayside monitoring systems. The intention was also to compare the data with historical maintenance data from the train operators' maintenance management system MAXIMO. However, this data was discovered to be corrupt and could not be used for the intended purpose.

Qualitative data was collected by informal interviews with system vendors, train operators and maintenance personnel. Observations were made regarding installation procedures and the use of the wayside monitoring systems.

The data collection and analysis in relation to the case studies are more thoroughly described in chapter 6.

2.8 Validity and reliability

Construct validity refers to which degree a measure represents the intended target of the study (Dane, 1990). An approach used to strengthen construct validity is called triangulation, which aims at using joint methods to collect data (Yin, 2003). In the performed case studies data was collected by different wayside monitoring systems. This approach is believed to reinforce the construct validity.

External validity determines the generality of the findings (Hertzog, 1996). External validity of case studies determines if it is possible to take a broader view of the findings beyond the performed case study (Yin, 2003).

The findings from the case studies were compared with the results from the literature study covering rail systems worldwide. From this comparison, the results derived from the case studies from Malmbanan are believed to be generic and therefore possible to apply to the whole Swedish rail system. The external validity is therefore believed to be corroborated.

Reliability determines the amount of errors and biases in the performed study. It is important that the methods applied for data collection are described to achieve a high reliability (Yin, 2003). In this thesis the methods for data collection are described to reinforce the reliability.

3 Theory

he theory that is of key relevance in this thesis is maintenance theory, that is on the overall area of the research, but also the theory on the more detailed issue of the interaction between wheel and rail.

This chapter follows the structure of the research focus area, see Figure 3. It starts by defining the failure and fault definitions, then describes the field of maintenance, focusing on the condition based maintenance approach, with the support of condition monitoring. The theory of maintenance is then followed by the theory of the applied problem area of wheel and rail interaction in railway.

3.1 Failure and fault

A system is intended to deliver a required function. Here, the rail system delivers a freight and passenger transportation. Such a system can experience both failures and fault, impacting on the required function or system service.

A required function may be defined as a function or a combination of functions of an item, which is considered necessary to provide a given service (IEV 191-01-05). Therefore, it is valuable to start the maintenance process when a required function is impaired by a failure or a fault, to avoid interruption of the system service. The definitions of failure and fault are not always stringently described in the literature (Söderholm, 2005). The distinction between them is that a failure is an event and a fault is a state (IEV 191-04-01). However, a failure may be defined as the termination of the ability of an item to perform a required function (IEV 191-04-01). A fault is here defined as the state of an item characterized by inability to perform a required function, excluding inability during preventive maintenance or other planned actions, or due to lack of external resources (IEV 191-05-01).

Faults and failures are connected slightly differently to the maintenance process. Faults are mostly connected to corrective maintenance, at least on a functional level, but not necessarily on a system service level. Hence, failures are often connected to preventive maintenance, such as condition based maintenance in which the condition monitoring equipment is used to discover a developing fault and enable the possibility to prevent it. (Holmgren and Söderholm, 2006)

3.2 Maintenance

Originally seen as a necessary evil and now looked upon as a way to improve the business process, maintenance as a subject has developed tremendously during the last decades. Maintenance theory is a multidisciplinary subject. It spans from technical details to organizational methods and human behavior. (Liyanage and Kumar, 2002; Liyanage and Kumar, 2003)

Requirements on safety, functionality, reliability and cost effectiveness of complex systems are continuously growing as the use of them in industry, as well as the service sectors and everyday life, is in constant expansion (Süleyman, 1996).

This highlights the area of maintenance as a key factor for retaining and restoring the levels of safety, functionality, reliability and cost effectiveness of complex systems that are expected by the stakeholders. Industrial organizations aspire to make profit with the use of equipment and employees and the profit is the difference between the income of the end product and the cost of the operation process. One of the costs in the process is maintenance. (Kelly and Harris, 1978)

Some authors see maintenance as a way to create value in the process and also as one possibility to create additional value, see Liyanage and Kumar (2002) and Liyanage and Kumar (2003). Others state that even though maintenance may have a value-creating role within an organization, there are also some situations when maintenance by itself is insufficient and other approaches, such as modification, are necessary. However, maintenance can compensate for system degradation caused by operational environment and usage. Hence, maintenance is necessary and valuable, but it can only compensate for the deficiencies compared to the intended system design, see Söderholm et al. (2006).

When looking on the downtime of a process due to a breakdown, it can be seen that the actual repair time can be a very small part of the total downtime (Smith and Dekker, 1997). Other factors can affect the downtime to a greater extent. Fault reports, fault detection, getting the right documentation, planning of the repair, requisition of spare parts, information retrieval, testing and start up time for process will all affect the total downtime. These factors are defined in the maintenance standards as the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function (IEV 191-07-01). These factors are also covered in the Swedish Standard stated in a slightly different way as the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function (SS EN 13306). To understand the role of maintenance in a system view it can be seen in the context and relation to operation and modification as described by the Swedish Standard SS 441 05 05, see Figure 5.

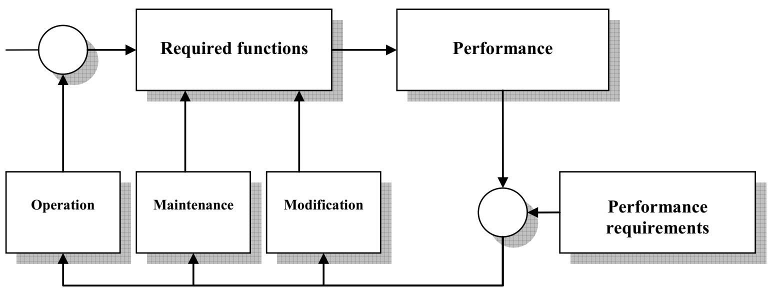


Figure 5. The relations between maintenance, operation and modification.

The performance of the system is dependent on the stated design parameters, which are based on the required functions. Stakeholders have performance requirement on the system. The required functions are set in the initial design state to achieve the performance requirements set for the operation of the item/system, which is the combination of all technical and administrative actions intended to enable an item to perform a required function, recognizing necessary adaptation to changes in external conditions (IEV 191-01-12).

During the use of the item/system the performance is the output. If there is a gap between the performance and the performance requirements some action has to be taken. If the gap is due to degradation of the item/system the action is maintenance. If the gap instead is due to change in the performance requirements, there will be a need for modification of the item/system, which includes the combination of all technical and administrative actions intended to change an item (IEV 191-01-13). These actions are made to meet a new level of performance requirements (Söderholm et al., 2006).

The area of maintenance is often further divided into more specific approaches on how the practical maintenance activities are conducted. The two main approaches are seen as either corrective or preventive. These are then divided into more detailed approaches. The maintenance activities as described in SS EN 13306, see Figure 6.

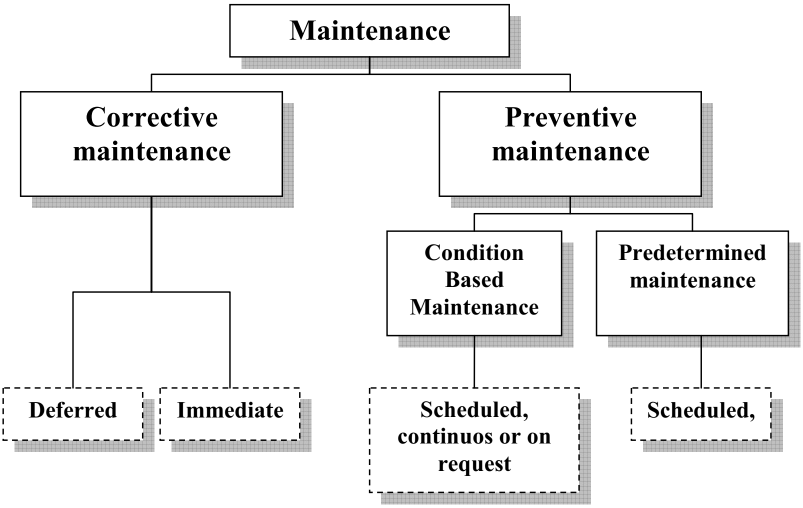


Figure 6. Maintenance divided into corrective and preventive activities (SS EN 13306)

Corrective maintenance is the maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function (IEV 191-07-08). However, this maintenance approach based on repairs when a breakdown has occurred is in most cases a very expensive and inefficient way of conducting maintenance. When an unpredicted failure occurs, the maintenance activities are harder to plan, therefore the efficiency of the maintenance work is affected. Due to the lack of time to prepare for the maintenance work it will take longer to make the repair. For example, more time for get the right spare parts, specialists, etc. Also the downtime of the process is affected when an unpredicted breakdown occurs. The process has been disturbed and has to be started again. It can take a long time before the process is running at full speed again. But in some cases it can actually be most appropriate to have corrective maintenance, for example if both the safety risk and the critical consequences of a failure are nonexistent and the maintenance crew can as fast as possible get the information about the failure with the necessary documentation at hand. This makes it possible for maintenance crews to have the right equipment and spare parts with them to enable a quick repair, as it is not always economically viable to have predetermined or condition based maintenance, for example in the case of non-critical components or systems. (Starr, 1997; Bengtsson, 2004)

With a preventive approach the maintenance is carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of failure or the degradation of the function of the item (IEV 191-07-07). With preventive maintenance, the goal is to detect and prevent faults before they create disturbances in the system. The key factor of preventive maintenance is that it is possible to detect fault indications at an early state which makes it possible to determine when the fault has to be corrected and also possible to plan the maintenance activities in a proactive way. With a higher degree of maintenance planning the total downtime of the process can be decreased, increasing the availability of the system. In cases where breakdowns in the process can lead to danger to life and health, for example in the aviation and nuclear industries, it is viable to have a higher degree of preventive maintenance than is motivated by purely technical reasons, for example, the negative business effect for an airline company, due to the bad publicity of a plane crash. In the case of a nuclear plant a major failure in the process can have catastrophic consequences.
The preventive maintenance approach can be divided into two main groups, predetermined maintenance and condition-based maintenance.

Predetermined maintenance is defined as preventive maintenance carried out according to established intervals of time or number of units of use but without previous condition investigation (SS-EN 13306, 7.3). Both methods are preventive activities but predetermined maintenance is scheduled based on knowledge and experience about the technical system or the specific item (Starr 1997; Bengtsson, 2004). Condition-based maintenance is described in more detail in the following section as it is a focus area in the thesis.

3.3 Condition-based maintenance

Condition-based maintenance is based on the possibility to aggregate information about the actual condition or performance of the system or item (Jardine, et al., 2005).

Condition-based maintenance is defined as preventive maintenance based on performance and/or parameter monitoring and the subsequent actions (SS-EN 13306, 7.4). In this definition it is also stated that the performance and parameter monitoring may be scheduled, on request or continuous.

With the application of condition-based maintenance the possible benefits are improved safety and reliability of the technical system, also the potential of decreasing both the cost of operation and support during the lifespan of the system. (Mobley, 1990; Becker et al., 1998; Söderholm, 2005)

To enable the use of this approach, there is a demand for methods or technology that can be used to obtain information about the actual condition. The possibilities can be scheduled, on request or continuous. With tools to monitor the condition it is possible to easier predict wear and degradation rates to take proactive decisions concerning maintenance activities. This makes it possible to have a predictive maintenance strategy since the maintenance activities are based on the condition of the item.

The definition of predictive maintenance describes it as condition-based maintenance carried out following a forecast derived from the analysis and evaluation of significant parameters of the degradation of the item (SS-EN 13306, 7.5). However, Bengtsson (2004) argue that this standard could be redefined as:

“Condition-based maintenance carried out following a forecast derived from the analysis and evaluation of significant parameters of the condition of the item.”

Bengtsson (2004) replaces the word degradation in the standard definition with condition since degradation is defined in the standard as an irreversible process in one or more characteristics of an item with either time, use or external cause (SS-EN 13306, 5.5).

Bengtsson (2004) argues that using degradation is overstating the case since the intention of condition-based and predictive maintenance is to find and correct a deviation in the performance of the item before it becomes irreversible.

This leads to the question of how the condition should be monitored to support a condition-based maintenance strategy. Shrieve (1992) states that condition-based maintenance is the use of information acquired through condition monitoring and that the development of both condition monitoring and condition-based maintenance will require that some issues have to be considered during the development, for example:

1. Machine and fault specific parameters to be monitored.
2. On and off-line elements
3. Sensor fits
4. Data acquisition and signal processing requirements
5. Data management and reporting.
6. Operator interface.
7. External data communication

3.4 Condition monitoring

Different maintenance activities aim at collecting information about an item's condition. There is inspection and monitoring. The term inspection is defined as checking for conformity by measuring, observing, testing or gauging the relevant characteristics of an item (SS-EN 13306, 8.1). The term monitoring is defined as an activity, performed either manually or automatically, intended to observe the actual state of an item (SS-EN 13306, 8.2).

This is to be distinguished from inspection as it is used to evaluate any changes in the parameters of the item with time. The activity can further be continuous, over a time interval or after a given numbers of operations and is usually carried out in the operating state. (SS-EN 13306, 8.2)

In some of the condition monitoring definitions there is a distinction between condition monitoring, human observations and machine performance monitoring. In literature the use of condition monitoring is also referred to as health monitoring. In this thesis on the other hand the term condition monitoring takes into account these aspects as condition monitoring.

A definition of the term condition monitoring by Milne (1992) describes it as the continuous or periodic measurement and interpretation of data to indicate the condition of an item to determine the need for maintenance which is normally carried out with the item in operation, in a operable state or removed but not subject to major stripdown.

So the monitoring methods could range from human observations using the senses with inspections at fixed intervals to automated continuous measurements with sensor technology.

Condition monitoring can be seen to have been in use for many decades if we count human observations, whereby skillful maintenance technicians have been able to estimate condition using their expertise and knowledge about the equipment. With the help of new technology there is now the possibility to have continuous observations. The true strength of automated condition monitoring is for example in cases when the development of a failure to a fault is very rapid or for example when large numbers of units have to be observed, as in the case with railway with a large amount of vehicles connected in a train set moving over large distances. The technology is also objective in its observations.

When deciding on using a condition monitoring system there are some functional requirements that have to be developed, these functional objectives of the system are described by Shrieve (1992) as:

1. Provide information regarding current condition.
2. Provide forecast of future condition.
3. Detect and diagnose developing faults.

Shrieve (1992) further states that the ability of the system to achieve these stated objectives is dependent on the fundamental elements for condition monitoring and condition-based maintenance.

1. Data collection
2. Data analysis
3. Data interpretation
4. Use of information
5. Maintenance feedback

From this, the three first elements would concern the condition monitoring part and the two last would concern condition-based maintenance, how to actually use the information to support the maintenance management. (Schrive, 1992)

One key aspect in the implementation of condition monitoring is the fact that the monitoring systems themselves are only providers of measurement data. The benefits of the technology lay in the challenge of transforming a huge amount of measurement data into useful information so that it would be possible to determine and locate any developing failure and also make an estimation of the remaining lifetime for the system or specific item/object. The information can then be a support to make a decision leading to an action being taken or avoided. To successfully implement the condition monitoring concept it is necessary to have good knowledge of the whole system that is going to be monitored. The challenges are not only to understand the technical aspects of the system but also the human aspects in operation and maintenance. An implementation of a new maintenance regime has to be implemented throughout the organization as the monitoring technology itself only is a means to an end. Condition monitoring systems provide the data needed to aggregate information about the condition of the system or item. The diagnosis of the information is what the maintenance decisions then are based on.

With the help of condition monitoring, data is collected from the process. The data is then transformed into information. The information can then be used in the decisions support system. With the decision support the maintenance management personnel plan the maintenance activities that then are conducted by the maintenance technicians. The condition-based maintenance procedure is presented in a simplified view in Figure 7.

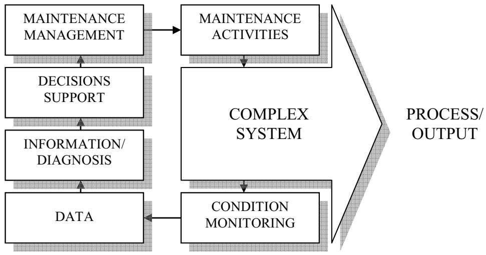


Figure 7. A simplified view of the condition-based maintenance procedure, from condition monitoring to maintenance activities

3.5 Wheel and rail interaction

A good understanding of the interaction between wheel and rail are of importance to understand the interest of possibilities to monitor the dynamic behavior of the vehicles in track. Even tough railway vehicles have a uniquely low rolling resistance due to the steel-on-steel contact and a badly performing vehicle will accelerate the degradation of the wheels and at the same time affect the wear and degradation rate of the rail. The goal is to match the characteristics of both vehicles and infrastructure to achieve the best possible interaction in the rolling contact. (Enblom, 2004)

The wheelset is a unit of two steel wheels attached rigidly to an axle, there are also wheelsets with independently rotating wheels, but they are in limited use. (IHHA, 2001)

The function of the wheelset following the rail is achieved mainly due to two important design factors. This is called self-steering or self-guidance. (Esveld, 2001; IHHA, 2001; Berghuvud, 2001)

The first is the conical rather than cylindrical design of the wheels. This means that the wheels have a larger rolling radius as the rolling contact position approaches the flange. It's the difference between the rolling radii between the two wheels in the wheelset that gives it self-steering ability. On a straight track it gives the effect of a self-centering force if there is lateral displacement of the wheelset. It also gives the ability to adjust the lateral position on tangent track to compensate for diameter differences between the two wheels. The conical design also has a positive effect on the radial adjustment of the wheelset in curves. The effect of this is more rolling, less slipping and hence less wear. (Esveld, 2001; IHHA, 2001; Berghuvud, 2001)

The second factor is that the wheels are also designed with flanges that are positioned on the inside of the track and used when the self-guidance of the wheelset is insufficient for guidance. The lateral forces from the flange contact will avoid a derailment of the wheelset. This lack of self-guidance can for example be due to poor track geometry or inadequate vehicle suspension, causing the wheel to make flange contact with the rail. In situations when there is a larger lateral displacement, for example in curves and on switches, the lateral clearance between the wheelset and the track can be too small to restrict lateral displacement through only the force of the centering effect from the conical design. But if the flange of the wheel in fact touches the rail head it can cause high lateral forces, wear and energy losses. (Esveld, 2001; IHHA, 2001; Berghuvud, 2001)

The conical design of the wheelset that can be described as a di-cone with two cones back-to-back, gives it a dynamic behavior of lateral movement on straight track. Lateral displacement of the wheelset from its central position in the track will be adjusted by the different rolling radii of the wheels. This initiates a harmonic wave movement in the track, the effect is often referred to as the Klingel movement. From the parameters of the wheel and rail the movement has a frequency. This can make the vehicle ride unstably if the frequency of the Klingel movement becomes similar to the natural frequency of the rolling stock, with depending factors such as dynamic behavior and the speed of the rolling stock. If the amplitude of the movement becomes too large it will result in flanging and the lateral movement will become different because of the rebound of the wheelset as it gets into flange contact with the rail. This will result in a behavior known as hunting. Instead of a harmonic movement the wheelset will zig-zag on the track, and this unstable movement of the wheelset can initiate flange climb which can lead to a derailment. The function of self-centering in the wheelset design is at the same time what makes a single wheelset unstable at all speeds. (Esveld, 2001; IHHA, 2001)

The solution of connecting two wheelsets in the horizontal plan will counteract on the instability that can be seen in the case of a single wheelset. The wheelset becomes a part of a bogie consisting most often of two wheelsets in a unit connected to the car body. The performance of the bogie will affect the interaction between the wheels and the rail. This coupling design can give some drawbacks in curving and guidance on straight track. One other design factor is the suspension between the bogie and the car body. This will affect the stability and dynamic ride behavior of the vehicle. So the total design of the coupling between the wheelsets in the bogie as well as the design of the suspension will affect the ride quality of the vehicle. (IHHA, 2001)

The displacement of the wheelset both laterally and twisted, referred to as the angle-of-attack of the wheelset, will cause a slip in the rolling contact between the wheel and the rail. This effect causes forces in the contact patch and the phenomenon called creep.

Creep: Elastic deformation of the wheel and rail material in the vicinity of the contact patch. (WRI course, 2005: Contact mechanics. Sawley, K.)

