

# Management of condition information from railway punctuality perspectives

Rikard Granström

Luleå University of Technology  
Department of Civil, Mining and Environmental Engineering  
Division of Operation and Maintenance Engineering

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**Management of condition information  
from railway punctuality perspectives**

**RIKARD GRANSTRÖM**

Luleå University of Technology  
Department of Civil, Mining and Environmental Engineering  
Division of Operation and Maintenance Engineering  
Luleå Railway Research Centre



**Technology is the solution.**

**But what is the task to be solved?**

**Swedish Defence Material Administration (FMV)**

**Tekniken är lösningen.**

**Men vilken är uppgiften?**

**Försvarets Materielverk (FMV)**



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Rikard Granström

Älvsbyn, June 2008





## ABSTRACT

Due to the increasing need for transportation and environmental concerns, there is a social and political will to transfer transportation services from roads to rail. The increasing demand for railway transportation services has a significant effect on important stakeholder requirements, such as safety, punctuality, dependability, sustainability and costs. This in turn affects railway practices concerning operation, maintenance and modification. Simultaneously, the ongoing deregulation of state-owned railways has caused new organizations to enter the railway sector. Hence, the punctuality of the railway is dependent on a combination of multiple required functions that are concurrently provided by different stakeholders, e.g. the infrastructure manager, infrastructure maintenance contractors and traffic operators. In Sweden, Banverket (the Swedish Rail Administration) is the infrastructure manager and has the overall responsibility for railway punctuality. This means that Banverket has to coordinate and stimulate the stakeholders to provide the required functions in order to achieve the delivery of punctual transportation services.

The purpose of this research is to explore and describe how information about the condition of technical systems can support stakeholders within the Swedish railway in improving punctuality by means of more effective and efficient maintenance. The focus is on delays that are caused by the absence of required infrastructure functions, even though the interaction with the rolling stock is considered through the study of critical interfaces. Condition monitoring technologies are focused on as the primary application for obtaining condition information on technical systems. Hence, the research is intended to provide knowledge about how condition information can be used in the quest to provide the quality required from the Swedish railway transportation service at an adequate cost for society. To fulfil the stated purpose, empirical data have been collected by document studies, interviews, workshops, observations and field measurements. Examples of covered data are train delay statistics, failure statistics, No-Fault-Found (NFF) events and wheel impact forces. The data have been analysed through statistical and analytical approaches (e.g. Failure Mode and Effects Analysis, FMEA), as well as by applying theories related to principal-agent problems, Scientific Management and international dependability standards.

The thesis describes how the maintenance effort required by infrastructure maintenance contractors is affected by the maintenance effort conducted by traffic operators (and vice versa). The interaction between infrastructure and rolling stock has a significant effect on the systems' punctuality and the degradation of bound capital. Hence, effective punctuality improvements through maintenance efforts must be based on a holistic railway system perspective, i.e. a joint consideration of infrastructure and rolling stock. The thesis also presents how condition information can be used as a management tool to stimulate the fulfilment of performance requirements made on railway stakeholders. It is also shown that the same information can be used to predict and plan necessary preventive maintenance tasks, as well as to support continuous improvement of the technical systems. However, unless stakeholder needs are acknowledged and unless proper scientific investigations precede the formation of requirements and the applications of condition monitoring technologies, it is likely that the desired system performance improvements will not be realised. In summary, the thesis outlines a possible scenario in which condition information could support railway stakeholders in improving the punctuality of the railway system by means of more effective and efficient maintenance.

Keywords: Maintenance, punctuality, stakeholders, management, condition monitoring, railway, condition information.



## **SAMMANFATTNING (SUMMARY IN SWEDISH)**

Det ökande behovet av transporter samt en ökande miljömedvetenhet har ökat efterfrågan på och nyttjandet av järnvägstransporter. Det ökande behovet av järnvägstransporter har en signifikant påverkan på viktiga intressentkrav såsom säkerhet, punktlighet, tillförlitlighet, hållbarhet samt kostnader. Detta påverkar i sin tur järnvägens tillämpningar beträffande drift, underhåll och modifieringar. Samtidigt har den pågående avregleringen av järnvägen medfört att nya organisationer har kommit in på järnvägsmarknaden. Följaktligen är punktligheten på järnvägen beroende av en kombination av många krävda funktioner som för närvarande är tillhandahållna av olika intressenter, till exempel infrastrukturhållare, underhålls-entreprenörer för infrastruktur och trafikoperatörer. I Sverige är Banverket infrastrukturhållaren som har det övergripande ansvaret för järnvägspunktlighet. Detta innebär att Banverket måste koordinera och stimulera intressenter att tillhandahålla krävda funktioner för att kunna tillfredställa leverans av punktliga transporttjänster.

Syftet med denna forskning är att utforska och beskriva hur information beträffande tekniska systems hälsa kan stödja intressenter inom den Svenska järnvägen till att förbättra punktligheten genom ett effektivare underhåll. Fokus ligger på förseningar som är orsakade av frånvaro av krävda infrastrukturfunktioner, även om interaktion med rullande materiel beaktas genom studier av kritiska gränssytor. Tillståndsovervakningsteknologier är fokuserade som den primära applikationen för erhållandet av information om de tekniska systemens hälsa. Därmed är forskningen avsedd att bidra med kunskap om hur tillståndsinformation kan användas för att tillhandahålla krävd transportservice på den svenska järnvägen till en adekvat kostnad för samhället. För att tillfredställa syftet med forskningen har data inhämtats genom dokumentstudier, intervjuer, seminarier, observationer och fältmätningar. Exempel på avhandlad data är; tågförseningsstatistik, felrapportstatistik, inget-fel-funnet-händelser (No-Fault-Found, NFF) samt hjulkrafter. Data har analyserats genom statistiska och analytiska ansatser, till exempel felmod- och effektanalys (FMEA), men även genom teorier relaterade till principal-agent-problemet, Scientific Management och internationella tillförlitlighetsstandarder.

Avhandlingen beskriver hur den av en underhållsentreprenör krävda underhållsinsatsen påverkas av det underhåll som trafikoperatörer utför (och vice versa). Detta har en signifikant påverkan på systemets punktlighet samt degraderingen av bundet kapital. Följaktligen så måste effektiva punktlighetsförbättringar genom underhållsinsatser baseras på ett holistiskt järnvägssystemperspektiv, till exempel ett gemensamt beaktande av infrastruktur och rullande materiel. Avhandlingen visar också hur tillståndsinformation kan användas som ett ledningsverktyg för att stimulera uppfyllandet av prestationskrav lagda på järnvägsintressenter. Det är också illustrerat att samma information kan användas för att prediktera och planera nödvändiga förebyggande underhållsåtgärder likväl som att stödja kontinuerlig utveckling av det tekniska systemet. Emellertid, om intressenternas behov inte tillkännages och om inte vederbörliga vetenskapliga utredningar föregår utformandet av krav samt tillståndsovervakningsapplikationerna, är det troligt att de eftersträvsvärda systemprestandaförbättringarna uteblir. Sammanfattningsvis så bidrar avhandlingen med ett möjligt scenario för hur tillståndsinformation kan stödja järnvägsintressenterna till att förbättra punktligheten hos järnvägssystemet genom effektivare underhåll.

Nyckelord: Underhåll, punktlighet, intressenter, management, tillståndsovervakning, järnväg, ledning, tillståndsinformation.



## LIST OF APPENDED PAPERS

This thesis includes the following five papers, appended in full.

- PAPER 1 **Granström, R. & Söderholm, P.** (2005). Punctuality measurements effect on the maintenance process: a study of train delay statistics for the Swedish railway. *Proceedings of the 8<sup>th</sup> international conference and exhibition of Railway Engineering, 29<sup>th</sup>-30<sup>th</sup> June 2005*, London, UK.
- PAPER 2 **Granström, R. & Söderholm, P.** (2008). Condition Monitoring of Railway Wheels and No Fault Found Problems. *Accepted for publication in: international journal of COMADEM.*
- PAPER 3 **Granström, R., Söderholm, P., & Kumar, U.** (2008). A system and stakeholder view of maintenance for punctuality improvement. *Accepted for publication in: Journal of Quality in Maintenance Engineering (JQME).*
- PAPER 4 **Granström, R.** (2008). A system and stakeholder approach for the identification of condition information: a case study for the Swedish railway. *Accepted for publication in: International Journal of Rail and Rapid Transit.*
- PAPER 5 **Granström, R.** (2008). Scientific maintenance management for improved railway punctuality. *Submitted for publication.*



## LIST OF RELATED PUBLICATIONS

The author has also written a number of publications that are not appended in this thesis, but are related to the studied research area.

**Granström, R.** (2003). *Verification test for wheel impact detection system at Krokvik. Verifieringstest hjuskadedetektoranläggningen Krokvik* (in Swedish). Technical report, Banverket Northern Region, Luleå, Sweden.