In the case of the lateral displacement of the wheelset the effect is longitudinal creep due to the different rolling radii of the wheels and if the wheelset has an angle-of-attack the effect is lateral creep due to the lateral forces that come in to play. The displacements of the wheelset from its best rolling state will increase the wear and degradation of both wheel and rail. (WRI course, 2005)

In the bogie the wheelsets can also be displaced differently to each other. These displacements states are referred to as bending and shear.
Bending mode is when the two wheelsets are twisted relative to one another. This is more often referred to as the angle of attack of the wheelset. Shear mode is when the two wheelsets are laterally displaced

relative to one another. In the design of the bogie, constraints against these movements can be applied, but there has to be a balance in it. Different combinations of stiffness in the different mode directions will affect the guidance and the curving characteristics of the vehicle both positively and negatively. It is a design challenge to develop a bogie that will have all the best characteristics of the both modes and still not be too costly or hard to maintain. (IHHA, 2001)

Another much more important issue in the wheel/rail interaction is the actual smoothness of the surfaces in the contact patch between the wheel and the rail. The steel-on-steel rolling contact is very low resistance, but the contact patch is no bigger than 8-12 mm in diameter (Magel et al, 2002). So any irregularities in the surfaces can make the rolling contact very uneven. With the high loads that are carried on the vehicles it can result in very high dynamic impact forces in the vertical direction, inflicting much damage on both wheel and rail.

These irregularities are most often of concern for the wheels, as they can for example lead to wheel flats due to breaking or out-of-round wheels (Johansson, 2005). These wheel defects can damage the rail for several miles if not detected in time. But defects in the rail can also cause damage to the wheels that then will damage even more rail.

Bearings are also another important component in the bogie. The bearings are also sensitive to the dynamic impact forces that can be inflicted by defects in the rolling contact. A failure of a bearing can have consequences that are severe for the vehicle and the whole train set as well as the infrastructure. A so called burnout in a bearing can lead to a derailment of a vehicle and as a consequence the whole train set can derail. A derailment usually results in extensive damage to both vehicles and track which leads to a direct repair cost for the railway. But another significant consequence that increases the cost of a derailment is that traffic cannot use the line while the track repairs takes place. (Barke and Chiu, 2004)

3.5.1 Stress state concept

In the concept of the “stress state” it is in the overlap between poorly performing vehicles and the weakest infrastructure that the wear and degradation occurs, see Figure 8. (Tournay and Cummings, 2005)

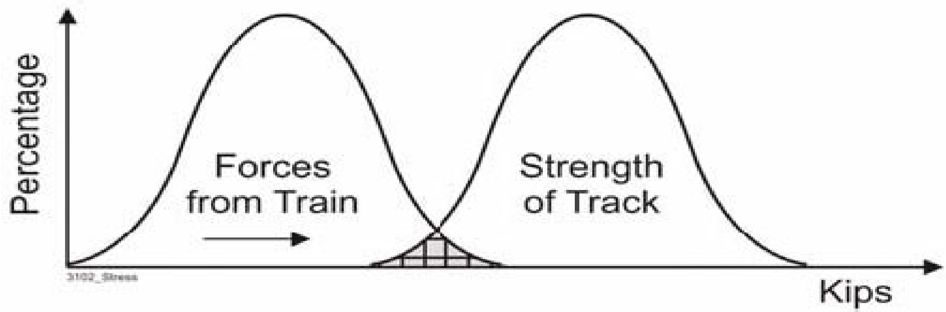


Figure 8. The stress state concept (Tournay and Cummings, 2005).

This concept focuses on the stress state of the track and the necessity to reduce the overlap of the highest forces from bad performing vehicles and the weakest parts of the infrastructure. In practice the best policy is to strengthen the weakest infrastructure and rectify the poorest performing vehicles. The need to find ways of detecting these deficiencies in both infrastructure and rolling stock is a requirement for this approach. (Berggren, 2005; Tournay and Cummings, 2005)

This also shows that there is a huge benefit for the infrastructure owner to identify vehicles with bad performance.

4 An overview of technologies for wayside condition monitoring

Several products already exist for monitoring the condition of cars and locomotives that operate on railways. The systems are continuously being improved and new technologies are being developed. In this chapter a small insight is given into the existing technologies that are commercially available.

4.1 System definitions

Today there are many commercial products for condition monitoring of railway vehicles (Blevins et al., 2003; Waring, 2003; Irani et al. 2003; Iden, 2003; Lagnebäck, 2004; Lagnebäck and Kumar, 2005; Granström, 2005; Barke and Chiu, 2005). The monitoring technology can be classified either as reactive or predictive (Southern, 2005). For the implementation of condition-based maintenance much focus is laid on the predictive systems, since this would provide possibilities for a proactive maintenance approach.

Most of the condition-monitoring systems for railway vehicles are focused on the wheel and bogies since these are the parts that have the largest impact on the performance and are also the mayor cost drivers in maintenance.

Many of the products for condition monitoring of railway vehicles are wayside monitoring systems and not directly mounted on the vehicles. In many cases, it still would not be economical to have sensors on every vehicle to monitor the entire vehicle condition because the cost of monitoring would become more costly than handling the faults if they occur. The vast number of vehicles that are in use on the railway makes it very costly to equip them all and also it is a challenge to both organize and maintain detector technology on every vehicle.

Possibilities exist in the railway sector however due to the fact that the vehicles are track bound and that the vehicles are most often used on specific routes even though they may be used over very long distances. But this makes it possible to monitor the vehicles with equipment standing adjacent to the track. The amount of monitoring systems and detectors can then be limited but still monitor and measure a large number of vehicles.

In Sweden there are some detector systems already installed in the track. But they are mainly used as reactive go/no-go systems with the focus on protecting the infrastructure from extensive damage. This has often been the focus when installing detectors: to protect the infrastructure from existing faults on the vehicles. But to use the systems more extensively and gather information over longer periods with the possibilities of trending the performance of the vehicles and their components makes it possible to achieve a proactive approach to decrease the degradation rate of both vehicles and infrastructure components. For this approach there is a need for more predictive monitoring systems.

4.2 Reactive systems

Reactive Systems detect actual faults on the vehicles; many of these faults are hard to predict or have very short failure to fault time. In most cases the information from these systems is not suited for trending, but is of importance to protect the equipment from further damage due to the fault. The systems also have reactive characteristics and they don't use the information in a trending way, even if the information could be used in that way. Some examples of systems and detector technology that are used in a reactive way are (Southern, 2005):

- Dragging Equipment Detector
- Hot Box Detector and Hot/Cold Wheel Detector
- Sliding wheel detector

4.2.1 Dragging equipment detector

The dragging equipment detector is used to detect equipment that is hanging below the vehicle. There are simple mechanical detectors as well as more advanced vision technology. The mechanical detectors are often designed with a vertical standing plate or beam located between the rails and also on the outside of the rails. The detector is self restoring and can be connected to a radio system or signaling system so that the train driver will be notified when it has been triggered off by dragging equipment knocking down the plate or beam. (Barke and Chiu, 2005)

Another technology used for dragging equipment detection is accelerometers installed in steel boxes between the rail and above the sleepers. (Barke and Chiu, 2005).

The detector receives an acoustic indication when something hits the device. The design of the device is strong enough to withstand an impact from dragging equipment and still be ready to detect the next occurrence. (Matoba, 2000)

Vision technology is also a technology that can be used in the application of dragging equipment detection. With images of passing vehicles it is possible to compare the situation with a picture of the expected profile to detect any deviations between the expected profile and the photographed profile. (Barke and Chiu, 2005)

4.2.2 Hot box detector and hot/cold wheel detector

Hot box detectors have been in use since the 1960s and are designed to detect overheated journals (hot boxes) since a bearing failure can have catastrophic consequences if it happens when the vehicle is in service. Inadequate lubrication or mechanical flaws in the wheel bearing will cause a higher friction that will significantly increase the temperature in the bearing indicating a failure in the performance of the bearing. The hot box detector detects the heat emitted from the failing bearing. The overheating of the bearing can however be very rapid and therefore provide a very short window for detection before a total burnout. Bearings can have defects for a long time and only show small variations in temperature but when they are about to seize there will be a large and rapid increase in temperature. This heat up from a normal state to a catastrophic level can be as fast as 30-60 seconds. (Newman et al, 1990)

This phenomenon makes it necessary to use several detectors evenly located to cover a railway. In North America there are a large amount of hotbox detectors located along the railway. But some derailments still occurr due to bearing failures even though the detectors are positioned with a distance of 15-30 kilometres. (Barke and Chiu, 2005)

The hot/cold wheel detector is similar to a hot box detector. It detects the heat radiation from the wheel. The technology is used to detect skidding wheels or wheels with inadequate breaking performance. By measuring the temperature of the wheels at places where the brakes are applied and comparing the readings between wheelsets it is possible to identify wheels that have too much or too little breaking force. A high temperature can indicate a locked wheel whereas a low temperature can indicate inadequate breaking performance and a possible fault in the break mechanism.

Both detectors use infrared technology to detect the heat radiation from the bearings and the wheels. This technology is used to measure the temperature.

Any object warmer than 0°K sends out energy in the form of infrared radiation. This makes it possible to measure the temperature of an object without contact and thus creates the possibility to measure moving objects. With optics and electronics the radiation is converted into an electrical signal. (Wikipedia, 2007)

Heat radiation from objects can also be detected by infrared cameras. This technology makes it possible to pinpoint areas with high or low temperatures. The application of this technology used as a sliding wheel detector has been used by ConRail in Philadelphia, USA and was developed due to a high rate of derailments due to braking problems. The system uses thermal imaging and digital image processing to scan the wheel and predict if the wheel is sliding instead of rolling. Under normal breaking the speed is only reduced and the wheel is still rolling and the wheel is then evenly heated all around the wheel rim. But if there is a locked wheel and it is sliding in the interface between the wheel and rail the heat will build up in the bottom of the wheel. (Steets and Tse, 1998)

This technology can also be used as a handheld infrared camera. This has been used for example during an evaluation of the hot box detector in Sweden (Granström, 2003). The infra red technology has the potential to be used in several applications in the future.

Such technology is in use on the Swedish railway, with detectors that have the function of both hot box detection as well as hot wheel detection.

The technology used in the hot box detection application has evolved from the early analogue systems with responsive thermoresistors and the digitalization of the signal from the pyroelectronic sensors to advanced high speed photon scanners. This rapid responsive system makes it possible to detect bearing temperatures on high speed trains operating at speeds up to 360 km/h. (Barke and Chiu, 2005)

4.2.3 Sliding wheel detectors

Sliding wheel detectors are systems that are designed to detect wheels that are sliding or skidding due to the fact that they are not rolling as fast as they should compared to the velocity of the whole vehicle. Mechanical failures or human errors can cause sliding or skidding wheels to occur and if undetected they can result in derailments.

The hot/cold wheel detector can detect wheels that are skidding or sliding from the heat signature of the wheel. There is also a system with an infrared camera that is used to detect sliding wheels by detecting the heat build up at the contact point on a sliding wheel. Both systems have already been mentioned. Other solutions to detect this unwanted rolling performance are digital image processing. The wheel is then equipped with identification points, for example white dots, evenly positioned around the wheel. A sequence of pictures from the image system is analyzed to detect the movement of the dots in relation to the vehicles velocity. It is then possible to predict if the wheel is rotating as normal, partially rotating or sliding. (Barke and Chiu, 2005)

There are also mechanical Sliding wheel detectors. The detector uses a roller that comes in contact with the flange of the passing wheel. An optical encoder then measures the angle of rotation of the roller. The prediction of a sliding or a normally rolling wheel is determined by the rollers direction of rotation. If the wheel is rotating normally the roller rotates backward and if the wheel is sliding the roller rotates in the same direction that the vehicle is moving. (Barke and Chiu, 2005)
The detector is mounted in the track and is connected to a signal system to alert the driver that a wheel is not rotating as it should. (Southern, 2005)

An example of the benefits of an automatic sliding wheel detection system comes from Pacific National in Australia. Since the installation of a prototype detector in November 2001 the number of skidding wheel incidents had dropped by 31% and there had not been a derailment due to skidded wheels from the time of the installation up to 2005. (Southern, 2005)

4.3 Predictive systems

Predictive systems are capable of measuring, recording and trending the ride performance of the vehicles and also specific components. From the collected information it is possible to analyze the condition of the equipment to predict possible failures and faults that may occur in a near or distant future. This makes it easier to plan the maintenance activities ahead and also to utilize the equipment in a more efficient way. Some examples of systems and detector technologies that are used in a predictive way are (Southern, 2005):

- Acoustic bearing detectors
- Vehicle performance monitoring/ Wheel condition monitoring
- Vehicle inspections

4.3.1 Acoustic bearing detectors

Acoustic measurements are a method that is growing in use. This technology uses microphones to record sounds from the passing vehicles.
The monitoring systems that are in use focus on the wheel bearings as it is well known that bearing defects produce vibrations at frequencies that can be connected to the characteristics of the defect (Stack et al., 2004; Barke and Chiu, 2005).
The development of the acoustic detectors arose out of the limitations of the Hot Box detector and a need for a more predictive system to monitor the health of the bearings. The development has proceeded and there are now a number of systems capable of detecting bearing defects by the acoustic signature. Two commercial product examples of the system type are the TADS™ and the RailBAM ™. Both systems use a set of microphones that are located at the side of the track to record the acoustic signature of the axle bearings on vehicles passing at normal track speeds. The systems have been in use in North America as well as Australia where they have been evaluated with good results. (Southern et al., 2004; Donnelly et al., 2005)
The systems can be used for trending the bearing performance to determine the optimum time for removal. The technology can not detect all bearing defects but is a more predictive system than the Hot Box detector since the bearings will generate an excessive amount of heat only at a late stage when there is a rapid degeneration of the internal components. (Cline et al., 1988)

The use of acoustic bearings detectors can significantly reduce the number of bearing failures in service. (Southern et al., 2004)

4.3.2 Vehicle performance monitoring

The monitoring systems are used for monitoring the performance of the vehicles, bogies and the individual wheelsets in the track, detecting for example lateral displacement, hunting and angle of attack. There are systems using the contact forces as well as non-contact monitoring systems. The contact systems are often based on strain gauges and/or accelerometers. The non-contact systems often use lasers and vision technology.

Contact measurements

By mounting strain gauges and accelerometers on to the rail it is possible to measure the forces that the vehicles induce into the track the wheel/rail force. The possibility to measure both lateral and vertical forces makes it possible to identify vehicles that are at risk of causing a derailment. A ratio between the lateral and the vertical force (L/V ratio) is used to indicate this risk. (Barke and Chiu, 2005)

In North America, TTCI (Transportation Technology Center Inc.) has developed a system called TPD (Truck Performance Detector). The system measures both vertical and lateral forces inflicted by the wheels on the rail. The system is installed with measuring points situated in a right hand curve, left hand curve and also in the tangent track between the curves. This gives the possibility to collect data on the vehicles behavior in both right and left curves as well as in tangent track. The angle-of-attack of the wheelset is also possible to determine through the measuring technique. (Tournay and Cummings, 2005)

The angle of attack is determined by the time difference between the right and left wheel passages over the measuring point. (Barke and Chiu, 2005)

There is also a system called HTD (Hunting Truck Detector) from Salient Systems. It has a similar design as a wheel impact detector with several strain gauges and accelerometers positioned over a longer distance. It measures both the lateral and vertical forces of the passing wheelsets. The measurements are evaluated to identify vehicles that have lateral movements such as hunting behavior in the track. The measurements are transformed into Hunting –Index to identify if the vehicle has too significant lateral movements which could lead to a derailment. In Australia similar developments have been made by BHP Research Laboratories. The cars are evaluated with a Lateral Movement Index (LMI) which indicates how much lateral movement the wheelset has over the measurement array. (Bowey et al., 1999)

Another application of the technology is that the force measurements can be used for weighing the vehicle. This can give the total weight of the vehicle, but can also be used to measure the weight ratio between wheel sets, bogies and vehicle sides to reveal misalignment of the cargo weight on the vehicle.

A Swedish company, Damill AB, uses strain gauges to measure lateral and vertical forces. Their measurement is made at a single point on both rails. A setup at the newly (2006) established Research station in Luleå is collecting data from passing trains. The goal is to use the measurements as input to the train operators as well as the infrastructure owner. This system and its function are described in more detail in one of the case studies.

Non-contact measurements

An example of non-contact technology is the T/BOGI (Truck/Bogie Optical Geometry Inspection) from the Canadian company WID (Wayside Inspection Devices Inc.) This product is an optical monitoring system for measuring the angle of attack and the lateral position of the wheels in relation to the rail. The system uses a laser and a camera to measure the position of the wheelsets. The system is also capable of measuring hunting behavior in the cars if there are several units being measured in succession. This system and its function are further described in one of the case studies.

4.3.3 Wheel condition monitoring

To evaluate the wheel condition it is the status of the wheel surface and the wheel profile that are of interest. But the crack propagation inside the wheel is also of great importance for the condition and life time of the wheel.

Contact measurements

Another application of the strain gauge measurement technology mentioned earlier is wheel impact detectors. This detector type aims to detect defects on the wheel surface. It measures the dynamic vertical forces induced on the rail during the whole rotation of the wheel. If there is a defect such as a wheel flat there can be high impact forces in the wheel/rail rolling contact that can inflict huge damages on the infrastructure. The detector system can also reveal out-of-round wheels. (Southern, 2005)

The system uses several measurement points over a distance that will cover at least one full rotation of the wheel. This type of system is one of the most utilized systems in Australia. (Southern, 2005)
There are already some systems installed in Sweden. They have been in use and have also been evaluated as to the reliability of detecting damages. (Granström, 2003)
The study showed that there is a good reliability in the readings from the system.

Mechanical profile monitoring systems are another contact-based system for measuring the wheel profile. The mechanical systems come into contact with the wheel flange and measure the change in the position of the mechanical arms which give an indication of the radial profile as well as the wear. The height of the flange is measured relative to the rail head. The measurement is based on the assumption that the tip of the wheel flange is not damaged or worn. (Barke and Chiu, 2005)

Non-contact measurements

Wheel profile measurements with laser and camera technology are a method that uses non-contact technology to measure the condition of the wheels. The lasers are often used as illumination and the pictures are automatically processed with computers to extract the profile of the wheel. It is possible to measure such parameters as rim thickness, hollow wear and flange height. The technology gives a good overview of the wear profile of the wheel. The possibility of trending the wear of individual wheels gives maintenance staff the possibilities to plan proactive wheel maintenance for maximizing the life length of the wheelsets. It is also useful for evaluating the vehicles' performance as uneven wear profile of wheels can give an indication of badly performing bogies.

4.3.4 Vehicle inspections

Vision technology can be used for monitoring in a large amount of applications such as break pad inspections to get an automated inspection process. It can also be used for detecting defect springs, missing end cap bolts, faulty handbrakes and coupler faults. These are just some of the possibilities of vision technology. (Barke and Chiu, 2005)

5 World overview

Several countries already have extensive systems for monitoring the condition of cars and locomotives that operate their railways. Many more countries are working with the implementation of the technology in their railway operation. In this chapter a small insight is given into the current situation and the developments that have happened and are ongoing in those countries that have come furthest in implementing the monitoring technology in practice.

5.1 North America

In North America hot box detectors have been in operation since the 1960s. Today the dominating detectors in use are hot box/wheel detectors and wheel impact detectors. There are thousands of hot box detectors deployed around the North American railway and during the last 20 years an extensive deployment of wheel impact detectors installed on the main lines means that around a hundred of them are in use. But new technology is continuing to be installed, such as acoustic bearing detectors, machine vision and vehicle performance detectors. (Lundgren, 2005)
The traditional and still dominating configuration is the stand alone hot box detector, and even if the detector has been developed into a sophisticated sensor it is still an isolated sensor on most railway systems.

In Canada trend monitoring of hot box/wheels and wheel impacts has been carried out for an extended period of time. The Canadian National Railways (CN) have been one of the pioneers within trend monitoring of railway vehicles. Up to 2002 the Canadian National Railways had installed 452 wayside detection systems from the Atlantic to the Pacific coast. These detector locations consisted of 452 hot box detectors and dragging equipment detectors. Also 324 of the locations were equipped with hot wheel detectors. In the beginning the hot box detectors were placed with a 25 to 30 mile spacing. During the mid 90s more detector locations were put into service to shorten the distance between locations to a 12 to 15 mile spacing. All the 452 detector setups give an alarm directly to the train staff. All the detectors are also connected to the main traffic control office, RTC (Rail Traffic Control Centre) in Edmonton, Alberta. There the personal can make trend and pattern analyses. This is done 24 hours a day, and it is possible for the RTC to send alarms to trains in traffic. Dramatic reductions in bearing failures have been seen and also that there are clear advantages both for service and safety with the use of trending of the measurements through an integrated detector system. (Blevins et al, 2003)

In the USA the work with the implementation of condition monitoring and condition-based maintenance has come a long way. Even though the situation in the USA is complicated by several different infrastructure owners as well as train operators they have been able to create a common condition monitoring system.

Earlier they had the same problems as in Canada, with the detectors out on the railway not being used for trending. The detectors were stand alone units that only sent alarms when a threshold was violated.
They tried to solve this by deploying more detectors with a smaller spacing to detect imminent failures. The problem was still that some failure events are so rapid that they could still happen between two detectors.
The performance could be just under the threshold on several earlier detectors. But since the detectors only were used as “go, no-go” alarms they often failed to prevent a breakdown. (Blevins et al, 2003)

In 2002 the Union Pacific Railroad in the USA initiated a computerized collecting process based on the technology developed by the Canadian National Railways. At the end of 2003 all of the 1200+ hot bearing detectors in Union Pacific’s railway net were scheduled to be connected to the system. One of the largest positive effects with use of trending is the considerable reduction in derailments caused by bearing breakdowns.

A huge benefit with an integrated trending system is the possibility to use the information to monitor the detectors. If one detector gives too many deviant measurement values it can be placed on a separate watch list. These are then controlled by staff for calibration or repairs. This is helpful in minimizing the amount of train delays caused by alarms from faulty detectors.

Another insight is the potential of connecting information from different kinds of detector types to get a better algorithm in the detection of imminent failures since many failure events are connected.

From these insights the Association of American Railroads (AAR) started the development of an Integrated Railroad Information System

(InteRRIS™) in 2000. The system went live in November 2000. (Hawthorne et al, 2005)

This is a single source database for performance data that is intended to collect measurements from all detectors for vehicle performance on the railroads in North America. The database is connected to another database containing records of maintenance activities. This database already existed due to the interchange rules in North America to keep track of billings of maintenance activities. The performance of the vehicles is connected to the maintenance activities. Today InteRRIS™ has performance data from the following detector types. (Tournay and Cummings, 2005)

• Acoustic Bearing Detectors (ABD)
• Hunting Detectors
• Truck Performance Detectors (TPD)
• Wheel Impact Load Detectors (WILD)

In 2003 the acoustic bearing detectors were integrated to the system and the next type of detectors to be added are wheel profile detectors. (Hawthorne et al. 2005) The InteRRIS™ system is open for data collection from new detector technology. The data from the detectors are also valuable in the development of predicting methods for vehicle performance. (Tournay and Cummings, 2005)

The available condition monitoring technology for railway vehicles has increased rapidly during recent years, this has created possibilities to identify vehicles with bad performance before they develop severe faults or inflict damages to the infrastructure. In North America the Association of American Railroads (AAR) has continued to implement a proactive approach in a concept called the Advanced Technology Safety Initiative (ATSI). The concept aims at reducing both track and vehicle maintenance and is expected to have a very positive effect on the infrastructure costs in the future. (Tournay and Cummings, 2005)

5.2 Europe

There is an ongoing development and deployment of condition monitoring equipment in Europe. In Great Britain there has been a dramatic reduction in wheel flats and out-of-round wheels since the introduction of the WheelChex® system in December 2000. Net work Rail and AEA

Technology Rail are working together with train and transport operators to reduce the number of damaged wheels that are rolling on the track undetected. Initially they have focused on detecting damages such as wheel flats and out-of-round wheels, but the monitoring equipment is said to be able to also measure other conditions. (Waring, 2003)

With the aim of reducing damaged wheels, Network Rail has bought 30 wheel Impact Detectors. The system used is called WheelChex®. The system measures the vertical forces in the rail from every individual wheel. The deployment of the systems started in the autumn 2000. The measured data from the WheelChex® system is correlated with identification data from an Automatic Vehicles Identification (AVI) system so that the measurements can be connected to specific wheels. Unfortunately there are several vehicles not equipped with the tags needed to be identified by the system. The vehicles are then identified with the help of Network rails TOPS/TRUST system. (Waring, 2003)

Since the introduction of the WheelChex® system it has been recorded that the alarms for wheel impacts over 350 kN has been reduced by 80% over a time period of 2 years. (2003) A similar trend has been recorded in Spain where the WheelChex® system also has been deployed. There they recorded an 80% reduction during an 18 month period, (2003). (Waring, 2003)

In the Netherlands there have been deployments of the GOTCHA system, a wheel-flat detection and Axle load measurement system, and the QUO VADIS system, a weigh-in-motion system. Both systems use optical fibre technology. The sensors are attached under the rail. The GOTCHA system is mainly a system for the track user and the QUO VADIS system is mainly a system for the track owner. But both systems are connected to a central server. The QUO VADIS system is installed at 38 locations. (2005) Together they are able to measure 80% of the traffic movement and a total of 96% of the ton kilometres. (Buurman and Zoeteman, 2005)

The advantages from the new systems have benefited both operators and infrastructure owners. On the operator side there has been an increased quality of the wheels and at the same time a decrease in repair cost. The number of broken springs as well as the amount of hot axles has decreased with 90% since the deployment of the systems.

For the infrastructure owners the systems have given a better overview of the actual usage of the track: how much tonnage and the movement they have on the track. For example during 2004 the systems gave an indication that the actual tonnage was 16% higher than the tonnage based on the timetable information. The more detailed knowledge about the usage of the track has made it possible to change maintenance strategies. There is, for example, an expected drop in maintenance cost for minor switches with €2 million per year due to the new usage-based inspections. The new inspection regime is tested in a pilot case, (2005). (Buurman and Zoeteman, 2005)

5.3 Australia

In Australia, BHP Billiton Iron Ore, that is one of the world's largest suppliers of iron ore, operate one of the heaviest railway transportation operations in the world with axle loads varying from 35 to 37 tonnes. The company operate its own railway system with both infrastructure as well as all vehicles being owned by the company. They operate two railway systems situated in the north west of Australia. (BHP Billiton, 2007)

The Traffic Control Centre at Port Hedland manages all train movements on the tracks. The signal system is not only used to control the train movements but is also used to control the wayside condition monitoring equipment. The signalling system is supported by specialized computer hardware and digital communications that are powered by solar technology. (BHP Billiton, 2007)

BHP Billiton Iron Ore uses several different wayside condition monitoring systems in its railway operations, such as hot box/wheel detectors, dragging equipment detectors, wheel impact detectors and weigh-in-motion systems. They also use hunting detectors, track performance measurements, acoustic bearing detectors and vision technology to inspect the cars. In the workshops the wheels are inspected with ultrasound for crack detection. (Lagnebäck, 2004)

The continuing improvement work and research since 1972 have made it possible for the railway to reach higher efficiency on both vehicles and infrastructure.

The improvements of the transportation operations have increased the axle loads from 30 to 37 tonnes and the aim is now set on 40 tonnes. The total system cost has been reduced due to operational savings even though the higher axle loads increase the wear rate of components. The total cost for railway transports has been reduced by 50 % between 1990 and 1998. (IRT, 2007)

The effect on the vehicle service life of many major components has been increased by up to three times, for example bogies, wheels and car bodies. The track life has been increased by up to 5 times between 1972 and 2000. This has reduced both capital and operating costs. These remarkable achievements are the result of several improvements that have been implemented, such as improved maintenance practices supported with condition monitoring and better understanding of the wheel/rail interface. There has also been development of new materials, track substructure and welding performance. (IRT, 2007)

The Australian Rail Track Corporation Ltd. (ARTC) is responsible for 10 000 kilometres of standard gauge interstate track, in an area covering South Australia, Victoria, Western Australia and New South Wales. The ARTC was created in 1997 with the objective of functioning as a unified counterpart to the national interstate rail network for train operators wishing to access the network. ARTC include in their objectives for the network the task of selling access to train operators, development of new business, capital investments and the management of the network including infrastructure maintenance. Train operators accessing the ARTC network pay a two part access charge. There is a fixed component, known as the “flagfall”, and a second charge based on mass and distance. The fixed charge is regardless of the size of the train and is charged for occupying capacity on the network. The variable charge is based on the gross tonnage of the train multiplied by the distance travelled. Nine major train operators use the ARTC network. The operators are: (ARTC, 2007)Queensland Rail

- CityRail
- Australian Southern Railroad
- CountryLink
- Great Southern Railway
- Pacific National
- Patrick Rail Operations

- Specialized Container Transport
- FreightLink

In the ongoing development of the railway operations efficiency on the ARTC network, ARTC is making a major investment of AUS $11.4 m (2005) to further expand its wayside monitoring program. The ARTC and the operators have regular meetings in a Wayside Steering Committee. In the Committee there is an ongoing development of an agreed predictive and preventive strategy of the monitoring and measurement of rolling stock. The aim is to further reduce derailment incidences and also to decrease the degradation of track quality due to poorly performing rolling stock. ARTC already have wayside condition monitoring equipment, such as wheel impact detectors and acoustic bearing detectors, deployed on a number of locations on the network. The systems have reduced both the number of wheel impacts and the amount of faulty bearings. The new investments in condition monitoring equipment are focused on the technologies of acoustic bearing detectors, wheel profile measuring equipment, angle of attack detectors, hunting detectors and wheel impact detectors, and dragging equipment detectors will also be installed. A new centralized database is also under development. The database will enable the operators to trend data for defect detection and also make it possible to use measurements from different monitoring systems to further analyse defects and also make it possible to increase maintenance resources providing better possibilities to repair multiple defects on a single maintenance stop. (Links, 2005)

6 Case studies

This chapter presents the case studies conducted with different technologies for condition monitoring of railway vehicles. The studies were made at the same time as the companies made a demonstration of the possibilities of their system for LKAB/MTAB. The measurements were mainly financed by LKAB/MTAB, but also by the Swedish Railroad Administration (Banverket).

6.1 General test information

In the research to find methods of implementing condition-based maintenance for railway vehicles a key issue is the possibility to monitor the actual behaviour and condition of the vehicles while in use. In the process of increasing the knowledge of available technology and the measuring possibilities they have, three different systems for monitoring the performance of the vehicles have been tested. In the three case studies carried out by Luleå Railway Research Centre during 2004, three different condition monitoring systems to monitor a number of critical parameters, such as angle of attack, tracking error, wheel profile, lateral and vertical forces in the rail, were of interest.

One of the systems has also been studied during 2006 during a fourth case study to get more insight into the measurements.

The results were evaluated to get knowledge about the possibilities of obtaining necessary information about the performance and condition of the vehicles for making decisions about the maintenance activities.

All the three condition-monitoring systems measure parameters on the wheel and bogies. The chosen focus area of the systems has its origin in the fact that the wheel maintenance cost for ore cars at MTAB is around 50 % of the total maintenance cost for the whole car fleet (Åhrén, 2002).

Also, other components often have a more predictive wear interval. An improvement on the rolling stock will have a positive impact on the rail wear and other infrastructure components. The potential here is probably in the same range or larger than for the rolling stock.

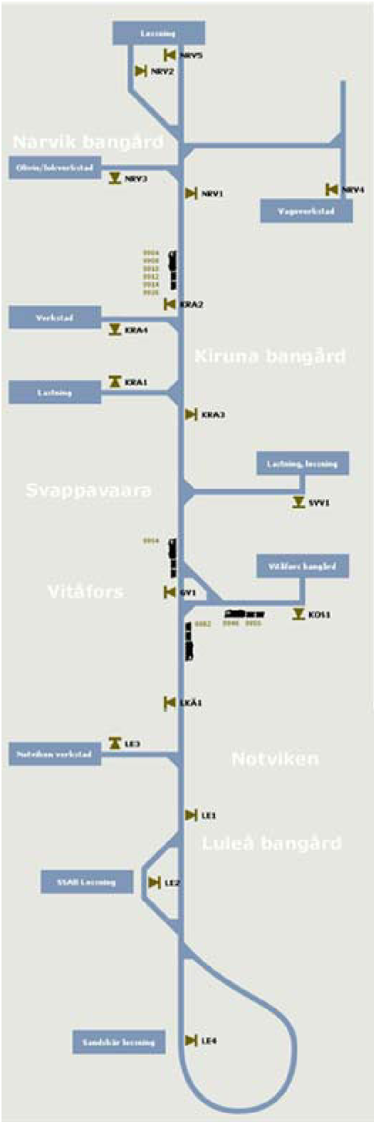
Two of the systems for detecting steering performance of bogies were tested out in the field during a week, measuring passing ore cars. This measurement was being connected to an identification system (ATI) so the readings of the passages are connected to each ore car in a database since all LKAB/MTAB vehicles are equipped with ID-tags, see Figure 9.

Figure 9. ID-tag on LKAB/MTAB vehicle

The system for wheel profile measuring was only tested in a prototype installation at a workshop.

Evaluation of data readings from different wayside condition monitoring systems in comparison with the actual condition monitored at the workshops and the historic maintenance data extracted from MTAB's own maintenance system MAXIMO, can give technical information about what kind of condition monitoring input is necessary for the implementation of condition-based maintenance on their railway vehicles. The two first systems have been cross-analyzed to see if the systems are measuring the same deviation in dynamic behaviour of the vehicles.

The measurements from the two first systems were connected to identification data from LKAB/MTAB's own system in use, the ATI (Automatic Train Identification system), see Figure 10.



Placement of ATI-readers
Along Malmbanan from
Narvik – Kiruna – Vitåfors – Luleå
there are 17 reading units that's register locomotives and cars that are travelling in both directions.
They are located on the following places:

*** Narvik ***
(NRV1) Station boarder Narvik
(NRV2) Unloading Narvik (0)
(NRV3) Olivin loading Narvik
(NRV4) MTAS workshop Narvik
(NRV5) Unloading Narvik (1)

*** Kiruna ***
(KRA1) Loading Kiruna
(KRA2) Kiruna North Plattvik
(KRA3) Kiruna South
(KRA4) MTAB Workshop Kiruna

*** Svappavaara ***
(SVV1) Svappavaara

*** Lakaträsk ***
(LKÄ1) Lakaträsk

*** Gällivare ***
(GV1) Gällivare Railway yard North
(KOS1) Koskullskulle

*** Luleå ***
(LE1) Luleå station
(LE2) Unloading Luleå SSAB
(LE3) Notviken, Euromaint workshop Luleå
(LE4) Unloading Luleå Sandskär

Figure 10. ATI placements along Malmbanan. [Courtesy: LKAB/MTAB]

The datasheet in Table 2 give information about the train passing. On the top there is general information: Time of recording, direction, total amount of axles and loco axles, locos and cars. The sheet then lists all the individual vehicles, in this case from 1-55. The second column lists the number of axles for the vehicle. The third column lists the individual ID-number. Forth and fifth column are time code for first and second reading of the vehicle. The last column indicates the travel direction of the vehicle and if it has traveled with A or B end first. This information is necessary to identify the individual wheelset on every vehicle.

Direction: Kiruna, Detector at 15:33 040612
3 Locos and 52 Cars
Loco axles = 14, Total axles = 222

L	5	1207	56000,12	56000,8	H 0 5 A
L	4	1232	56000,78	56001,32	H 0 4 A
L	5	1208	56001,45	56002,07	V 0 5 B
4	4	1359	56001,92	56002,61	V 0 4 B
5	4	9210260	56002,47	56003,11	V 0 4 B
6	4	9211621	56002,99	56003,54	V 0 4 B
7	4	Unknown	--------	--------	- - - -
8	4	9211535	56003,92	56004,61	V 0 4 B
9	4	1785	56004,42	56005,05	H 0 4 A
10	4	9210566	56004,86	56005,57	H 0 4 A
11	4	9210577	56005,44	56006,14	V 0 4 B
12	4	9211792	56005,93	56006,56	H 0 4 A
13	4	9210376	56006,5	56007,09	V 0 4 B
14	4	1622	56006,95	56007,58	V 0 4 B
15	4	9211578	56007,45	56008,14	V 0 4 B
16	4	9210274	56007,95	56008,58	V 0 4 B
17	4	9211591	56008,5	56009,13	V 0 4 B
18	4	9211628	56008,99	56009,58	H 0 4 A
19	4	1676	56009,51	56010,15	H 0 4 A
20	4	9210668	56009,95	56010,65	H 0 4 A
21	4	9211633	56010,51	56011,15	H 0 4 A
22	4	9211728	56010,97	56011,61	H 0 4 A
23	4	9211560	56011,51	56012,15	H 0 4 A
24	4	9210108	56012,01	56012,65	V 0 4 B
25	4	9210375	56012,52	56013,1	V 0 4 B
26	4	9211566	56013,02	56013,66	H 0 4 A
27	4	9211795	56013,52	56014,08	H 0 4 A
28	4	1761	56014,01	56014,59	H 0 4 A
29	4	9210579	56014,52	56015,1	H 0 4 A
30	4	9211638	56015,04	56015,66	V 0 4 B
31	4	9211589	56015,55	56016,06	H 0 4 A
32	4	1426	56015,98	56016,61	V 0 4 B
33	4	1775	56016,46	56017,09	H 0 4 A
34	4	9210307	56016,97	56017,59	H 0 4 A
35	4	9210349	56017,46	56018,09	H 0 4 A
36	4	9210298	56017,98	56018,66	V 0 4 B
37	4	9210575	56018,47	56019,09	H 0 4 A
38	4	1454	56018,97	56019,61	H 0 4 A
39	4	9210322	56019,5	56020,15	V 0 4 B
40	4	9210174	56019,95	56020,58	H 0 4 A
41	4	9211615	56020,39	56021,05	V 0 4 B
42	4	9210624	56021,01	56021,66	V 0 4 B
43	4	1784	56021,53	56022,08	V 0 4 B
44	4	9210672	56022,01	56022,67	V 0 4 B
45	4	1692	56022,45	56023,09	H 0 4 A
46	4	1626	56022,97	56023,6	H 0 4 A
47	4	9210461	56023,46	56024,08	H 0 4 A
48	4	1327	56023,97	56024,59	V 0 4 B
49	4	9211614	56024,51	56025,09	H 0 4 A
50	4	9211749	56025	56025,59	H 0 4 A
51	4	9211708	56025,52	56026,16	V 0 4 B
52	4	1435	56026,02	56026,65	H 0 4 A
53	4	9210355	56026,51	56027,09	V 0 4 B
54	4	9210217	56026,96	56027,6	V 0 4 B
55	4	9210510	56027,5	56028,07	H 0 4 A

Table 2. Data sheet with processed data from the identification system on one ore train passage. [Courtesy: LKAB/MTAB]

6.2 *Case 1: Truck/bogie optical geometry inspection*

This monitoring system is a commercial product that has been in use for some years. The system uses laser and camera technology to measure angle of attack and lateral position of the passing wheelsets.

6.2.1 Purpose of this case study

The purpose was to increase knowledge and evaluate a system that measures the angle of attack and the lateral displacement of the wheelsets, in order to decide if the technology was fulfilling the requirements for monitoring the performance of the wheels and bogies on the iron ore cars.

6.2.2 Study approach

The intention was to collect measurement data of the angle of attack and the lateral displacement and connect it to individual wheelsets for correlation with recorded maintenance historical data.

The data was collected during the time period 14-18 June 2004. The measurements were conducted during 5 days, but the actual measurement time was 4 days since the system was deployed around 12:00 the first day and then it was uninstalled at around 12:00 the last day. The geographical location was along the track on the north bound transport stretch of the iron ore line from Kiruna to Narvik.

Figure.11. Pictures of the measurement location,
Plattvik north of Kiruna on the route to Narvik.

The Truck/Bogie Optical Geometry Inspection (T/BOGI) monitoring system was installed on four pipes that were driven into the ballast of the track body. The detector was then lifted into position by three persons, see Figure 12. The whole installation was done in around three effective hours. The installation was slightly delayed due to train passages and the need to locate underground cables before it was possible to drive the pipes into the ground. The installation was made on one side of the track, see Figure 13. During the installation Banverket had personnel in charge of safety assigned to the location.

Figure 12. The four pipes in the ballast and the mounting of the monitoring equipment on to them during the field test at Kiruna (Sweden).

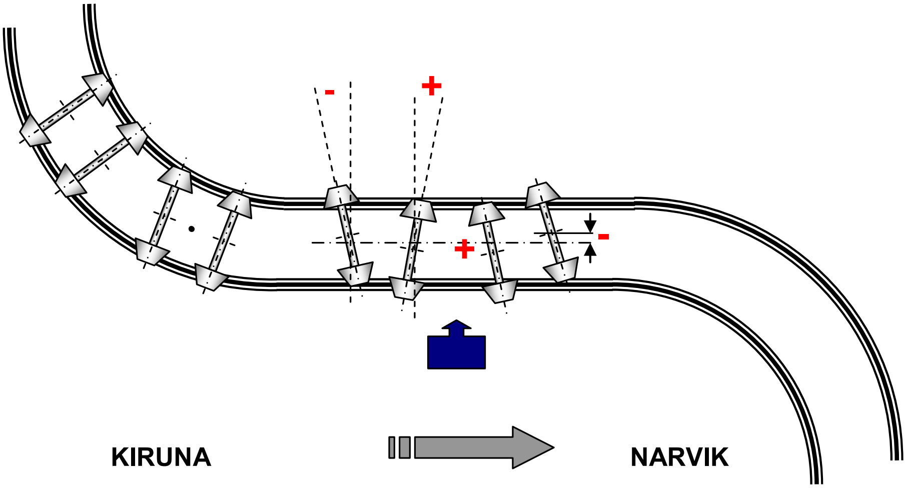


Figure 13. Installation of the T/Bogi system with the defined directions for the measured parameters and the geographical direction of the track. [Courtesy: WID Inc.]