**Granström, R. & Kumar, U.** (2004). Condition monitoring of railway infrastructure: a case study in northern Sweden. *Proceedings of the 17<sup>th</sup> International Congress on Condition Monitoring and Diagnostics Engineering Management (COMADEM), 23<sup>rd</sup>-25<sup>th</sup> August 2004*, Cambridge, UK.

**Granström, R.** (2004). *Verification and field test of FUES (hot-box detector system). Verifieringstest, fältprov FUES* (in Swedish). Technical report, Banverket Northern Region, Luleå, Sweden.

**Granström, R.** (2004). *Operation monitoring in signalling facilities. Driftövervakning i signalanläggningar* (in Swedish). Technical report, Division of Operation & Maintenance Engineering, Luleå University of Technology, Luleå, Sweden

**Granström, R.** (2005). *Maintenance for improved punctuality: a study of condition monitoring technology for the Swedish railway sector*. Licentiate Thesis, Division of Operation & Maintenance Engineering, Luleå University of Technology, Luleå, Sweden.

**Granström, R. & Söderholm, P.** (2006). "Verification and Utilization of Wheel Impact Detection Systems". *Proceedings of the 19<sup>th</sup> International Congress on Condition Monitoring and Diagnostic Engineering Management (COMADEM), 12<sup>th</sup>-15<sup>th</sup> June 2006, Luleå, Sweden*.





# TABLE OF CONTENTS

<b>ACKNOWLEDGEMENTS</b> .....	<b>I</b>
<b>ABSTRACT</b> .....	<b>III</b>
<b>SAMMANFATTNING (SUMMARY IN SWEDISH)</b> .....	<b>V</b>
<b>LIST OF APPENDED PAPERS</b> .....	<b>VII</b>
<b>LIST OF RELATED PUBLICATIONS</b> .....	<b>IX</b>
<b>TABLE OF CONTENTS</b> .....	<b>XI</b>
<b>1 INTRODUCTION</b> .....	<b>1</b>
1.1 RAILWAY PUNCTUALITY AND MAINTENANCE.....	1
1.2 SCOPE OF THE RESEARCH.....	3
<b>2 THEORETICAL FRAMEWORK</b> .....	<b>5</b>
2.1 PUNCTUALITY, AVAILABILITY AND MAINTENANCE .....	5
<b>3 RESEARCH PROCESS</b> .....	<b>9</b>
3.1 THE RESEARCH PROJECT.....	9
3.2 THE LICENTIATE THESIS.....	9
3.3 PAPER 1.....	11
3.4 PAPER 2.....	12
3.5 PAPER 3.....	13
3.6 PAPER 4.....	15
3.7 PAPER 5.....	17
<b>4 CONCLUSIONS</b> .....	<b>19</b>
4.1 RESEARCH QUESTION 1 .....	19
4.2 RESEARCH QUESTION 2 .....	20
4.3 RESEARCH QUESTION 3 .....	23
<b>5 DISCUSSION AND FURTHER RESEARCH</b> .....	<b>25</b>
5.1 PROBLEM DOMAIN.....	25
5.2 APPLICATION AREA .....	28
<b>6 REFERENCES</b> .....	<b>31</b>
<b>APPENDED PAPERS</b> .....	<b>35</b>



# 1 Introduction

*In this first chapter of the thesis, a short description of the research area will be outlined. Then the scope of the research, including the purpose, delimitations, and the research questions, will be presented.*

## 1.1 Railway punctuality and maintenance

Technology is a key element for our modern living standard. As we become more dependent on our technical systems, we tend to become more vulnerable to the consequences of the absence of required functions. Our vulnerability is exposed on occasions such as the mass power supply failure in southern Sweden caused by the storm Gudrun in 2004. Other well-known examples exposing our vulnerability to technical system failures are the Shadi Kor dam collapse (in Pakistan, on February 10, 2005), the explosion of the space shuttle Columbia (in the USA, on February 1, 2003), the massive power-supply failure in Italy (on September 28, 2003), the Hatfield train crash (in England, on October 17, 2000), the Concorde crash outside Paris (in France, on July 25, 2000), the Enschede train crash (in Germany, on June 4, 1998) and the explosion of a nuclear reactor in Chernobyl (in Ukraine, on April 26, 1986). As technical systems provide more services for us, we become more dependent on their functions and more exposed to their risks. The complexity of technical systems and the cost of operating and owning them are increasing, at the same time as the tolerance of the absence of their functions is decreasing. The stakeholder requirements for these systems' dependability, safety and cost outline the specifications for the design of the systems, which will affect the systems' operational life characteristics, need for maintenance and lifecycle cost (Blanchard, 1995; Ahlmann, 2002).