6.2.3 System description

This product is a condition monitoring system for measuring the angle of attack and tracking position of the wheels in relation to the rail. The system is a product from the Canadian company WID (Wayside Inspection Devices Inc.).

The WID Company is also a part of an alliance with three other companies. The alliance (WMA - Wayside Monitoring Alliance) offers a joint solution with four different measurement technologies and a common diagnostic program.

WID personnel installed and performed the measurements with their T/BOGI (Truck/Bogie Optical Geometry Inspection) system during the field test, see Figure 14.

Figure 14. T/BOGI installation at Kiruna during field test.

The system consists of an optical measuring unit that is installed wayside near the rail. The system uses a laser and a camera to measure the deviations in the track performance of the vehicle. In close range to the optical unit a connected computer unit is installed.
The laser generates a line of dots on the side of the wheel that is captured with the camera, see Figure 15.

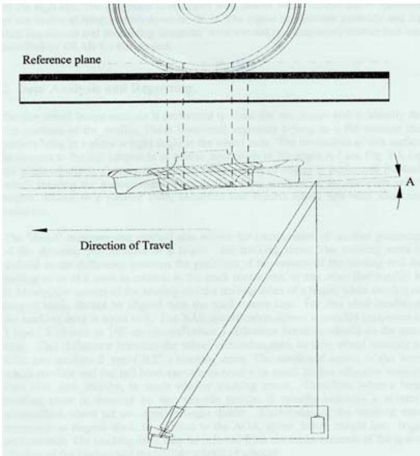


Figure 15. The principle of the laser camera angle
to the passing wheel. [Courtesy: WID Inc.]

The picture of the wheel is then analyzed in the computer unit at site when the train is passing. The measured values are recorded in a data file that can be sent by modem, radio or internet. The dots mark the wheel's outer profile and a line is fitted to the dots, see Figure 16.

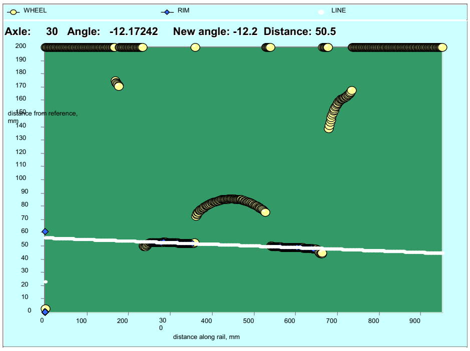


Figure 16. A picture from the system. [Courtesy: WID Inc.]

The automatic analysis of the picture gives the angle of attack and tracking position. The angle of attack (AOA) of a wheel set is defined as the angle between the track radial line and the center line of the wheel set's axle. The measured parameters are also combined to give a more detailed description of the whole bogie. This gives a definition of the dynamic behavior of the bogie. Angle of attack (AOA), tracking position (TP) and two other parameters are used in the system to evaluate the dynamic behavior of the bogie. The other two parameters are defined as Inter-axle misalignment (IAM) and tracking error (TE).

Angle of attack (AOA) for a wheel set is defined as the angle between the track radial line and the center line of axle on the wheel set. Tracking position (TP) is defined as the center line of the wheel set compared to the track center line, see Figure 17.

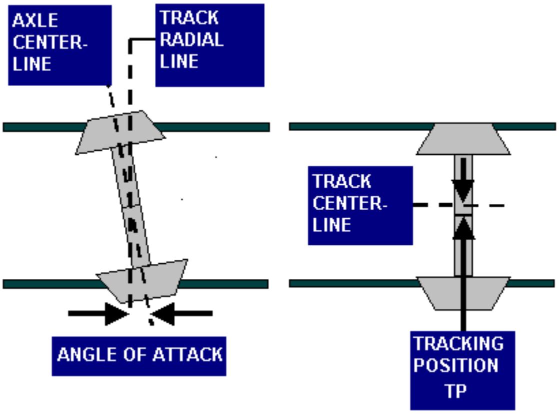


Figure 17. Angle of attack and Tracking position. [Courtesy: WID Inc.]

The deviations in the dynamic behavior of the wheel sets can increase the wear of both on the wheels and the rail. It also affects the rolling resistance that effects the energy consumption of the train. High values on the measured parameters indicate a vehicle with defects.

Inter-axle misalignment

The internal misalignment between the two wheelsets in a bogie, inter-axle misalignment (IAM), is defined as the angle of attack of the leading wheelset (AOAL), minus the angle of attack of the trailing wheelset (AOAT), see Figure 18.

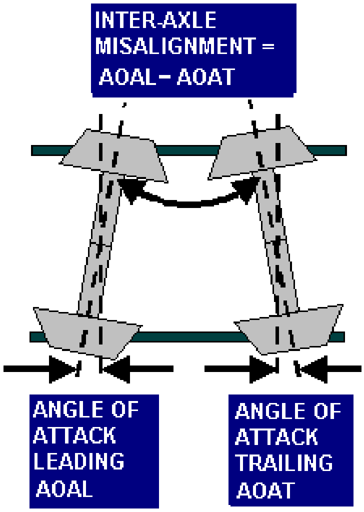


Figure 18. Inter axle misalignment. [Courtesy: WID Inc.]

Tracking Error (TE but also TrE)

The tracking error (TE) of a bogie is the lateral distance between the centrelines of the axles in the bogie and is defined as the tracking position of the leading wheelset (TPL)) minus the tracking position of the trailing wheelset (TPT)), see Figure 19.

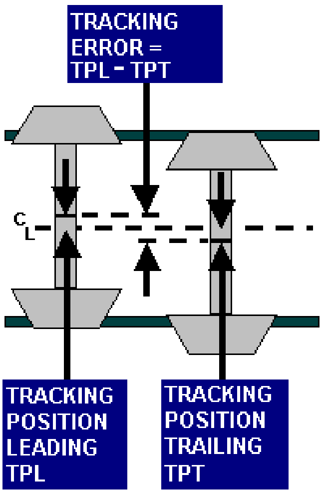


Figure 19. Tracking Error. [Courtesy: WID Inc.]

During the field test the system monitored.

Number of iron ore trains	
To Kiruna:	35
To Narvik:	35
Number of iron ore bogie-passes:	
To Kiruna:	3514
To Narvik:	3522
Total:	7036
Unique wagon ID monitored of total rolling stock fleet:	773 of ~900 (~85.9%)

6.2.4 Data analysis

During the field test several passages of ore trains were monitored. To best illustrate the results, two passages have been used. This is because the configuration of the train set was the same at both passages. The data was extracted from the data tables that WID presented, see Table 3.

tblOreBogies

ownerID	eqID	bogNum	rstCode	aeiDate	direction	eqNo	leadEnd	trAxNumLead	trAxNumTrail	bogAxNumLead	bogAxNumTrail	angleLead	angleTrail	posLead	posTrail	iam1	trEr1	rot1	shift1	speed	distC	distB	distP
LKAB	1302	A	2004-06-15-12-17	2004-06-15 12:18:00	Narvik	34	B	137	138	2	1	0,00	0,00	1,50	0,50	0,00	1,00		1,00	53,40	3531	1704	0
LKAB	1302	A	2004-06-16-04-47	2004-06-16 04:48:00	Kiruna	24	A	95	96	1	2	-0,10	0,00	-6,50	1,50	-0,10	-8,00		-2,50	62,50	1529	1709	0
LKAB	1302	A	2004-06-16-16-35	2004-06-16 16:36:00	Narvik	34	B	137	138	2	1	0,20	0,30	2,10	-2,00	-0,10	4,10		0,05	47,30	3534	1703	0
LKAB	1302	A	2004-06-17-23-03	2004-06-17 23:04:00	Kiruna	24	A	95	96	1	2	0,30	0,20	-4,00	2,00	0,10	-6,00		-1,00	63,20	1529	1719	0
LKAB	1302	A	2004-06-18-11-24	2004-06-18 11:25:00	Narvik	31	B	127	128	2	1	-0,20	-0,30	4,50	-0,60	0,10	5,10		1,95	49,10	3536	1712	0
LKAB	1302	B	2004-06-15-12-17	2004-06-15 12:18:00	Narvik	34	B	135	136	4	3	-0,20	0,50	-2,80	-1,10	-0,70	-1,70		-1,95	53,40	1543	1701	0
LKAB	1302	B	2004-06-16-04-47	2004-06-16 04:48:00	Kiruna	24	A	97	98	3	4	-0,20	0,10	-7,30	-1,00	-0,30	-6,30		-4,15	62,60	3533	1727	0
LKAB	1302	B	2004-06-16-16-35	2004-06-16 16:36:00	Narvik	34	B	135	136	4	3	0,40	0,10	0,30	-7,80	0,30	8,10		-3,75	47,20	1469	1703	0
LKAB	1302	B	2004-06-17-23-03	2004-06-17 23:04:00	Kiruna	24	A	97	98	3	4	0,20	-0,10	-1,60	-2,20	0,30	0,60		-1,90	63,10	3526	1722	0
LKAB	1302	B	2004-06-18-11-24	2004-06-18 11:25:00	Narvik	31	B	125	126	4	3	0,00	0,60	-4,30	-0,70	-0,60	-3,60		-2,50	49,00	1445	1701	0
LKAB	1304	A	2004-06-18-08-04	2004-06-18 08:04:00	Narvik	41	B	165	166	2	1	-0,20	0,50	-2,70	-8,50	-0,70	5,80		-5,60	50,10	3523	1696	0
LKAB	1304	B	2004-06-18-08-04	2004-06-18 08:04:00	Narvik	41	B	163	164	4	3	0,10	0,40	-2,50	-5,90	-0,30	3,40		-4,20	50,20	1550	1699	0
LKAB	1305	A	2004-06-15-12-17	2004-06-15 12:18:00	Narvik	22	A	87	88	1	2	0,50	0,10	4,20	6,90	0,40	-2,70		5,55	52,80	1526	1699	0
LKAB	1305	A	2004-06-16-04-47	2004-06-16 04:48:00	Kiruna	36	B	145	146	2	1	0,20	0,00	5,00	2,20	0,20	2,80		3,60	62,90	3530	1712	0
LKAB	1305	A	2004-06-16-16-35	2004-06-16 16:36:00	Narvik	22	A	87	88	1	2	0,00	0,40	-2,00	6,70	-0,40	-8,70		2,35	47,40	1476	1697	0
LKAB	1305	A	2004-06-17-23-03	2004-06-17 23:04:00	Kiruna	36	B	145	146	2	1	0,10	0,00	5,60	2,70	0,10	2,90		4,15	63,70	3543	1718	0
LKAB	1305	A	2004-06-18-11-24	2004-06-18 11:25:00	Narvik	19	A	77	78	1	2	0,30	0,60	0,80	6,10	-0,30	-5,30		3,45	49,20	1463	1709	0

Table 3. Example of data from the T/BOGI system. [Courtesy: WID Inc.]

The angle is measured in mrad and most of the readings have very small values, see Figure 20.

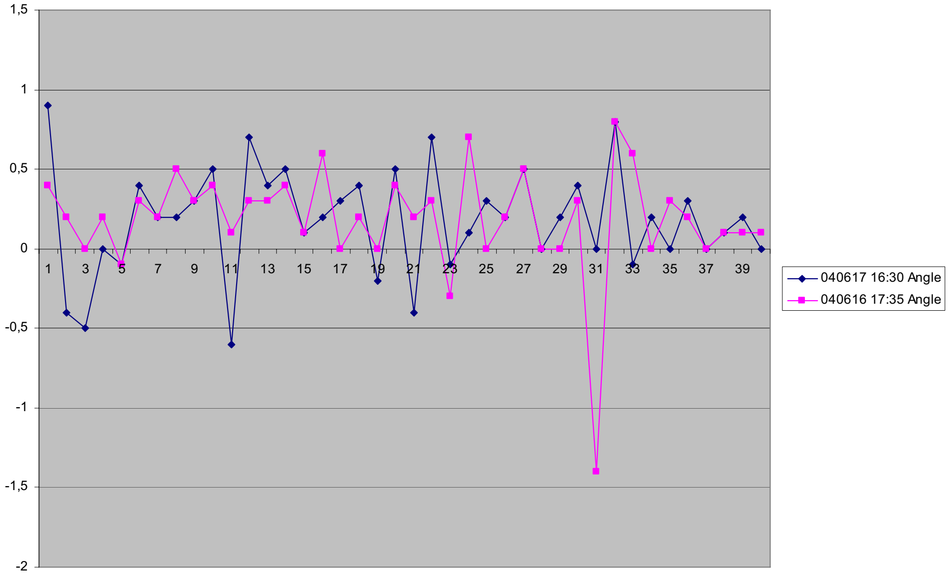


Figure 20. Angle on the 40 first axles in the same train set passing on 2004, June 16, 17:35 and June 17, 16:30

The position, also referred to as the tracking error (TrE), is measured in mm, see Figure 21.

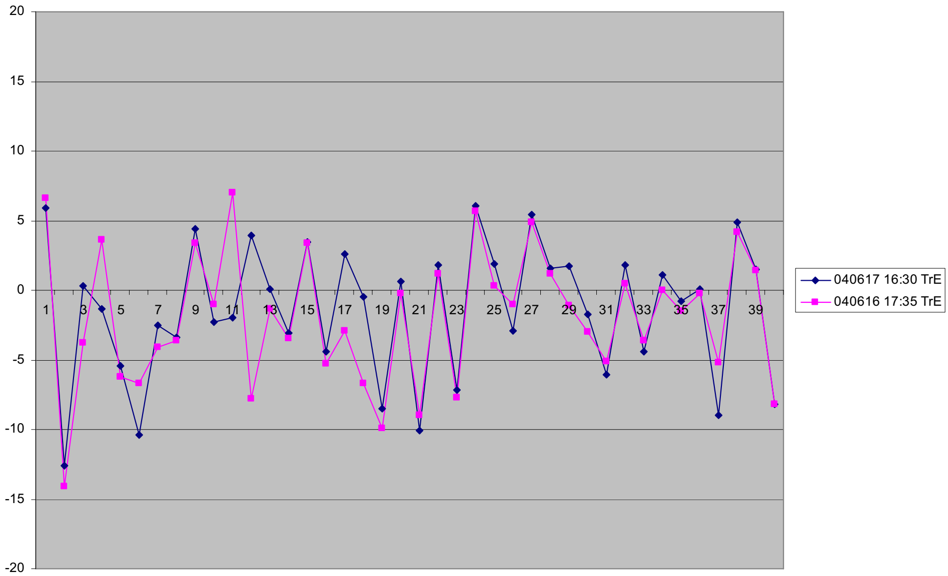


Figure 21. Position on the 40 first axles in the same train set passing on 2004, June 16, 17:35 and June 17, 16:30

6.2.5 Findings

The T/BOGI system that measures angle of attack, see Figure 20, and position, see Figure 21, showed good repeatability in the measurement between the two passages of the train with the same set up at both times.The system seem to have a good repeatability in the measurements. The two passages of the same train set in the same configuration give a good indication of this. But the total amount of measurement makes it dangerous to make to exact statements about the reliability and validity since the amount of data is quite small.

The validity of the measurements seems to be quite good in the case of the inspections made on the measurements. Two cars were inspected early during the field test based on high values on position. The inspection confirmed the expected wear that would be connected to that kind of deviation in steering performance. The bogie was also inspected by a bogie manufacture representative that was at the workshop. He gave a short report about the bogies to LKAB/MTAB, see Appendix 1.

The report states that the wear of the wheels correlates with readings of the detector system. It also gives suggestions of bogie problems that can be the cause of the bad performance of the bogies.

But with the small amount of data there is also a problem to make an exact statement about the actual validity of the measurements.

One of the goals of the measurements was to see if they had any correlation with the maintenance history data of the vehicles. This work revealed a problem with the use of the maintenance management system that wasn't known to the researcher before the measurements. The system is capable of keeping track of individual axles on the vehicles and the general perception was that this was done. However, once the extraction of data was started it became evident that there were corrupt data in the maintenance system. This made it impossible to give a correct analysis of the correlation of the measurement and the maintenance historical data.

6.2.6 Research implications

One limitation in the study is the small amount of measurement data, which makes it difficult to make any conclusive statement about the measurement system's reliability and validity. Hence in order to achieve a better result more measurements should be performed.

6.2.7 Practical implications

The technology is applicable on most types of railways using wheels on rail as long as there it is possible to get a clear visibility of the wheel from the side of the track. This makes it possible to use on most of the vehicles on Swedish railways.

The measured parameters would be a valuable input in detecting and evaluating the performance of railway vehicles on the Swedish railways, giving benefits to both train operators and infrastructure owners.

Some issues with the system's capability to measure during winter were raised, since the phenomena of snow-smoke (snörök) could limit the visibility for the camera technology, hence affecting the accuracy of the measurement.

To be able to use the measurement system to its full potential it is necessary to connect the measurements to the maintenance management database. This means that the history of individual items (e.g. wheelsets) should be recorded correctly in the database to enable the follow up of the measurements from the monitoring system. Without the possibility to compare current measurements with earlier measurements the possibility of trending is lost. Hence, the predictive capability would be strongly limited if the recording of measurements and historical maintenance data is not correct.

6.2.8 Value of study

From the study it has been shown that the system is usable on the Swedish railways. This makes the system one of the most promising ways of monitoring the condition and performance of railway vehicles on Swedish railways. Another important insight from the study is the problem with the connection between condition monitoring data and historical maintenance activities data at LKAB/MTAB. There is a need for an update in the use of the maintenance management system to be able to use condition monitoring systems to its full capability.

6.3 Case 2: Wheel/rail force measurements

The system is a product that is under an ongoing development, but is based on technology that has been in use in several countries. The system uses strain gauges deployed on the rail to measure the forces from the passing wheelsets.

6.3.1 Purpose of this case study

The purpose was to increase knowledge and evaluate a system that measures the lateral and vertical forces in the rail from the passing wheelsets, in order to decide if the technology was fulfilling the requirements for monitoring the performance of the wheels and bogies on the iron ore cars.

6.3.2 Study approach

The intention was to collect measurement data on the vertical and lateral forces and connect it to individual wheelsets for correlation with maintenance history data.

This case study was performed in parallel with Case Study 1: the data was collected during the time period 14-18 June 2004. The measurements were taken over 5 days, but the actual measurement time was 4 days since the system was deployed around 12:00 the first day and then it was uninstalled at around 12:00 the last day. The geographical location was along the track on the north bound transport stretch of the iron ore line from Kiruna to Narvik, see Figure 22.

Figure 22. Pictures of the measurement location, Plattvik north of Kiruna

The strain gauge measurement system was installed directly on the rail by personnel from Damill AB. The installation was slightly delayed due to some technical problems with the welding of the strain gauges on to the rail, see Figure 23. During the installation Banverket had personnel in charge of safety assigned to the location. The equipment was installed on both sides of the rail, see Figure 24.

Figure 23. Installation of strain gauges for measuring vertical and lateral forces during the field test at Kiruna (Sweden).

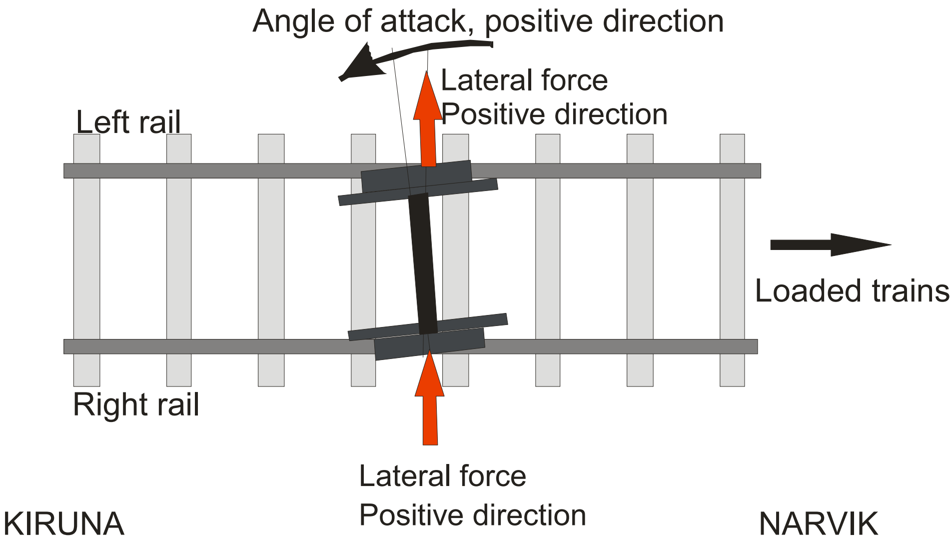


Figure 24. Installation of the strain gauge system with the defined directions for the measured parameters and the geographical direction of the track. [Courtesy: Damill AB]

6.3.3 System description

This system is a monitoring system that measures the strain in the rail and converts the measured values to forces from the wheels in relation to the rail. The system is produced by Damill AB.

Damill AB is a Swedish company that develops technical monitoring solutions and measurement methods for the industry. They have also performed measurements with the system for Banverket as a part of a project to develop a rail degradation prediction model, DeCoTrack.

Personnel from Damill AB installed and performed the measurements with their strain gauge monitoring system during the field test, see Figure 25.

Figure 25. Strain gauge installation at Kiruna during field test.

The installation consists of 16 strain gauges. The strain gauges are installed on the rail between two sleepers, since there is a deflection of the rail as the axle of a vehicle passes. A special software program is the base for distinguishing the different force directions. The measurements are in micro strain which is translated into forces.

During the field test the system monitored all train passages but due to the manual analysis of the measurements nine trains were chosen. The choices were loaded trains due to the higher forces they generate.

From the total passing trains during 16-17 June, there was a train set passing twice during that time period with the same set up both times.
These two where chosen in the further analyse.

Iron ore trains:	9
Iron Ore Bogie-passes:	1996

6.3.4 Data analysis

During the field test several passages of ore trains were monitored. To best illustrate the results, two passages have been used. This is because the configuration of the train set was the same at both passages.

The measurements of lateral forces showed a good repetition of readings between the two passages, see Figure 26.

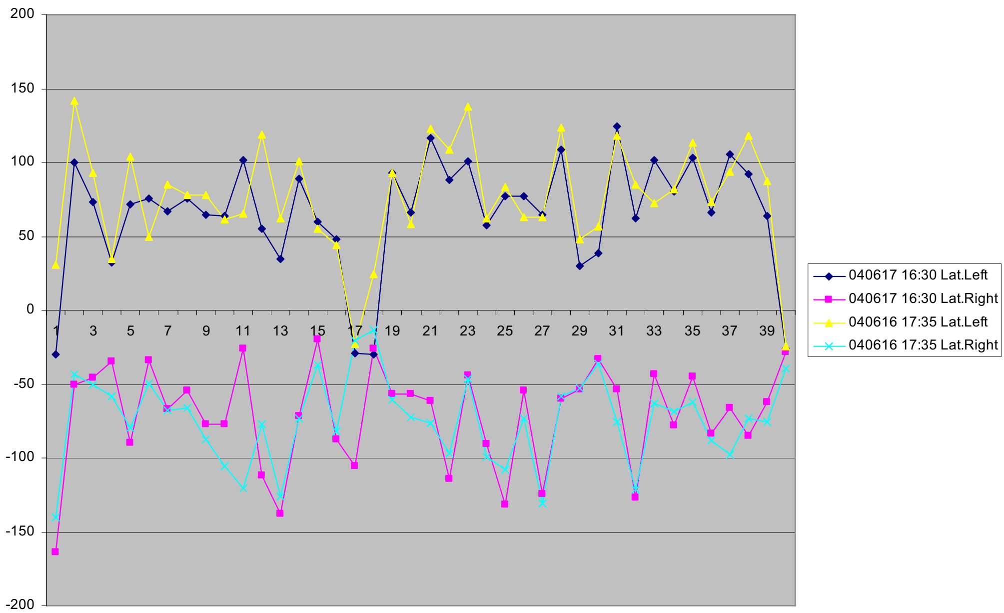


Figure 26. Lateral forces on the rail from the 40 first axles in the same train set passing on 2004, June 16, 17:35 and June 17, 16:30

The vertical forces also showed a good repetition of readings between the passages, see Figure 27 and Figure 28.

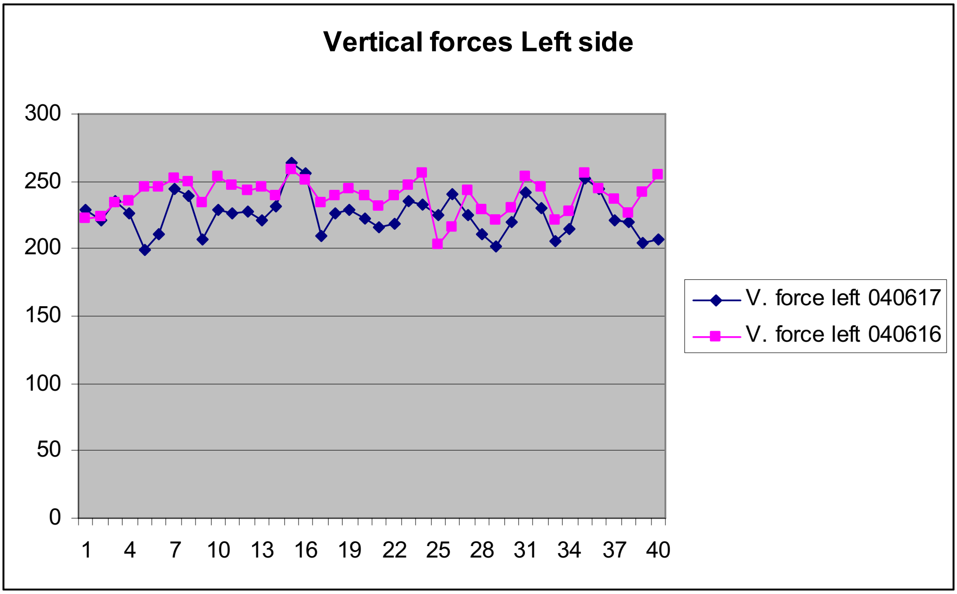


Figure 27. Vertical forces on the left rail from the 40 first axles in the same train set passing on 2004, June 16, 17:35 and June 17, 16:30

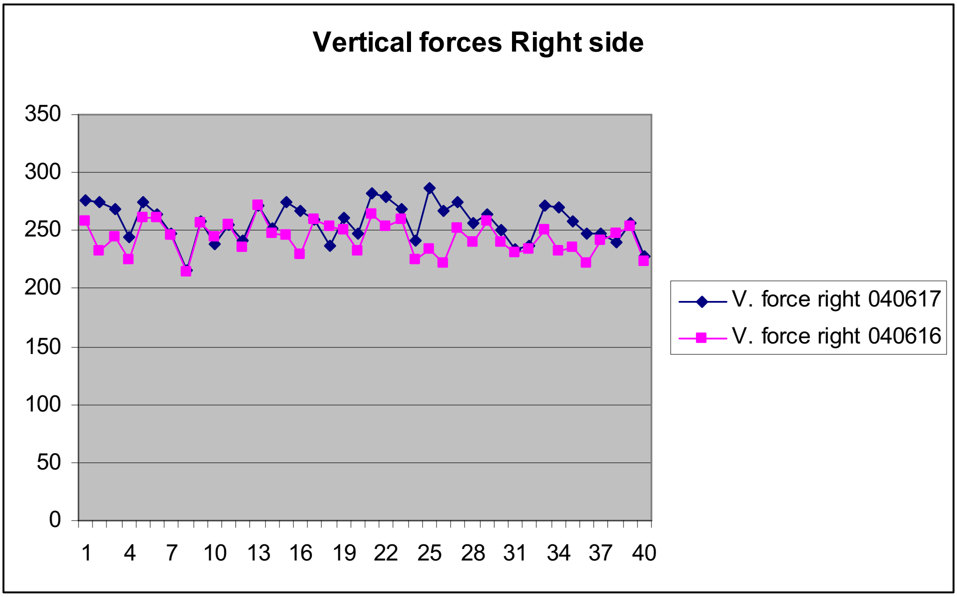


Figure 28. Vertical forces on the right rail from the 40 first axles in the same train set passing on 2004, June 16, 17:35 and June 17, 16:30

6.3.5 Findings

The strain gauge system that measures lateral and vertical forces showed good repeatability in the measurement between the two passages of the train with the same set up at both times.

The system seems to have a good repeatability in the measurements. The two passages of the same train set in the same configuration give a good indication of this. But the total amount of measurement makes it dangerous to make too exact statements about the reliability and validity since the amount of data is quite small.

The validity of the measurements was difficult to establish since no manual inspections were made based on the measurements. In a later case study there is an attempt to find some validity in the measurement in correlation with the condition of the wheels. Results are presented in Case Study 4.

In this case study the problem with the small amount of data makes it difficult to make an exact statement about the actual validity of the measurements.

One of the goals of the measurements was to see if the measurements had any correlation with the maintenance history data of the vehicles. This work revealed a problem with the use of the maintenance management system that wasn't known to the researcher before the measurements. The system is capable of keeping track of individual axles on the vehicles and there was the general perception that this was in use. But as the extraction of data was started it came evident that there are corrupt data in the maintenance system. This made it impossible to give a correct analysis of the correlation of the measurement and the maintenance history data.

6.3.6 Research implications

One limitation in the study is the small amount of measurement data, which makes it difficult to make any conclusive statement about the measurements system's reliability and validity. Hence in order to achieve a better result more measurements should be performed.

6.3.7 Practical implications

The technology is applicable on most types of railways using wheels on rail. This makes it possible to deploy the technology on Swedish railway to measure forces from all types of passing railway vehicles.

The measured parameters would be a valuable input in detecting and evaluating the performance of railway vehicles on the Swedish railways, giving benefits to both train operators and infrastructure owners.

The technology itself is quite simple as well as inexpensive in comparison with other systems.

To be able to use the measurement system to its full potential it is necessary to connect the measurements to the maintenance management database. This means that the history of individual items (e.g. wheelsets) should be recorded correctly in the database to enable the follow up of the measurements from the monitoring system. Without the possibility to compare current measurements with earlier measurements the possibility of trending is lost. Hence, the predictive capability would be strongly limited if the recording of measurements and historical maintenance data is not correct.

6.3.8 Value of study

From the study it has been shown that the system is usable on Swedish railways This makes it possible to have the system as one of the possible ways of monitoring the condition and performance of railway vehicles on Swedish railways. Another important insight from the study is the problem with the connection between condition monitoring data and historical maintenance activities data at LKAB/MTAB. There is a need for an update in the use of the maintenance management system to be able to use condition monitoring systems to their full capability.

6.4 Case 3: Wheel profile measurements, MBV-systems

The system is a prototype that is possible to develop into a product. The prototype is based on laser and camera technology that has been in use in several other applications.

6.4.1 Purpose of this case study

The purpose was to increase the knowledge and evaluate a system that measures the wheel profile of the wheelsets, in order to decide if the technology was fulfilling the requirements for monitoring the condition of the wheels.

6.4.2 Study approach

The intention was to test the technology of the wheel profile measurement prototype and verify it by measurements made by mechanical handheld wheel profile measurement equipment for correlation of the measurements to evaluate the possibilities of an automated wheel profile measurement system.

The data was collected during the time period 24 August 2004. The measurements were conducted during 1 day. The geographical location was in a workshop at Notviken just outside Luleå, see Figure 29.

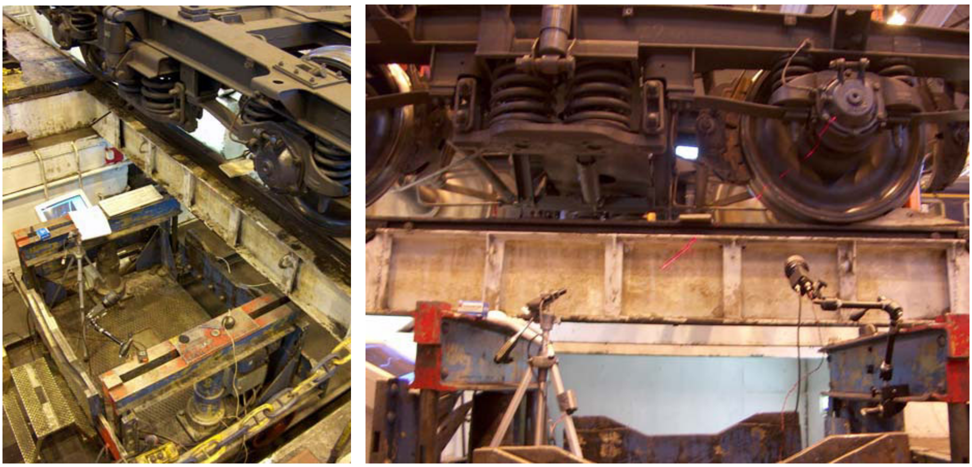


Figure 29. The prototype measurement set up in the workshop pit.

The prototype system for wheel profile measurements was set up at the workshop in a pit. The position of the equipment at a level under the rail was chosen to simulate a future wayside installation because the best visual view of the wheels is thus accomplished and at the same time the equipment is not in the way of activities around the track, such as snowplowing which is common in Sweden during the winter, see Figure 30.

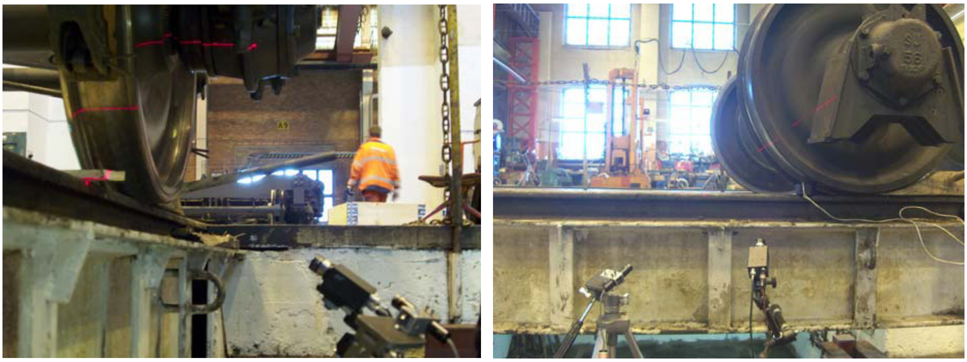


Figure 30. Prototype installation of laser and camera for wheel profile measurements.

6.4.3 System description

This is a prototype of a condition monitoring system for measuring the profile of the wheels with a laser and a camera. The system is a prototype from the Swedish company MBV-systems. MBV-systems are a company that develops technical monitoring solutions and measurement methods for the industry. The system is not yet developed but the necessary competence exists within the company. Therefore the measurement technology has only been tested in a simple prototype installation at a workshop to show the potential for developing the system.

The system uses a laser and a camera to measure the profile of the wheels on passing vehicles. The laser generates a line on the wheel that is captured with the camera. The picture is then processed in a computer with an algorithm to extract the wheel profile from the captured picture. The line created by the laser is extracted from the picture, see Figure 31.

Figure 31. The picture captured by the camera is recorded on a computer for processing.

The goal with the test of the prototype was to capture pictures which then were correlated with measurements with a handheld wheel profile measurement device, a MiniProf, see Figure 32.

Figure 32. The MiniProf [Courtesy: Greenwood Engineering] is a handheld mechanical measurement tool for manual wheel profile measurements with very high accuracy. It was used as a reference tool in the test.

The MiniProf measurement was used as a reference in the development of the algorithm for profile extraction from the captured picture. The algorithm was developed by MBV-systems. The actual algorithm is not presented as this is a potential product. The development process was made in stepwise development of the algorithm for the extracted laser curve in relation to the MiniProf profile curve. This is illustrated in Figure.33.

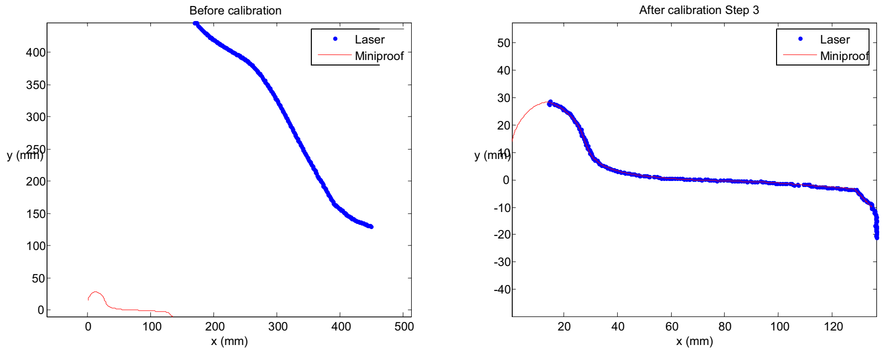


Figure 33. The extracted laser curve and the MiniProf profile curve. After three steps of calibrating the algorithm the curves have a similar shape. [Courtesy: MBV-systems.]

6.4.4 Findings

The prototype has the potential for development into a full scale monitoring system as it is possible to capture a picture and extract a wheel profile with the help of picture processing. It is possible to develop the algorithm for the transformation of the extracted laser curve into the actual wheel profile. In the test it was only applied to a small amount of measurements and would have to be more calibrated with several more measurements in a future development of the system. The set up of the laser and camera is also an issue as well as a challenge that has to be developed further. Restrictions around the track as well as the need for clear visibility of the wheels put demands on the design of a future wheel profile monitoring system.

The exact reliability and validity of the measurements by the technology is difficult to establish from the test. But it shows great potential for good accuracy in the measurements.

6.4.5 Research implications

One limitation in the test is the small amount of measurement data, which makes it difficult to make any conclusive statement about the measurements system’s reliability and validity. Hence in order to achieve a better result more measurements should be performed.

6.4.6 Practical implications

The technology shows good potential for use as an automated wheel profile monitoring system. This would decrease the need for manual inspections of the wheel profile as it would be of great support in the planning of maintenance activities concerning the wheels. This monitoring technology would be of great use in the direct follow up of the wear of the wheels, hence giving a good input in the planning of re-profiling of the wheels.

It would still be necessary for MBV-systems to do a lot of development before they could be able to launch a measurement system as a product. One major factor against such a development is the fact that products using the same technology are already available on the market. The test was conducted mostly to show that the competence to develop this system also exists locally.

One similar system has been deployed in Stockholm, Sweden. (2006) EuroMaint AB, a maintenance provider for railway vehicles are evaluating the usage of a wheel profile monitoring system. (Robertsson and Fry, 2006)

6.4.7 Value of study

A new insight from the study is that the knowledge necessary to develop a wheel profile monitoring system is available locally. It also showed that there seems to be a good potential in the technology for use as an automated measuring system with a good accuracy. Any further work to develop and evaluate this system was put on hold as the literature study had indicated that there are several systems available commercially.

6.5 Case 4: Cross analysis of Cases 1 and 2

The monitoring systems evaluated in the earlier case studies both monitor the performance of the iron ore cars on the track using different parameters. To see if the systems reveal the same" bad actors" a correlation study was made..

6.5.1 Purpose of this case study

The purpose was to increase the knowledge and evaluate the measurements from two different monitoring systems, one that measures the angle of attack and the lateral displacement of the wheelsets and the other that measure forces in the rail with strain gauges. The measurements were compared to find correlations between the measurements on the performance of the wheels and bogies on the iron ore cars.

6.5.2 Study approach

The intention was to use the collected measurement data from the two systems of the angle of attack and the lateral displacement as well as the measured lateral forces.

The results from the measurements of the T/BOGI system and the Lateral forces system were compared both between passages and between the two different systems.

6.5.3 System description

The two systems have been described in Case 1 and 2.

6.5.4 Data analysis

During the field test several passages of ore trains were monitored. To best illustrate the results, two passages have been used. This is because the configuration of the train set was the same at both passages. One train set passed two times loaded in the same car configuration during the field test. Some of these measurements are used to illustrate the weak correlation, see Figure 34.

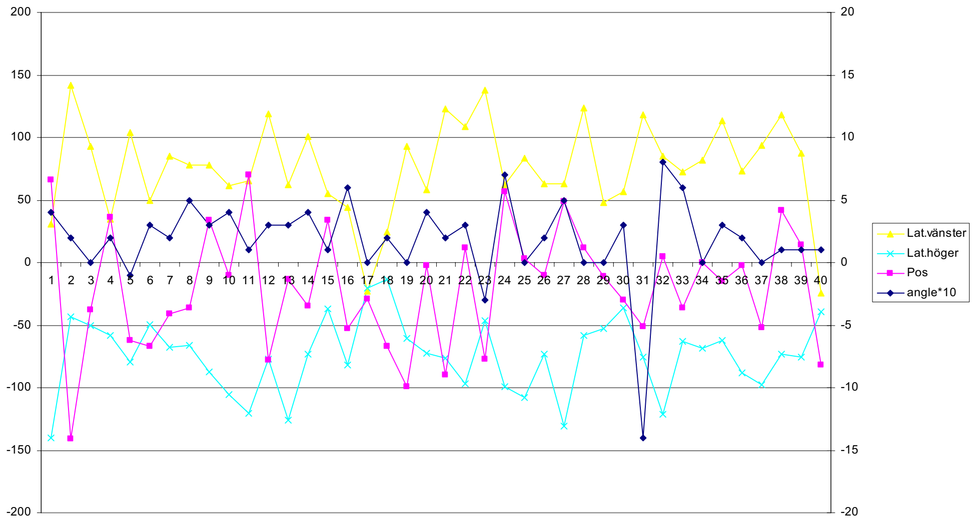


Figure 34. Angle, position and lateral forces, left and right, on the 40 first axles in the train set passing on 2004, June 16, 17:35

The same train set passed in the same configuration the day after, see Figure 35.