Transportation is one example of a critical service that is enabled by complex technical systems. From an environmental perspective, the railway has become a very attractive mode of transportation. However, as outlined above, failures within the railway system have caused and can cause accidents with extensive losses. The sole purpose of the railway sector is to satisfy an important part of society's need for transportation (European Commission, 2001; Espling, 2007). In order that the railway sector may stay competitive with other transportation modes (e.g. other land-bound vehicles, as well as aircraft and sea craft), it needs to be cost-effective and provide a reliable service. The basic functions of the railway have not changed much during the past 100 years. It still utilizes steel wheels on steel rail to provide transportation services from one destination to another, together with safety measures aimed at guaranteeing train separation (only one train per given track section at a given time). However, new requirements and technology have changed the degree of utilization quite dramatically. Technologies such as signalling and traffic control systems provide opportunities to increase the train speed, lessen the distance between trains and increase the number of trains on the track. At the same time as technology has made the railway more effective, it has also made it more complex and sensitive to disturbances. Hence, railways are today regarded as complex systems (Espling, 2007; Kobbacy & Murthy, 2008; Åhren, 2008). The complexity is due to the fact that the railway system is an integrated network that consists of hardware, software and human elements, as well as support facilities and activities (IEC 60300-3-14, 2004). Railway items in general have a fairly long life length. For example, the life length of some railway items stretches beyond forty years (Espling, 2004). This implies that the cost for items during their operational life will greatly depend on the effectiveness and the efficiency of their maintenance.

Today, there is a social need and a political will to transfer a significant portion of the Swedish domestic transportation service from roads to rail (European Commission, 2001). Hence, the railway traffic in Sweden is increasing (Banverket, 2006), which is having a direct impact on both the maintenance and the punctuality of the transportation service. The punctuality is being affected, since an increasingly crowded track (due to increased capacity utilization) is making the impact of infrastructure and rolling stock faults on train delays and knock-on train delays (trains that are delayed due to other delayed trains) more severe (due to reduced slack in the timetable). The increased capacity utilization of the infrastructure is also causing it to deteriorate at a greater pace, which is increasing the demand for maintenance and reinvestment to retain and restore the required functions of the railway system. Simultaneously, as the need for maintenance is increasing, there is less time for executing it due to the increased traffic. In addition, the infrastructure maintenance budget is more or less fixed (Banverket, 2004, 2005, 2006). Hence, in this new situation with increasing requirements and utilization levels with practically the same available resources, the effectiveness and efficiency of the necessary maintenance have to be improved to retain and restore the required functions of the infrastructure. Consequently, it is a delicate task to balance the maintenance efforts to achieve the required punctuality (as well as the required safety and dependability levels) with limited resources. This situation is resulting in new requirements for the prediction of degradation and the necessary maintenance concerning both the infrastructure and the rolling stock, to avoid unplanned corrective maintenance and allow timely performed preventive and corrective maintenance. At the same time, different studies show that 70-90 percent of complex systems fail prematurely after maintenance execution, see e.g. Broberg (1973), Nowlan & Heap (1978), Moubray (1997), Allen (2001) and Reason & Hobbs (2003). Hence, from this point of view also, excessive maintenance execution should be reduced to avoid maintenance-induced errors. Therefore, Condition-Based Maintenance (CBM) is in many cases favourable compared to predetermined (time-based) maintenance (which entails the risk of excessive maintenance execution). However, the successful implementation of CBM requires that appropriate functions at appropriate indenture levels of the technical system should be monitored and that tests at different maintenance echelons within the maintenance organization should be integrated in order to avoid testability deficiencies like No-Fault-Found (NFF) events; see e.g. Granström & Söderholm (2006) and Söderholm (2006). NFF is a critical testability deficiency within the automotive, aviation and train industries that has a strong negative impact on critical requirements such as dependability, safety and cost (Söderholm, 2006). Hence, to improve punctuality, there is a need for more effective (doing the right things) and more efficient (doing the things right) CBM.

Based on the challenging scenario described above, research has been initiated to explore how more effective and efficient infrastructure maintenance can contribute to punctuality improvements within the railway sector through the application of supporting condition monitoring technologies (Punctuality II, 2005).