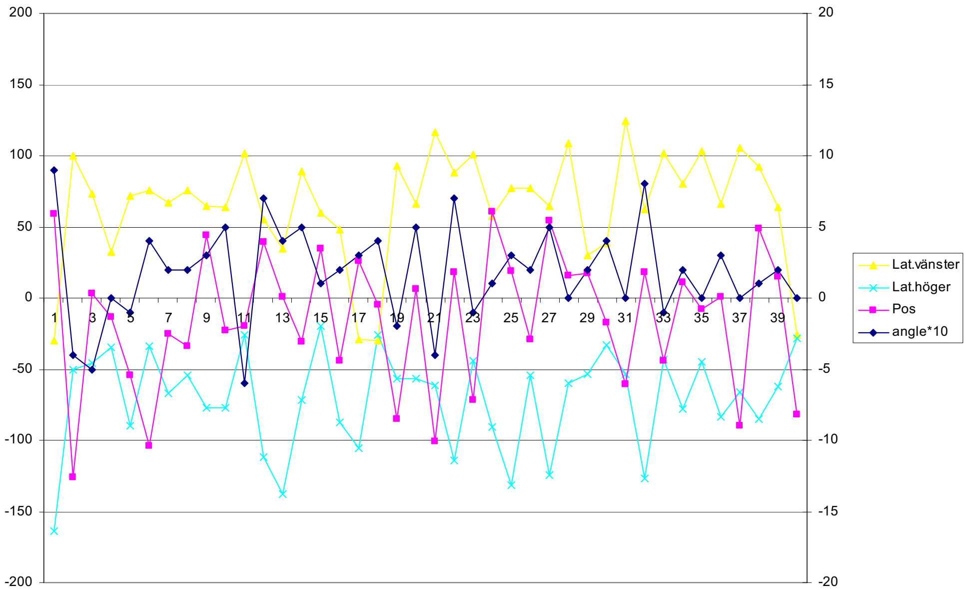


Figure 35. Angle, position and lateral forces, left and right, on the 40 first axles in the train set passing on 2004, June 17, 16:30

6.5.5 Findings

The analyses of the parameters gave no clear correlation between the measurements from the two different systems.

6.5.6 Research implications

One limitation in the study is the small amount of measurement data, which makes it difficult to make any conclusive statement about the exact correlation between the two measurements. Hence in order to achieve a better result more measurements should be performed.

6.5.7 Practical implications

To be able to use one or both of the measurement systems as input to the maintenance management the correlation between conditions of the iron ore cars and the measured data has to be established. The studies made during this thesis indicate that the systems can contribute with valuable measurement data, but there is a need for more measurements to establish the exact value. But the fact that the technologies are in use on several railways around the world (Lagnebäck, 2004) indicates that the systems are measuring valuable performance data that can be used as an indication of the condition and used in the maintenance process.

Even though both systems showed a good repetition of the measurements between the two train passages in the same configuration the observed lack of correlation between the systems indicates that they don’t measure the same deviations in the performance of the iron ore cars. So to achieve the best monitoring capability of the performance, hence condition, it would be preferable to use both systems.

6.5.8 Value of study

The new insight of the study shows that high lateral forces and lateral displacements or angles of attack on wheelsets don’t have to correlate with each other even though both measurements can indicate a deviation in the performance of the wheelset.

6.6 Case 5: Development of the lateral forces measurements

The system is a product that is under an ongoing development, but is based on technology that has been in use in several countries. The system uses strain gauges deployed on the rail to measure the forces from the passing wheelsets.

6.6.1 Purpose of this case study

The purpose was to increase the knowledge and evaluate a system that measures the lateral and vertical forces in the rail from the passing wheelsets, in order to decide if the technology was fulfilling the requirements for monitoring the performance of the wheels and bogies on the iron ore cars.

6.6.2 Study approach

The intention was to collect measurement data on the vertical and lateral forces and connect it to individual wheelsets and correlate these measurements with wheel profile measurements.

The data was collected during the time period 27-29 September 2005.
The geographical location was on the south bound transport stretch of the iron ore line from Gällivare to Luleå. The force measurements were made on the southbound loaded trains on a location north of Luleå. The measurements were analyzed and some of the wheelsets were identified as "bad actors" with higher values than the average value of the train set. Personnel from Damill AB conducted the force measurements. The "bad actors" were then reported to personnel waiting in Luleå at the terminal. After the train sets were unloaded they were stopped for a short time to be able to get some wheel profile measurements from identified wheelsets. The wheel profile measurements were conducted with a MiniProf, a handheld mechanical wheel profile measurement tool.
The measurements were limited to measurements only on one side of the vehicles to limit delays to the regular traffic. But the wear profile of one wheel can give a good indication of the behaviour of the whole wheelset.

6.6.3 System description

This system is a monitoring system that measures the strain in the rail and converts the measured values to forces from the wheels in relation to the rail. The system is produced by Damill AB.

Damill AB is a Swedish company that develops technical monitoring solutions and measurement methods for the industry. They have also performed measurements with the system for Banverket as a part of a project to develop a rail degradation prediction model, DeCoTrack.

Personnel from Damill AB installed and performed the measurements with their strain gauge monitoring system during the field test.

The monitoring system is now measuring continuously (December 2006) as a part of a Research Station installation established by JVTC (Luleå Railway Research Center). The measurements are presented online on the internet and interested parties can view the measurements. An example of a presentation is illustrated in Figure.36.

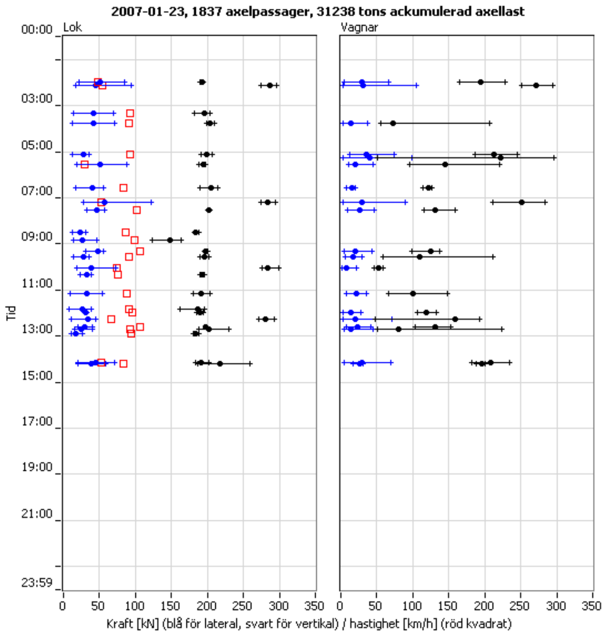


Figure 36. Picture of the measurements presented on the online internet website. Blue is lateral forces, black for vertical forces and the red square is the speed. On the left is the locomotive and on the right all the cars in the train sets. [Courtesy: Damill AB.]

6.6.4 Data analysis

Some of the indicated “bad actors” were measured with a Miniprof to get a measurement of the wheel profile, see Figure 37, 38, 39, 40, 41 and 42.

Figure 37. Picture of the measurement of wheel profiles on ore car Uno 3055 at the terminal in Luleå. [Courtesy: Damill AB.]

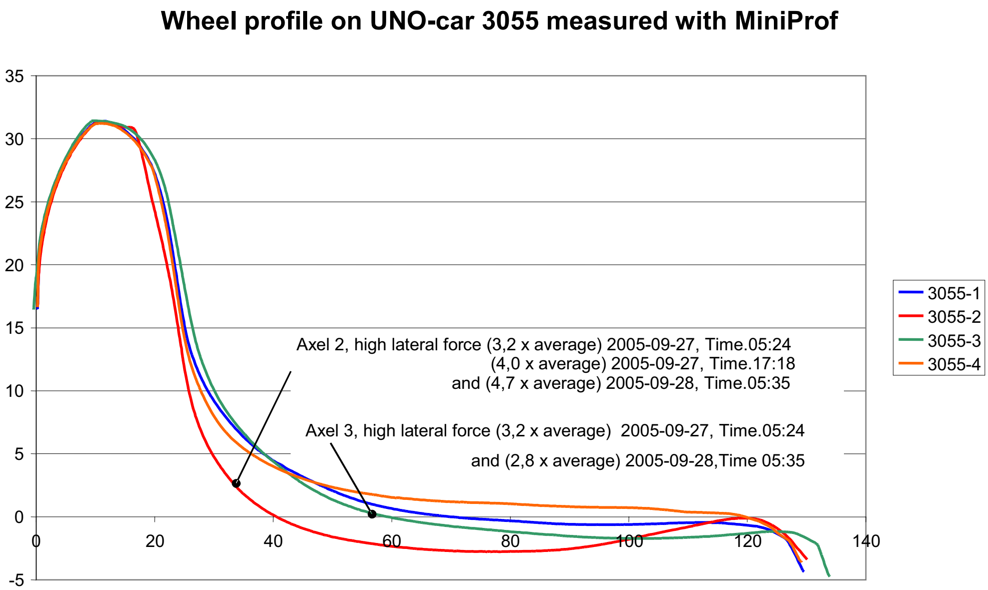


Figure 38. Wheel profile measurements from UNO-car 3055 [Courtesy: Damill AB.]

Figure 39. Picture of the measurement of wheel profiles on ore car Uno 3073 at the terminal in Luleå. [Courtesy: Damill AB.]

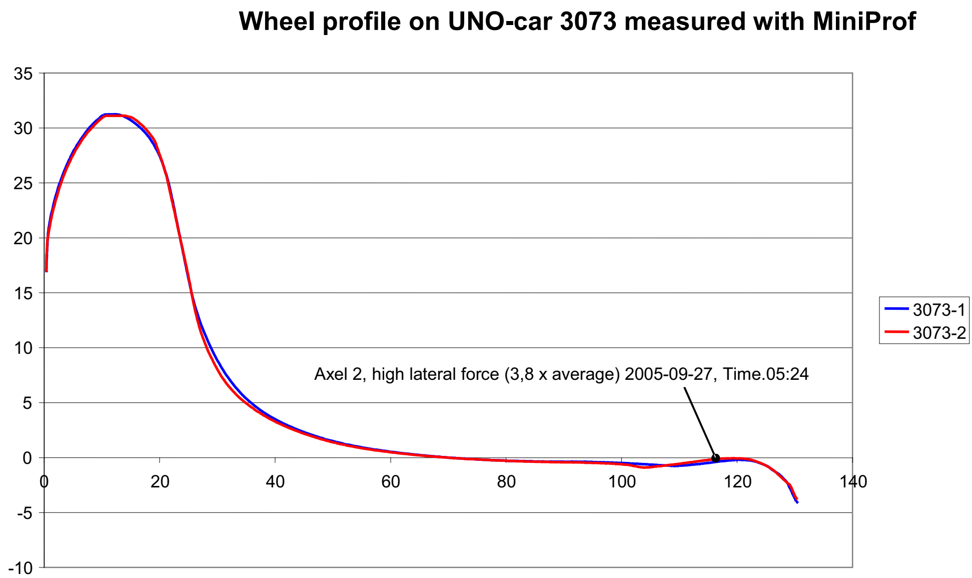


Figure 40. Wheel profile measurements from UNO-car 3073 [Courtesy: Damill AB.]

Figure 41. Picture of the measurement of wheel profiles on ore car Uno 3046 at the terminal in Luleå. [Courtesy: Damill AB.]

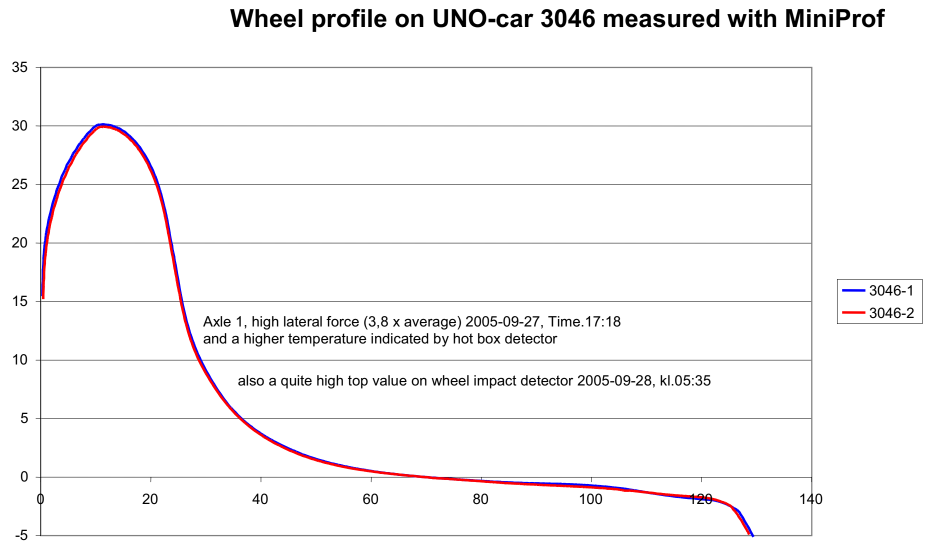


Figure 42. Wheel profile measurements from UNO-car 3046 [Courtesy: Damill AB.]

6.6.5 Findings

From the measurements of the lateral and vertical forces with the strain gauge system some of the wheelset were identified as “bad actors”. The wheel profile measurements were then used to get some validation between high forces and bad condition. From the two measurements there seem to be some correlation between high forces and a bad condition of the wheelset. Several of the measured wheels that indicated high forces also had a high degree of wear.

In this case study the problem with the small amount of data makes it difficult to have an exact statement about the actual validity of the measurements.

6.6.6 Research implications

One limitation in the study is the small amount of measurement data, which makes it difficult to make any conclusive statement about the correlation between the measured forces and the measured wheel profiles. Hence in order to achieve a better result more measurements should be performed.

6.6.7 Practical implications

The development of the system is an ongoing process at Damill AB. The possibility to identify “bad actors” among the wheelsets with this technology can be used as input to the planning of the maintenance activities at the workshops. The system measurements are also used as input in the further use and development of a rail degradation model, DecoTrack, developed by Dan Larsson at Damill AB, and evaluated for the Swedish Railroad Administration (Banverket). (Larsson, 2005)

6.6.8 Value of study

The insights of the study are that there seem to be a correlation between higher forces and wheels with a degraded condition. This further highlights the possible use of the system as a valuable condition monitoring system applicable on Swedish railway.

7 Discussion

In this chapter the view of condition monitoring and condition-based maintenance is discussed. Potentials, issues and challenges for the whole railway system with the implantation of a new maintenance strategy are examined.

Condition monitoring of railway vehicles and railway infrastructure can be a powerful tool for enhancing maintenance effectiveness. With the opportunity to monitor the whole system, the railway industry can further develop the concept of condition-based maintenance. (Simms et al., 1996; Blevins et al., 2003; Waring, 2003; Irani et al. 2003; Irani, 2003; Iden, 2003; Lagnebäck, 2004; Lagnebäck and Kumar, 2005; Granström, 2005; Barke and Chiu, 2005) In a deregulated railway industry, as in Sweden, condition monitoring could support the interface between the infrastructure owner and the train operators and also be useful in the interface between the infrastructure owner and the maintenance entrepreneurs.

With better knowledge and control of the status of the system, the different stakeholders will have better input to the maintenance process. It supports both the technical and the economic interface between the stakeholders. With a condition monitoring system the technical status is measured, which could give input to the financial agreement. The possibility to measure the condition of the system provides a tool that gives more exact technical status levels that affect the financial agreement in the contracts between the stakeholders. For example between the infrastructure owner and the train operators the measured condition of the wheels could affect the charge the operators have to pay for using the rail.
Detecting differences in the dynamic behaviour of the vehicles has earlier mostly been used as a tool to protect the infrastructure from major damage due to failures on the vehicles. But it is now seen as a powerful tool to support the maintenance planning of the vehicles. Good results have been seen in North America, with the InteRRIS™ system (Irani et al. 2003; Irani, 2003)

In the case of the maintenance entrepreneurs, it could provide an opportunity to follow up the status of the infrastructure. It could also be helpful in the event of an actual failure to follow up what caused this and who the possible problem owner is.

7.1 Maintenance (today/future)

In the railway industry the maintenance intervals are often traditionally time- or mileage-based, and these intervals are often based on earlier experience or on the supplier's specification. This method of maintenance can be further improved, if the variations in wear can be more accurately anticipated, see Figure 43.

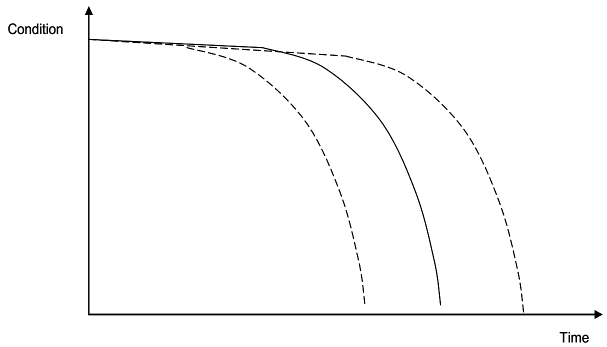


Figure 43. Average wear and the spread for the condition of a component

The interval-based concept often has the effect that the maintenance intervals are set at the minimum level of the component's average life length. But even so, it is possible to have components that deteriorate faster than anticipated due to, for example, some failure caused by an external factor.

Maintenance based on actual condition would be more economical. Condition monitoring is also a powerful tool for detecting failures and unpredicted deterioration in the condition of components. This can increase both the safety and availability of the system and also optimize the use of components, see Figure 44.

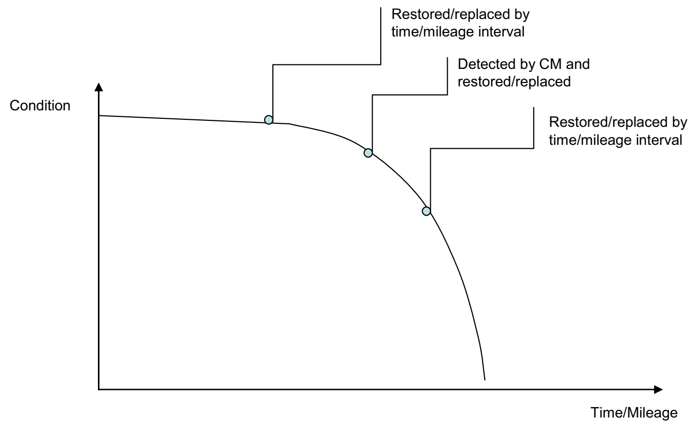


Figure 44. The use of condition monitoring to find the best point for restoring/replacing the component instead of using predetermined intervals.

To achieve the goal of bringing the railway industry from time/mileage-based maintenance to more condition-based maintenance, there have to be ways to monitor the condition and thereby be able to predict the remaining life length of the component.

The wheel/rail interface is the most important parameter in the vehicle's condition. This is where most of the cost for maintenance on both railway vehicles and infrastructure occurs.

There are also systems for measuring the condition and status of the infrastructure from systems mounted on trains or service vehicles, and the measured condition correlated to geographical information, from for example GPS-systems. This would give a good overview of the total infrastructure condition. This provides an opportunity to have continuous control of the infrastructure status to follow up the degradation, but also to locate potential incipient failures and problem areas in the infrastructure. It is also important to monitor the condition to avoid potential accidents. For example a derailment is very costly and can cause loss of life.

In electrified railways there is another technical interface between the vehicles and the infrastructure, the overhead wires and the pantographs on the trains, see Figure 45.

Figure 45. LKAB/MTAB iron ore locomotive IORE. (Sweden): Pantograph with automatic drop function to protect the interface when a failure occurs on the surface of the pantograph. [Courtesy: Rickard Granström]

A failure in the wheel/rail interface can lead to for example a derailment. However, a breakdown in the pantograph/overhead wire interface can be very costly, as it can cause disturbance in the traffic for a very long time. There are systems on the market for monitoring the condition and status of the overhead wires and the pantographs. (Granström, 2005) In Sweden there is an ongoing test (2005) to check the status of the pantographs of passing trains. It uses image analyzing of the passing train, photographed with cameras mounted on the infrastructure. The purpose is to control the condition of the pantographs, as a faulty pantograph can induce failures on the overhead wire.