To complicate the issue further, the Swedish railway sector is partly deregulated. This means that private entities (infrastructure maintenance contractors) are allowed to compete for contracts to perform infrastructure maintenance. This also applies to rolling stock operation, where private entities (rolling stock operators) are allowed to run trains on the rail network. Both the maintenance contractor entities and the traffic operator entities are profit-driven. Hence, a reasonable behaviour to be expected of these entities is that they should fit their activities to the context which they operate within to maximise profit (Olsson & Espling,

2004; Espling, 2007; Nyström, 2008). In Sweden, 80 percent of the railway network is owned by the Swedish Government (Banverket, 2006). The Government controls the infrastructure and most of the Swedish railway sector through Banverket, which is the infrastructure manager in Sweden. Banverket's main objectives, stated in the governmental transport policy objectives, are to ensure system safety, cost-effectiveness, reliability of service and sustainability, for example in terms of environmental impact and longevity of transportation provision for the public and for industry. Punctuality is, next to safety, Banverket's most important goal (Fahlen & Jonsson, 2005). Governmental requirements state that Banverket has a sector responsibility for the railway, which means that it has an overall responsibility for the whole railway (Banverket, 2006). This implies that Banverket should monitor and actively pursue development throughout the railway sector. Hence, Banverket has the overall responsibility for improving punctuality, among other things (Ericsson et al., 2002). Therefore, Banverket has to coordinate and stimulate the stakeholders to provide the required functions in order to achieve the delivery of punctual transportation services.

## **1.2 Scope of the research**

**Purpose:** The purpose of this research is to explore and describe how information about the condition of technical systems can support stakeholders within the Swedish railway in improving punctuality by means of more effective and efficient maintenance.

Hence, the research is intended to provide knowledge about how condition information can be used in the quest to provide the required quality of the Swedish railway transportation service at an adequate cost to society.

**Delimitations:** In accordance with the project definition (Punctuality II, 2005), this research mainly focuses on Condition-Based Maintenance (CBM) of railway infrastructure.

More specifically, the focus in this research is on delays that are caused by the absence of required infrastructure functions, even though the interaction with the rolling stock is considered through the study of critical interfaces. The reason for this delimitation is that Banverket owns the infrastructure and can affect the train operators mainly through the interaction between the rolling stock and the infrastructure.

Condition monitoring technologies are focused on as the primary application for obtaining information about the condition of the technical systems. The delimitation is due to the definition of the project (Punctuality II, 2005) and the research financiers' interests.

Since the focus is on improved punctuality through maintenance efforts in the utilization and support phase, it is assumed that proper maintenance is sufficient to retain or restore the required functions. Hence, in this study maintenance considerations in the design phase of the railway system, e.g. through approaches such as design for maintenance or designing out maintenance, are not considered. However, design for maintenance is considered in the sense that the introduction of condition monitoring technologies is a design-for-maintenance task. Furthermore, issues related to timetables, for example, are also excluded. Hence, it is assumed that timetables provide sufficient means (time windows) for operators and contractors to provide the required services.

The research is mainly restricted to the Swedish railway context due to the accessibility of relevant information (e.g. documents, respondents and empirical material). Another reason for this delimitation is that Banverket has contributed financially to the project, which makes personnel within Banverket willing to support the project in other ways as well.

**Research questions:**

To fulfil the purpose of the research, this thesis contributes to answering three research questions:

- RQ 1. How can information about the condition of technical systems support the stakeholders within the Swedish railway in improving punctuality by means of more effective and efficient maintenance?
- RQ 2. How can necessary system condition information be identified?
- RQ 3. How can stakeholder interrelations and the introduction and utilization of condition monitoring technologies be managed to improve punctuality?

The relationships between the research questions and the appended papers are illustrated in Table 1.

<b>Paper</b>	<b>Research Question 1</b>	<b>Research Question 2</b>	<b>Research Question 3</b>
1		X	
2	X		
3	X	X	
4	X	X	
5	X		X

Table 1. *Relationships between the appended papers and the stated research questions.*

## 2 Theoretical framework

*This chapter presents some theories with complementary perspectives on punctuality, availability and maintenance, with a focus on railways. Examples of some central definitions are also provided.*

### 2.1 Punctuality, availability and maintenance

Punctuality is acknowledged as a key performance indicator within the railway sector (Åhren, 2005; Åhren, 2008). To some extent punctuality indicates the railway system's ability to deliver transportation services on time (at the end station) in accordance with a timetable. According to the *Swedish National Encyclopaedia*, a person who is punctual 'keeps exactly to the agreed time'. Hence, punctuality is the fulfilment of an agreement at a specific time between different parties. Within the railway, this agreement is manifested by a timetable, which describes where and at what time a specific transport is to be located. The timetable is an agreement between the infrastructure manager and the traffic operators which also stipulates allotted time windows for other activities on the infrastructure, e.g. infrastructure maintenance. Rudnicki (1997) defines punctuality as: 'a feature consisting in a predefined vehicle arriving, departing or passing at a predefined point at a predefined time'. Punctuality is usually calculated by dividing the number of punctual trains by the total number of trains, and the result is then presented as the percentage of punctual trains (Olsson & Haugland, 2004; Nyström, 2005; Nyström, 2008). In summary, punctuality should be treated as the extent to which an event takes place when agreed (Nyström, 2008). In order to gain a broader understanding of unpunctuality and its causes, train delay statistics can be used (Nyström & Kumar, 2003; Granström, 2005; Nyström, 2008). There are many different causes of train delays, e.g. the weather, sabotage, infrastructure or rolling stock faults, passengers, animals, the inability to leave freight terminals on time, missing train drivers, and maintenance activities interfering with scheduled traffic (Nyström & Kumar, 2003; Granström, 2005; Nyström, 2008). However, in accordance with the stated delimitations (see Section 1.2), this research mainly considers causes that are related to the required functions of the railway system.

There are different views and definitions of what a system is. According to ISO/IEC 15288 (2002), a system is: "a combination of interacting elements organized to achieve one or more stated purposes". Deming (1993) stated that "a system is a network of interdependent components that work together to try to accomplish the aim of the system". Hence, a system consists of a number of elements that interact to achieve an aim (Söderholm, 2005). There are also different types of systems, e.g. technical systems, non-technical systems and stakeholder systems (see, e.g., Söderholm, 2005). Another distinction that can be made between systems is that between the 'system-of-interest' and the 'enabling system', see ISO/IEC 15288 (2003). The system-of-interest is the system whose lifecycle is under consideration, e.g. the railway system (i.e. the joint consideration of both the infrastructure and the rolling stock) in this thesis. The enabling system is: "a system that complements a system-of-interest during its lifecycle stages, but does not necessarily contribute directly to its function during operation" (ISO/IEC 15288, 2003). In this thesis, the enabling system is the organization providing railway maintenance. The railway system is characterized by one-dimensional movement, the ability to provide fast transportation, the ability to transport heavy cargo, steel wheels on steel rail providing low friction, low energy consumption, long braking distances and only one train at a time per track section (Gullberg, 2000). An item is any part, component, device, subsystem, functional unit, equipment or system that can be individually con-

sidered (IEV 191-01-01). Hence, an item can be infrastructure and rolling stock individually or jointly considered, or an infrastructure or rolling stock subsystem, e.g. turnout, track, signal, wheel, pantograph, or engine.

Closely related to punctuality is availability performance, which is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided (IEV 191-02-05). This ability depends on the combined aspects of the reliability performance, the maintainability performance and the maintenance support performance (IEV 191-02-05), see Figure 1.

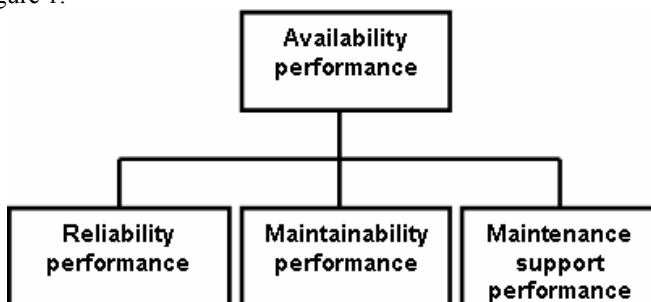


Figure 1. *Availability performance is the combination of reliability performance, maintainability performance and maintenance support performance (IEV 191-02-05).*