The information from the different measurements can be connected to prediction models and expert systems to function as decision support. These systems will develop further over time and become more accurate with an increasing amount of collected data.

Condition monitoring is a tool to control the standard of the vehicles from the infrastructure point of view. Monitoring the condition of the infrastructure could also help to avoid failures in the opposite direction as the condition of the infrastructure affects the vehicles. A fault in the infrastructure can lead to a fault in the vehicle which can then as it moves along the track affect more of the infrastructure.

7.2 Organisational aspects

To be able to conduct condition-based maintenance, analyses and trending of the collected measurements have to be made. Therefore, it is important to have both a technical system and a good organization for handling the collected data, so that appropriate maintenance effort is done. This creates possibilities for continuous improvement in operation.
(File, 1991; Williams et al., 1994)

Many companies in the process industry are using CMMS (computerized maintenance management system) which is a powerful tool in asset management when used in the right manner. But a problem with the use of this is often the input to the system. (Wireman, 1997)

Data that have to be manually reported and are not generated automatically into the system often tend to have quality problems. When depending on data from, for example, maintenance workers the form of reporting should be as automatic and standardized as possible to make it easy to use. It is also important that the staff that will do the actual reporting understand the essentials and get feedback on the effects. For the system to be as effective as it can be, all staff working with it must be motivated to use and give input to the system. It is therefore very important to try to show the benefits for all and give them continuous feedback on the ongoing work process and the status of it both in the big picture and directly affected individual work area. The success in implementing CMMS systems is very dependent on human factors and this is an important issue to bear in mind in the implementation of the system.

It is also important to develop strategies and organizations to handle the information in the best interest of both the rail- and vehicle-owners. Finding a balance is a concern in the Swedish railway industry that is divided between different stakeholders consisting of mainly one track owner, several train operators and a number of maintenance entrepreneurs.

7.3 Economical aspects

Using condition monitoring for railway vehicles has impact on both infrastructure and vehicles as the economical benefits are to be found on both sides of the wheel/rail interface. In the U.S., the railway industry is said to save more than $40 million per year by removal of high impact wheels using the WILD system (Wheel impact detectors). (Lundgren, 2005; Hawthorne et al, 2005) There is also an expected net saving exceeding $200 million over a time period of 20 years with the implementation of wheel profile monitoring systems. Other potential savings are calculated at $4 million per year with break shoe monitoring systems and a $7.5 million saving due to a reduction in derailments caused by broken wheels due to heat build up by faulty breaks. (Lundgren, 2005)

As the railway industry in Sweden is divided among different stakeholders, they have their own economical goals. But the optimal operation and maintenance of the total system is still the same as in a railway industry with only one stakeholder. So there is a “best” total economic solution for running the system. The problem in a divided railway system is how to transfer money between stakeholders.

To find a good economical platform for total asset management in a deregulated railway industry, some form of partnering could be a possible solution. (Barlow et al. 1997; Espling and Olsson, 2003; Espling, 2004; Skeggs, 2007) The partnering philosophy was developed in the construction industry. Skeggs (2007) states the leading principles in partnering:

“Partnering is best considered as a set of collaborative processes. Processes which emphasise the importance of common goals and raise such questions as how such goals are agreed upon, at what level are they specified and how are they articulated?”

A partnering solution could be good way of working for a best total asset management in a deregulated railway supported with condition monitoring for setting and controlling both goals and status levels for a joint condition-based maintenance strategy of the total railway system.

The technical interface between the stakeholders in a divided railway system is linked to the economical interface. The technical interface and the economical interface between vehicles and infrastructure are also connected in an indoor railway system, but the economic interface is more transparent, as the total economic goal is a common one In the case of divided stakeholders, there are individual economical goals, short- and long-term, that are maybe not always are synchronized.

A problem could for example be if the train operators have very short transport contracts with respect to the cost of investments in new equipment, so that they have to buy cheaper/used equipment/vehicles to be able to make the economy work during the contract period, as they cannot be sure that they will have the contract for the next period. This affects the standard of the vehicles that will traffic the infrastructure. If the vehicles have a lower condition/status, this will increase the wear on the infrastructure. It will affect the cost for maintaining the infrastructure and one major effect could be a shorter total life length of the infrastructure, see Figure 46.

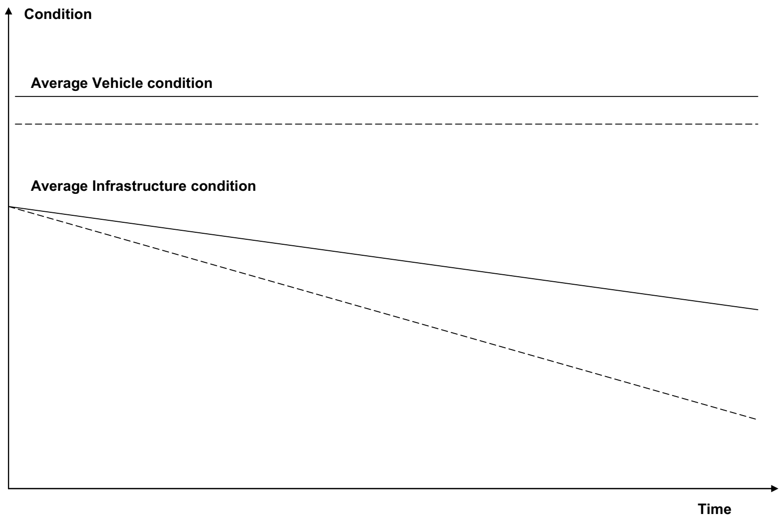


Figure 46. The average vehicle condition will affect the deterioration speed of the infrastructure.

The Life Cycle Cost (LCC) for the infrastructure owner will then increase. This shows the issue of a best total economical solution, see Figure 47.

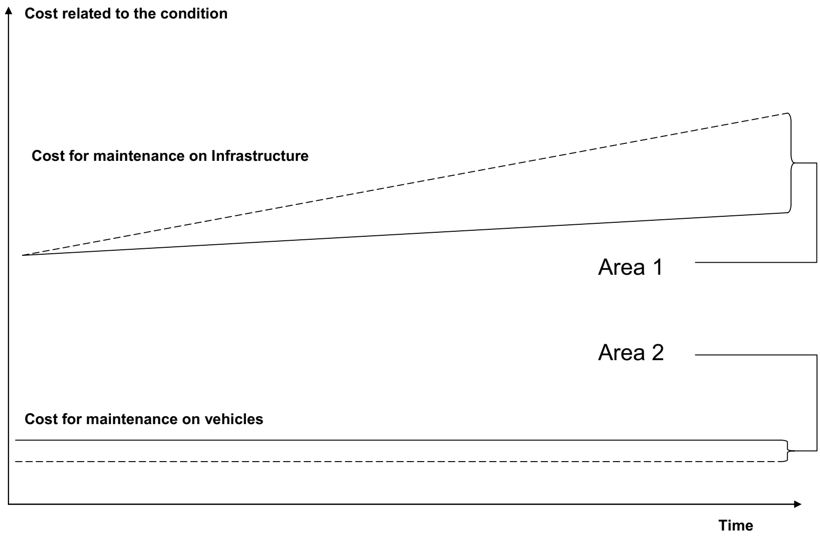


Figure 47. If the total cost in area difference in Area 1 is larger than Area 2 there is a total cost saving over the time period.

For example an infrastructure owner could benefit from having differentiated freight charges depending on the quality of the vehicles using the railway. This would give the train operators an incentive to improve the standard of the fleet to get a lower freight charge. In a calculation in a short perspective the infrastructure owner might get less income from the freight charges, but will still get a lower LCC on the infrastructure due to a longer life length because of decrease in wear and induced failures. (Larsson and Gunnarsson, 2001; Åhrén, 2002)

7.4 Maintenance management

Condition monitoring is a tool for the maintenance management and function as input to the decision support. The condition monitoring information is combined with information about the operation to plan the maintenance activities in an effective way to achieve increased equipment life, uptime and decrease costs to reach a better business result.

The maintenance management decisions can be seen as determined by three main areas, see Figure 48.

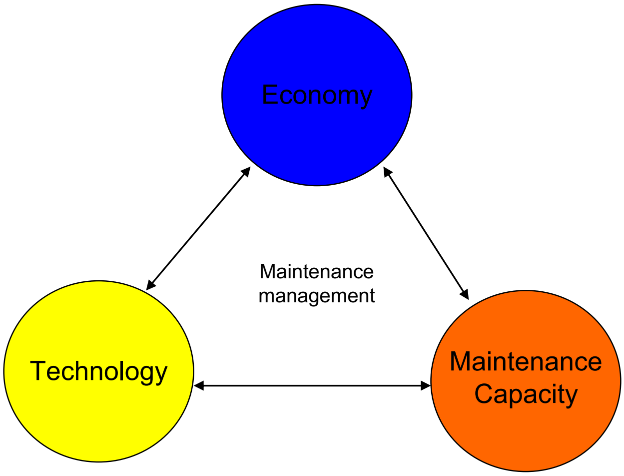


Figure 48. Maintenance management main decision affecting areas

Connected to these areas are specific factors that affect the operation and maintenance of the process, see Figure 49.

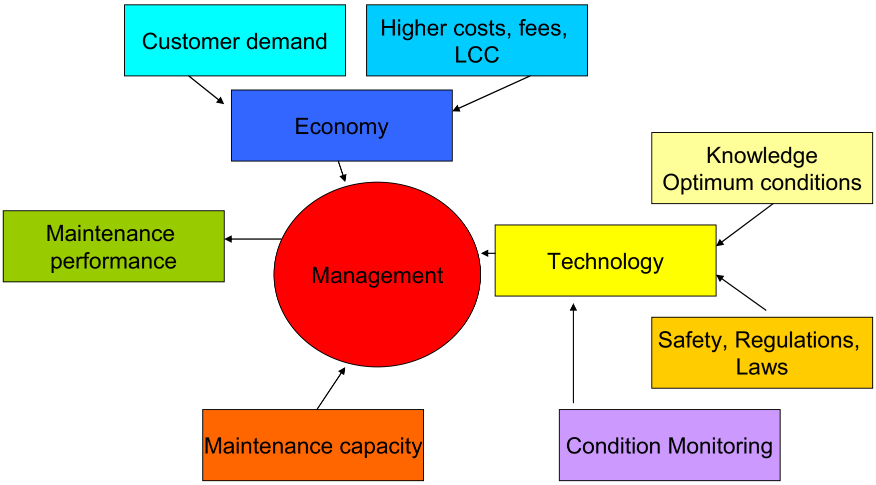


Figure 49. Maintenance management with the input to the management decision process that gives the output of maintenance performance

The output becomes the maintenance performance. The performance then feeds back into the model again as input to different areas that affect the process. For example as input measured by the condition monitoring system or as input from customers in the economy. A similar structure exists in both the infrastructure and the train operator's organization and there are several interfaces that connect to one another in different areas.

7.5 Condition monitoring approaches

In the process of implementing condition-based maintenance there is an initial step to determine which vehicle/component is a "bad actor", and at what level the workshop should perform the maintenance activities. For MTAB it is wheel wear that accounts for the major cost in maintenance. (Åhrén, 2002)

The condition monitoring systems give different approaches for monitoring of the condition. In the case of iron ore cars the defects in steering performance will cause increased wheel wear. Wheel wear is the symptom of the steering performance defect. Condition monitoring can then be viewed as two strategies: Cause-Symptom or Symptom-Cause approach.
In the study of the three system of interest in the case studies, two could be said to be Cause-Symptom systems and the third to be a Symptom-Cause system.

The two systems tested in the field test, angle of attack and lateral forces are Cause-Symptom systems in the case of wheel wear. The third system for wheel profile measurement, only evaluated in a simple prototype installation in the case study, is a Symptom-Cause system.

In the two first systems knowledge has to be acquired to know what type of wear the deviations in steering performance will cause on the wheel. In the case of the wheel profile measurement it monitors the actual wear, and in that case, knowledge about what deviation in steering performance is causing this wear has to be acquired.

Best is to use more than one system and have systems of both kind of strategies to get a complete picture of the connection between cause and symptom.

7.6 Maintenance levels

When implementing condition-based maintenance new levels have to be set to control the maintenance efforts. For example levels like flange height are a critical factor and their critical level are set by rules.

But today there are a lot of levels that are not set by rules and, to find the optimal level for maintenance, efforts have to be calculated during the implementation of condition-based maintenance. The transition from distance-based maintenance to a condition-based maintenance organization also demands a more flexible maintenance planning. To set the maintenance levels from the values generated by the parameters monitored by the different condition monitoring system, a maintenance capacity approach would be recommended. This means that the new levels for what are known as bad actors should be set at a level so that they don't exceed the maintenance capacity at the workshop. It is not good for the organization to have cars just standing and waiting for a time slot at the workshop especially when capacity is at a premium.

It is recommended to set the first levels from the maintenance capacity perspective and then as the implementation proceeds trim the levels as the standard of the overall condition on the cars increases.

The levels used in the case studies to point out bad actors can easily be changed to point out more or less bad actors.

To give an example, this can be illustrated in the case of lateral forces, see Figure 50.

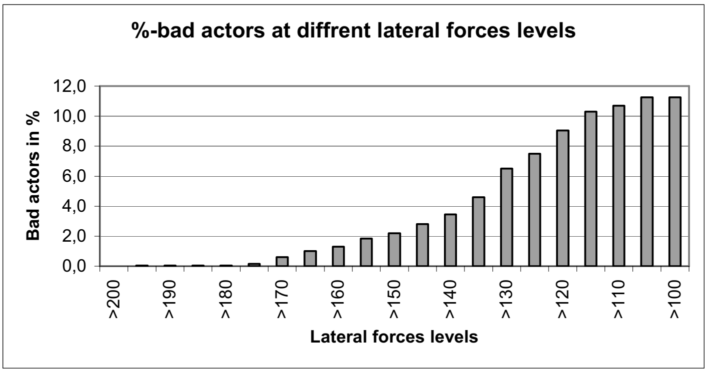


Figure 50. Showing the increased amount of "bad actors" with different levels of the lateral force indication of bad actors.[Courtesy: Damill AB]

7.7 *Future vision*

The future vision is to use condition monitoring of the total performance of both vehicles and infrastructure to support the maintenance activities made within the total system, see Figure 51.

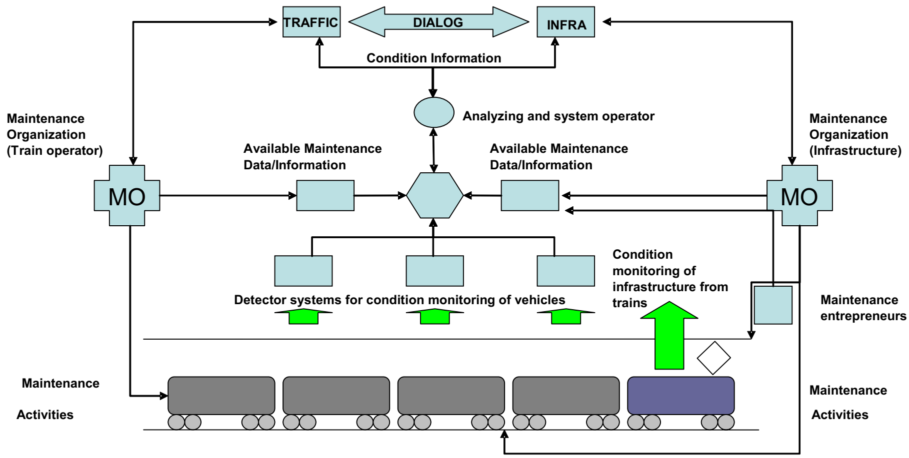


Figure 51. Future vision of a system with continuous feedback on the condition and the effects of maintenance activities on both vehicles and infrastructure

With a system that supports all the stakeholders, there will be an opportunity to implement condition-based maintenance in a total management perspective even in a deregulated railway system. One important key factor in the vision is the possibility to measure the status of the assets in a way that is continuous, correct and accepted by all the stakeholders.

To build a condition-based maintenance system that supports all stakeholders even in a deregulated railway system, the interfaces between the different stakeholders have to be supported with the right tools. The tools for building a total asset management system for a railway system are available and can be adapted to both indoor and outdoor/deregulated railway systems. There are of course several challenges to overcome before the total system can be fully functional.

Technical solutions for the direct condition monitoring function are in use and there is an ongoing development of new and improved ways of monitoring the condition. The outcome of the ongoing process is that the technical knowledge about the wheel/rail interface and the dynamics of vehicles is increasing.

Much work also has to be done inside the organizations to support the people that work with the operation and maintenance, as there will still be humans working with the railway system even after the implementation of a condition-based maintenance system.

One major difference between an indoor railway system and a deregulated railway system with several different operators and infrastructure owners is that there exist some further challenges in the economic interface between the stakeholders. But with the right tools, methods and strategy there are ways to overcome these challenges, such as for example the partnering philosophy that already exists.

In Sweden there are also challenges at a political level to overcome, which affect the possibility of setting new standards for economic agreements between the infrastructure owner and the train operators. But if the platform for the total system is provided with a well functioning condition monitoring system, there will be a strong factor for changes in this area as well. The condition monitoring system in itself supports all the stakeholders anyway, since a wayside condition monitoring system for the vehicles functions as protection of the infrastructure from bad actors and for the train operators as a service for input to their maintenance process.

For the full implementation of the vision there will have to be tools and methods that will support all the interfaces between the different stakeholders in a divided railway system.

8 Conclusions

The purpose of this thesis was to study and analyze wayside condition monitoring equipment for railway vehicles, in order to support the implementation of a condition-based maintenance strategy.

8.1 Answering the research questions

There are three research questions stated in this thesis. The performed research can be related to these questions which were stated in the beginning of the research process.

1. How can the condition and performance of a railway vehicle be monitored by wayside condition monitoring technologies?

From the literature study several technologies for measuring the condition and performance of a railway vehicle have been identified. There are technologies ranging from strain gauge, acoustic, laser, camera and ultrasonic measurements. These are all technologies that can be deployed wayside to measure parameters on passing railway vehicles.

Some of these technologies have been further evaluated on their ability and usefulness on the Swedish railway system. The case studies and the literature study indicate that the technologies are generic in their usefulness on most railways using wheels on rail as their main function.

The findings of the literature study, compiled in the overviews in chapter 4 and 5, as well as the case studies in chapter 6, contain information about the technologies that can be used to measure the condition and performance of a railway vehicle.

2. What kind of information can be extracted from the achieved measurements from wayside condition monitoring technologies?

Information about the vehicles performance as well as the direct condition, for example wheel profile, can be extracted from the measurements. This is a direct measurement that can give information about the actual wear of the wheel. In the case of performance it can be the forces generated on the track by passing axles or the position and angle of the axles. This information is then used to identify the actual problem causing the deviation in performance of the vehicle. The information is evaluated with knowledge about the vehicles dynamic characteristics to pinpoint the cause of the performance deviation.

The findings from the literature study and the case studies compiled in chapters 4, 5 and 6 describe the information that can be extracted from the measurements. Some of the monitoring technologies measure the performance of the vehicle, hence do not measure the direct condition of the vehicle as argued in the discussion, chapter 7. These can be seen as systems that are cause-symptom oriented in the focus of the wheel wear, for example, such systems as lateral forces measurements. The cause is high forces causing the symptom of high wheel wear. As a result of this, the reason for the performance deviation has to be identified. Other systems measure the direct condition of a component, this is argued in the discussion, chapter 7, to be symptom-cause oriented. For example a wheel profile measurement system. This measures the direct wear of the wheel, hence the symptom of some performance deviation.

3. What are the possible benefits of applying wayside condition monitoring technologies for condition-based maintenance of railway vehicles?

The direct benefit of applying wayside condition monitoring technologies is that it supports the three functional objectives stated by Shrieve (1992)

1. Provide information regarding current condition.
2. Provide forecast of future condition.
3. Detect and diagnose developing faults.

By finding wayside condition monitoring technologies that fulfil the objectives there are many economical benefits that can be achieved through higher availability, less accidents and derailments of vehicles, increased life of both wheel and rail due to decreased wear through better utilization of equipment. This has been documented on railways that have implemented wayside condition monitoring. These findings from the literature study highlight the benefits it is possible to achieve with the help of wayside condition monitoring, see chapter 5 and also in the discussion chapter 7.

The future benefits of implementing condition monitoring and condition-based maintenance for railway vehicles are also suggested in the discussion, see chapter 7.7.

8.2 Conclusions in relation to purpose, goal and delimitations

The results of the literature study and the case studies have given a positive indication that there is a good potential in the existing technologies for condition monitoring to work as valuable input in the maintenance management of railway vehicles to support a condition-based maintenance strategy. The monitoring systems and the technologies that have been evaluated in the case studies are in use at different locations and the measurement data are used as input to the maintenance management.