Reliability performance is the probability that an item can perform a required function under given conditions for a given time interval (IEV 191-12-01). Maintainability performance is the probability that a given active maintenance action, for an item under given conditions of use, can be carried out within a stated time interval, when the maintenance is performed under stated conditions and using stated procedures and resources (IEV 191-13-01). Maintenance support performance is the ability of a maintenance organization, under given conditions, to provide upon demand the resources required to maintain an item, under a given maintenance policy (IEV 191-02-08). Hence, two of these factors, reliability performance and maintainability performance, are related to the technical system, while maintenance support performance is related to the maintenance organization (Blanchard & Fabruycky, 1998; Goffin, 2000; Blanchard, 2001; Söderholm, 2005). Consequently, the technical system’s need for maintenance is more or less decided in the design and manufacturing stages for a specific function or performance (Blanchard & Fabruycky, 1998; Goffin, 2000; Blanchard, 2001). In the design of a technical system and its required functions, there is a trade-off between reliability performance (designing out maintenance) and maintainability performance (designing for maintenance), see Söderholm (2005). However, when dealing with complex technical systems (such as within the railway), it is beneficial also to design the support system concurrently with the technical system, in order to achieve an even better trade-off. One important reason for this integration, from a condition-based maintenance perspective, is to coordinate tests implemented in the technical system (Built-in Tests, BIT) with tests that are external to the technical system and implemented at different echelons of the support system. See Söderholm (2005) for a further discussion about test integration and coordination in the design stage of complex technical systems.



In order that a system may perform according to the stated requirements, a number of functions need to be designed into the technical system. However, these required functions may degrade or become obsolete in the utilization stage, due to a degrading system condition or increased requirements. In this case the system experiences a failure or a fault. A fault is characterised as the inability of an item to perform a required function (IEV 191-05-01). A fault is a state which can be distinguished from a failure, which is an event, failure being the termination of the ability of an item to perform a required function (IEV-191-04-01). The reason for the classification of faults and failures is that an unsatisfactory condition can either be a real inability to perform a necessary function, or represent a judgment, based on physical evidence, that the item will soon be unable to perform such a function (Söderholm, 2005). A fault is the inability of a system to meet a specified performance standard, e.g. stated as punctuality requirements for transportation. This includes a total inability of the system to perform a specific function, as well as a situation where the system performs the function at a lower level than required (Söderholm, 2005). For example, a railway track fault may be characterised as the inability of the track to carry traffic, or as its inability to carry traffic at a dedicated speed. A failure is an identifiable physical condition which indicates that a fault is imminent. A failure is thus related to the fact that the system will, within a period of time, develop a fault (Nowlan & Heap, 1978; Söderholm, 2005). For example, degradation of the rail head is an identifiable physical condition which indicates that the rail (within a period of time) will lose its ability to carry traffic, or lose its ability to carry traffic at a dedicated speed. Hence, the degradation of the rail head is a failure. Failure of a technical system may be due to the degradation effects of its elements, which may be caused by ageing, the design configuration, the environment, or abuse of the system (Nowlan & Heap, 1978; Moubray, 1997; Coetzee, 1997; Markeset & Kumar, 2003; Söderholm, 2005).

One way to deal with failures and faults is maintenance, which is the combination of all the technical and administrative actions, including supervision action, intended to retain an item in, or restore it to, a state in which it can perform a required function (IEV 191-02-05). Maintenance activities are typically divided into corrective or preventive activities. Corrective maintenance is carried out after fault recognition and is intended to put an item into a state in which it can perform a required function (IEV 191-07-08). Preventive maintenance is maintenance carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of failure or the degradation of the functioning of an item (IEV 191-07-07). Preventive maintenance can be divided into predetermined maintenance or Condition-Based Maintenance (CBM). Predetermined maintenance concerns repair or replacements that are carried out at specific intervals, based on elapsed time, operating hours, distance, number of cycles or any other relevant measures (IEC 60300-3-14, 2004). CBM includes condition-based tasks that consist of condition monitoring, inspection and functional testing (IEC 60300-3-14, 2004).

To enable CBM, the health of the system must be monitored, i.e. by condition monitoring, which results in collected data that represent the system health in some way (Mobley, 1990; Martin, 1993; Campbell & Jardine, 2001; Söderholm, 2005). A simple form of condition monitoring is manual inspections. Condition monitoring technologies are in many cases used to detect signals similar to what human senses can detect, e.g. heat, noise or vibrations. For more extensive reviews of condition monitoring technologies applied within the railway, see Granström (2005) and Lagneback (2007). Diagnostics is concerned with the interpretation of the collected health data and the conclusion drawn about the system's current health (Martin,

1993). Based on the diagnostic information, decisions about CBM can be made (Mobley, 1990; Campbell & Jardine, 2001; Litt et al., 2000; Hess & Fila, 2002; Söderholm, 2005). An extension of diagnostics is prognostics, which (based on known degradation patterns, for example) tries to predict the future health of a technical system (Blanchard, 1995; Becker et al., 1998; Söderholm & Akersten, 2002).