The results from the five case studies indicate that the technology evaluated could be used as reliable and valid monitoring equipment on the Swedish railway network. In the evaluation of the equipment, measurements has been focused on railway vehicles at LKAB/MTAB since they have been one of the main initiators of the thesis work regarding a way to arrive at a condition-based maintenance strategy for railway vehicles on the Swedish railway. The equipment seems to function well in measuring the vehicles that are used by LKAB/MTAB. The monitoring equipment should also be applicable to measure other railway vehicles on the Swedish railway network due to the basic performance deviations that are measured by the systems since the dynamics of the vehicles are of the same characteristics.

The goal to collect and compile information that contributes to the knowledge that supports and facilitates an implementation of condition-based maintenance for train operators has been successful, the case studies have given practical information about the functionality of some of the condition monitoring technologies available. They show a good potential to be used as contributors of condition and performance data to be used as decision support in a condition-based maintenance management strategy. The literature studies have given valuable information about other available technologies as well as the use of them. The benefits achieved on other railways show that there are benefits to be found in an implementation of condition monitoring for train operators in Sweden. The literature study also gives a good indication of large economic benefits for the infrastructure owners with an implementation of condition monitoring systems for the rolling stock. Since, the improved condition and performance of vehicles on the railway will have a positive effect on the degradation rate of the infrastructure.

The research was not interested in the creation of new technology but looking at ways to use already available technology. The evaluated monitoring systems in the case studies show a good potential to be used as input to support the maintenance activities. The research work has revealed some other technological and organizational challenges inside LKAB/MTAB other than the actual condition measurements in the implementation of a condition-based maintenance strategy. There is, for example, a need for an upgrade in the maintenance management software to meet the needs of data handling.

The decision to mainly evaluate wayside technology for condition monitoring has not been a limitation in finding potential technologies. Literature studies of condition monitoring on railway vehicles indicate that most of the condition monitoring technologies that are being developed, deployed and in use are based on wayside technology.

The case studies were focused on monitoring systems measuring the wheel and bogie performance since the wheel/rail interface was the focus area stated in the limitations. The literature study has indicated that these types of systems are being deployed at a growing rate on railways around the world to increase both efficiency and safety of the railway operations.

Some other monitoring systems have been mentioned as well and they also have a good potential to contribute with valuable measurement data that can support a condition-based maintenance strategy.

9 Further research

Knowledge of the practical use of the technologies in railway industries around the world has to be expanded. To learn from those who already have implemented the technologies will be valuable input. It is necessary to learn how to implement the technology and how to use it in the daily as well as long term operation and maintenance process and to find out what challenges and issues can arise during the implementation. It is also important to determine how to organize the organization to handle a new maintenance strategy and if there is a need for more and newer software and other technologies. These are aspects that are of interest. The aim is also to find the economic benefits that have been achieved on both infrastructure and vehicles. They can then be documented to prove the value of an investment in new condition monitoring technology to support a future implementation on the Swedish railway network.

Also the knowledge of the correlation between defects on the vehicle with deviant performance concerning the specific car types used on the ore line as well as the rest of the Swedish railways can be developed further through more measurements with the different monitoring systems and inspections of the actual conditions of the vehicles. This will be useful in the evaluation of the measurement data collected by the monitoring systems for the possibilities to develop prediction models between measurements and actual condition and degradation progress.

The next step in the research is to visit some of the leading actors in the field of condition monitoring and condition-based maintenance on railway networks to get an insight into how to be successful in the implementation of condition monitoring equipment and a condition-based maintenance strategy. The aim is to find and document proof of the actual benefits that have been recorded in these organizations to compare with the situation on the Swedish railways to find a way to evaluate the possible benefits that could be achieved in the Swedish railway industry.

10 References

Alvesson, M. and Sköldberg, K. (1994). Tolkning och reflektion: Vetenskapsfilosofi och kvalitativ metod. Studentlitteratur, Lund. (In Swedish)

ARTC (2007). Australian Rail Track Corporation Ltd
http://www.artc.com.au/about/about.htm (2006-03-03)

Banverket (1997). 30 Tonnes on Malmbanan/Ofotenbanen, Internal report collection consisting of main report + 32 sub-reports (1996). In Swedish and Norwegian. (2 reports in English.)

Barke, D., Chiu, W. K. (2005). Structural Health monitoring in the railway industry: A review. Structural Health Monitoring, 2005 Vol. 4. pp. 81-93, Journal, Electronic access: http://shm.sagepub.com

Barlow, J, Cohen, M,, Jashapara, A and Simpson, Y. (1997) Towards Positive Partnering. Bristol: The Policy Press.

Becker, K. C., Byington C. S., Forbes, N. A. and Nickerson G. W. (1998) Predicting and preventing machine failures, the Industrial Physicist, 4, pp. 20-23.

Bengtsson, M. (2004). Condition-based maintenance systems – an investigation of technical constituents and organizational aspects. Licentiate thesis, Department of Innovation, Design and Product Development, Mälardalen University, Sweden, ISBN: 91-88834-68-9

Bengtsson, M. (2002). Condition-based maintenance on rail vehicles – Possibilities for a more effective maintenance strategy.
Department of Innovation, Design and Product Development, Mälardalen University, Sweden

Berggren, E. (2005). The role of vertical track stiffness measurements in condition-based maintenance of railway tracks – A pilot study.
Report, Royal Institute of technology, KTH, Sweden, ISRN: KTH/AVE/RTR-05/31-SE

Berghuvud, A. (2001). Curving performance and nonlinear dynamic behavior of freight cars with three-piece bogies. Doctoral thesis 2001:09, Luleå University of Technology, Sweden, ISSN: 1402-1544, ISRN: LTU-DT—01/9—SE

BHP Billiton (2007). http://ironore.bhpbilliton.com/repository/operations/rail.asp (2007-01-31)

Bladon, K., Rennison, D., Izbinsky, G., Tracy, R. and Bladon, T. (2004) Predictive condition monitoring of railway rolling stock.
CORE- Conference On Railway Engineering, 20-23 June 2004, Darwin, Australia

Blevins,W., Morgan, R., Pinney, C. (2003). Integrated Wayside Systems to Improve Safety and Efficiency. Proceedings IHHA 2003 Specialist Technical Session – Implementation of Heavy Haul Technology for Network Efficiency –May 5-9, 2003, Dallas, Texas , USA

Bowey, R., Donnelly,R. (2005). Wayside monitoring to drive vehicle maintenance. Proceedings 8th International heavy haul conference IHHA, 14-16 June 2005, Rio De Janeiro, Brazil

Cline, J.E., Bilodeau, J.R., and Smith, R.L. (1988). Acoustic wayside identification of freight car roller bearing defects. Proceedings of the IEEE/ASME Joint Railroad Conference 1988, Piscataway, NJ, USA: IEEE, pp. 79–83.

Choe, H.C., Wan, Y., Chan, A.K. (1997). Neural pattern identification of railroad wheel-bearing faults from audible acoustic signals: comparison of FFT, CWT, and DWT features. Proceedings of SPIE – The International Society for Optical Engineering 1997, Bellingham, WA, USA: Society of Photo-Optical Instrumentation Engineers, pp. 480–496.

Dane, F.C. (1990). Research methods. Brooks/Cole Publishing Company, Pacific Grove.

Donnelly, R., Lynch, M., Darby, M. (2005). The use of automation and technology in improving maintenance practices in heavy haul railroad. Proceedings 8th International heavy haul conference IHHA, 14-16 June 2005, Rio De Janeiro, Brazil

Enblom, R. (2004). Simulation of wheel and rail profile evolution – wear modelling and validation. Licentiate thesis, Royal Institute of technology, KTH, Sweden, ISBN: 91-7283-806-X

Eriksson, L. and Wiedersheim-Paul, F. (1997). Att utreda, forska och rapportera. Liber ekonomi, Stockholm. (In Swedish)

Espling, U. (2004). Ramverk för en drift- och underhållsstrategi ur ett regelstyrt infrastrukturperspektiv. ISRN: LTU-LIC –04/45—SE, Licentiate Thesis, Luleå University of technology, Sweden

Espling, U., Olsson, U. (2003). Partnering for Railway Network Efficiency. Proceedings IHHA 2003 Specialist Technical Session – Implementation of Heavy Haul Technology for Network Efficiency –May 5-9, 2003, Dallas, Texas , USA

Esveld, C. (2001). Modern railway track, 2nd edition. TU Delft, MRT-productions, Netherlands, ISBN 90-800324-3-3

File, W.T. (1991). Cost effective maintenance – Design and Implementation. Butterworth – Heinemann Ltd 1991, UK, ISBN 0-7506-1006-9, (1991)

Granström, R. (2005). Maintenance for improved punctuality – A study of condition monitoring technology for the Swedish railway sector.
ISRN: LTU-LIC –05/88—SE, Licentiate Thesis, Luleå University of technology, Sweden

Granström, R. (2003). Verifieringstest hjulskadedetektoranläggningen Krokvik 2003/02/17-21. Banverket Projektering, Rapportbeteckning: 3500101–TBRNP-002, (2003-03-05)

Hawthorne, K. Wiley, R.B. Guins, T. (2005). Wayside monitoring with ATSI aids wagon maintenance. Railway Gazette, June 2005.

Herzog, T. (1996). Research methods and data analysis in the social sciences. HarperCollins, New York.

Holmgren, M. (2006). Maintenance-related incidents and accidents. ISRN: LTU-DT –06/37—SE, Doctoral Thesis, Luleå University of technology, Sweden

Iden, M. (2003). Integration of Wayside Detection Technologies with Predictive Rolling Stock Inspection ad Maintenance. Proceedings IHHA 2003 Specialist Technical Session – Implementation of Heavy Haul Technology for Network Efficiency –May 5-9, 2003, Dallas, Texas ,USA

IHHA (2001). Guidelines to best practices for heavy haul railway operations: Wheel and rail interface issues. International Heavy Haul Association, Library of congress control No: 2001 131901, USA

Irani, F., Wiley, R.B., Guins, T.S. (2003). Network Efficiency Gains Using a Detector-Based Information Management System. Proceedings IHHA 2003 Specialist Technical Session – Implementation of Heavy Haul Technology for Network Efficiency –May 5-9, 2003, Dallas, Texas , USA

Irani, F. (2003). Development and implementation of wayside detection systems for vehicle health monitoring. Abstract no: 5.5, WCRR2003, The World Congress on Railway Research 28/9- 1/10 2003, Edinburgh, Scotland, UK

IRT - Institute of Railway Technology, Monash University (2007). http://www.eng.monash.edu.au/railway (2007-01-31)

Jardine, A., Lin, D. and Banjevic, D. (2005). A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mechanical Systems and Signal Processing, Volume 20, Issue 7, October 2006, Pages 1483-1510

Johansson, A. (2005). Out-of-round railway wheels – causes and consequences. Chalmers University of technology, Sweden, ISBN 91-7291-641-9

Kelly, A. (1989). Maintenance and its management. Monks Hill, Conference Communication.

Kelly, A. Harris, M J. (1978). Management of industrial Maintenance. Buttersworth and Co. Ltd., ISBN 0-408-01377-X

Kumar, S. (2006). A study of the rail degradation process to predict rail breaks. ISRN: LTU-LIC –06/73—SE, Licentiate Thesis, Luleå University of technology, Sweden

Lagnebäck, R. (2004). Tillståndsbaserat underhåll för malmvagnar – en förstudie. Master Thesis, Luleå University of technology, Sweden

Lagnebäck, R. and Kumar.U (2005). Potential of condition monitoring on railway vehicles: a case study. Proceedings 8th International heavy haul conference IHHA, 14-16 June 2005, Rio De Janeiro, Brazil

Larsson, D. (2005). An Improved Method to Monitor Vehicle Steering Performance – Facilitating both Train and Track Maintenance.
In: Proceedings of the 8th International Heavy Haul Conference, Rio, Brazil, June 14-16, 2005.

Larsson, D. (2004). A study of the track degradation process related to changes in railway traffic. ISRN: LTU-LIC –04/48—SE, Licentiate Thesis, Luleå University of technology, Sweden

Larsson, D., Gunnarsson, J. (2001). A Model to Predict Track Degradation Costs. Proceedings IHHA 2001 Brisbane

Links, ARTC News letter. (2005).
http://www.artc.com.au/docs/news/links/Links%2012.pdf
LINKS No. 12 December 2005

Liyanage, J. P. and Kumar, U. (2002). Process of Maintenance Performance
Management and Its Imperatives within the Offshore Petroleum Industry (Part III): Integration of Maintenance Performance to Corporate Value Process. SMRP Solutions*,* 2002:3.

Liyanage, J. P. and Kumar, U. (2003). Towards a value-based view on operations and maintenance performance management. Journal of Quality in Maintenance Engineering*,* 9**,** 333-350.

LKAB, (2007). http://www.lkab.com/ (2007-01-30)

Lundgren, J. (2005). Advanced rail vehicle inspections system. Proceedings 8th International heavy haul conference IHHA, 14-16 June 2005, Rio De Janeiro, Brazil

Magel, E., Kalousek, J., Roney, M. (2002). Stress reduction, railroad style: the contact area where wheel meets rail is about the size of a dime. Making it as stress-free as possible can save big dollars. Railway age, July 2002

Matoba, K. (2000). Detection and warning systems form first line of defense. Railway Track and Structures, 96(4) April 2000.

Mckillop, B., Pearon, M. (1997). END OF THE LINE : A History of Railways in Papua New Guinea. Port Moresby, Papua New Guinea. Originally published by University of Papua New Guinea Press, 1997

Milne, R. (1992). The role of expert systems in condition monitoring. Proceedings 4th International conference on Profitable Condition Monitoring, 8-10 December, Stratford-upon-Avon, UK

Mobley, R:K. (1990). An introduction to predictive maintenance. Van Nostrand Reinhold, New York

Moubray, J. (1991). Reliability-centred maintenance. Oxford, Butterworth-Heinemann.

Newman, R.R., Leedham, R.C., Tabacchi, J., Purta, D., Maderer, G.G. and Galli, R. (1990). Hot bearing detection with the ‘SMART-BOLT’.
In: IEEE Technical Papers Presented at the Joint ASME/IEEE/AAR Railroad Conference (Association of American Railroads) 1990, Chicago, IL, USA, IEEE, IEEE Service Center, Piscataway, NJ, USA, pp. 105–110.

Nordmark, T (2004) A benchmarking of heavy haul railway operators around the world. Internal report (Not public)

Parida, A. (2006). Development of a multi-criteria hierarchical framework for maintenance performance measurement. ISRN: LTU-DT –06/37—SE, Doctoral Thesis, Luleå University of technology, Sweden

Rao, B.K.N (1996). Handbook of Condition Monitoring. Oxford : Elsevier Advanced Technology.1996.

Robertssson, T., Fry, K. (2006). Condition monitoring, how it can be applied for railway vehicles – a pilot study for SJ X2000 high speed trains. Proceedings from COMADEM 2006, Luleå, Sweden

Rostow, WW. (1962). The process of economic growth. W.W. Norton and Company, Inc., SBN 393-00176-8

Shrieve, P. (1992). Implementing a cost effective machinery condition monitoring program. Proceedings 4th International conference on Profitable Condition Monitoring, 8-10 December, Stratford-upon-Avon, UK

Simms, J.M., Smith, R.A. (1996). Strategic options in railway maintenance management: maintenance philosophies and new technologies. COMADEM '96 -Condition Monitoring And Diagnostic Engineering Management, Sheffield Academic Press, Sheffield, UK, ISBN 1-85075-635-X,

Skeggs, C. (2007). Project partnering in the international construction industry. http://www1.fidic.org/resources/contracts/skeggs.asp (2007-01-28)

Smith, M.A.J., Dekker, R. (1997). Preventive maintenance in a 1 out of n system:The uptime, downtime and costs. European Journal of Operational Research 99 (1997) 565-583

Southern, C. (2005). PACIFIC NATIONAL: Condition Monitoring and Wayside Detection Strategy. (Internal document)

Southern, C., Rennison, D., Kopke, U. (2004). RailBAM® - An advanced bearing acoustic monitor: Initial operational performance results. CORE-Conference On Railway Engineering, 20-23 June 2004, Darwin, Australia

Stack, J., Harley, R., Habetler, T. (2004). An Amplitude Modulation Detector for Fault Diagnosis in Rolling Element Bearings. IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 51, NO. 5, OCTOBER 2004 pp.1097-1102

Starr, A. G. (1997). A Structured Approach to the Selection of Condition-based Maintenance. In proceedings from the 5th International Conference on FACTORY 2000, UK, Cambridge.

Steets, P.G., Tse, Y.H. (1998). Conrail's integrated automated wayside inspection. Proceedings of the IEEE/ASME Joint Railroad Conference 1998, Piscataway, NJ, USA: IEEE, pp. 113–125.

Swedish Standards Institute (2001). Maintenance terminology.
SS-EN 13305

Söderholm, P. (2005). Maintenance and continuous improvement of complex systems – Linking stakeholder requirements to the use of built in test systems. ISRN: LTU-DT –05/52—SE, Doctoral Thesis, Luleå University of technology, Sweden

Süleyman, Ö. (1996). Reliability and Maintenance of Complex Systems**.** Published Springer 1996, ISBN 3540611096

Tournay, HM., Cummings, S. (2005). Monitoring the performance of railroad cars by means of wayside detectors in support of predictive maintenance. Proceedings 8th International heavy haul conference IHHA, 14-16 June 2005, Rio De Janeiro, Brazil

Waring, R. (2003). Fewer damaged wheels through the use of impact detectors. Abstract no: 26.5, WCRR2003, The World Congress on Railway Research 28/9- 1/10 2003, Edinburgh, Scotland, UK

White, E. N. (1973). Maintenance planning, control and documentation. Epping, Essex, Gower.

Wikipedia (2007). http://www.wikipedia.org/ (2007-02-14)

Williams, J.H. Davies, A. Drake, P.R. (1994). Condition-based maintenance and machine diagnostics. Chapman and Hall, London, UK, ISBN 0 412 46500 0,

Wireman, T. (1997). Computerized Maintenance Management Systems - Second edition" , ISBN- 0-8311-3054

WRI course (2005). Wheel-Rail Interaction course. 11-13 June, 2005, Rio De Janeiro, Brazil

Yin, R. (2003). Case study research: Design and methods. Sage, Thousand Oaks.

Åhrén, T. (2002). Utvärdering av underhållskostnaden för hjul och räl på sträckan Kiruna – Riksgränsen. Bachelor Thesis, Luleå University of technology, Sweden (In Swedish)

Appendix 1.

October 4, 2004

RE: Bogie Inspection-WID

In regard to the bogies and wheelsets inspected at your MTAB shop in June from a test sample of wagons pulled from service using the newly installed WID monitoring system, in general, it confirmed which bogies were operating abnormally. The primary cause of the abnormal wheel angle of attacks and lateral wheelset shift appears to be the axle box and pedestal roof interface interlocking. The metal liner between the two surfaces in the sample wheelsets inspected is locking them together, like jigsaw puzzle pieces, not allowing the wheelset freedom of movement to find its optimum system operating condition. These deformed liners were observed in the wheelsets pulled from service as well as reconditioned wheelsets awaiting installation.

The following are Nathan Reese's and my observations from the bogie inspections:

1. Wagon #1651 had 2 wheelsets laterally shifted and one wheelset has a bad profile with false flange in conjunction with a steep tread angle. The lateral wheelset displacement in this wagon can be attributed to pedestal roof to axle box connection being interlocked due to the deformed liner. Interestingly, there was no bogie gib wear. The WID data was confirmed.

2. Wagon #9211771 was inspected and one bogie has 26mm wheelset shift and slight gib wear. There was a heavy front rim (6mm plus) rollover, along with a tread worn hollow and steep front tread taper. Again, this appeared to be related to the interlock pedestal liners and associated tread profile. The mate bogie in this wagon was reported to be ok by the WID inspection and it was confirmed during our inspection.

3. In regard to the looking at the AR-1 equipped wagon that was previously bogie tested, there appeared to be abnormal wear patterns in sideframe pedestal legs. The unusual bearing cup contact and dishing effect appears to be related to AR-1 adaptor pedestal lug setup or clearances. The pads and steering arms looked ok, so my impression is the concave pedestal condition is related to the setup. Engineering is looking for the earlier reports, but is having difficulty locating them due to the move from the Chicago office to Granite City. Once they are located, we can discuss in further detail with you.

In summary, the bogies and wheelsets inspected during the shop teardowns agreed with the WID data. If you have any questions, please contact me. We are looking forward to good results from the upcoming bogie tests.

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