Condition monitoring can improve the reliability performance of a technical system by supporting the management of redundancies, which in turn will ensure that the required functions are available (Söderholm, 2005). Condition monitoring can improve the maintainability performance of a technical system through enhanced fault diagnosis, which is the collective term for actions taken for fault recognition, fault localization and cause identification (IEV 191-07-22). Condition monitoring can improve the maintenance support performance of the support system, e.g. through the forecasting and planning of maintenance tasks by a joint consideration of the technical system's health, together with factors such as operation, maintenance capacity, economy and the risk of facing the consequences associated with a fault. However, it should be noted that there are also some drawbacks with condition monitoring. For example, an inadequate implementation of condition monitoring may lead to unwanted events such as false alarms and No-Fault-Found (NFF) events, of which the latter may erode any benefits that condition monitoring may have (Hawkins, 2002). See Söderholm (2007) for a review of the NFF phenomenon.

### 3 Research process

*This chapter describes the applied research process. First the research project is briefly presented, then the research process is divided into some publications that report on parts of the research. Hence, the chapter contains summaries of the author's licentiate thesis and the papers appended in this PhD thesis. Within each summary there are explanations of the methodological choices performed.*

#### 3.1 The research project

Based on the challenging scenario described in Chapter 1 (*Introduction*), Banverket has initiated research projects to explore how more effective and efficient maintenance can contribute to punctuality improvements within the Swedish railway sector. In April 2002 a research project at Luleå Railway Research Centre (JVTC) was initiated. The purpose of the project was to explore how the punctuality of the railway system could be improved by more effective and efficient maintenance (with a primary focus on infrastructure maintenance). The project was divided into two parts, i.e. Punctuality I and Punctuality II. The first part of the project (Punctuality I) focused on the exploration of different characteristics of train delay reporting and measurements to assess punctuality performance, see Nyström (2008). In January 2003, the European Union's Structural Funds (Mål 1) granted the project additional funds for a complementary perspective. This second part of the project (called Punctuality II) was initiated in May 2003 and was intended to focus more on the contribution of condition monitoring technologies to improved punctuality by means of more effective and efficient condition-based maintenance. This thesis is connected to the second part of the punctuality project, i.e. the Punctuality II project.

#### 3.2 The licentiate thesis

Granström, R. (2005). Maintenance for improved punctuality: a study of condition monitoring technology for the Swedish railway sector. Licentiate Thesis, Division of Operation & Maintenance Engineering, Luleå University of Technology, Luleå, Sweden.

#### Background

There are two milestones with major deliverables included in the second part of the research project described above (i.e. *Punctuality II*). The first major deliverable is the licentiate thesis, while the second major deliverable is this PhD thesis. The licentiate thesis was delivered in the middle of the project, while the PhD thesis concludes the project. This section summarises the licentiate thesis, which is available in full format through the website of the library at Luleå University of Technology, see <http://epubl.ltu.se/1402-1757/2005/88/index.html>.

#### Research questions

Three research questions of the licentiate thesis are:

1. How do train delay statistics reflect causes of failures useful for maintenance management?
2. How can a link between condition monitoring and punctuality be described?
3. How can current condition monitoring applications at Banverket support maintenance management?

## **Methodology**

The research presented in the licentiate thesis is divided into three parts:

- Archival analysis of punctuality and train delay statistics in Sweden. This approach is related to research question 1 of the licentiate thesis.
- Linking condition monitoring technologies to punctuality, through a combination of archival analysis of delay and punctuality statistics and analytical analysis (e.g. Failure Mode & Effect Analysis, FMEA) of some critical technical systems and their interfaces. This approach is related to research question 2 of the licentiate thesis.
- Condition monitoring case studies that explored the accuracy of different condition monitoring technologies. This approach is related to research question 3 of the licentiate thesis.

## **Findings**

From the performed studies, it was observed that monitoring technologies were most commonly used as protective devices, e.g. as go/no-go systems and not as systems to support condition-based maintenance. However, the information that was collected through monitoring systems could in some cases be used to support condition-based maintenance.

Furthermore, it was observed that, even though (in some cases) monitoring systems deliver accurate data on the conditions of the monitored items, applying condition monitoring technologies alone is not a natural enabler of improved punctuality. Monitoring technologies such as go/no-go devices, e.g. detector systems, have in many cases a negative impact on punctuality.

It was also observed how the stakeholders who could benefit from a certain type of monitoring data were not always the ones who possessed it. Hence, information collected by Banverket on the condition of the rolling stock could have been used by traffic operators to forecast and plan preventive maintenance activities.

Within the studies it was observed that the characteristics of the problems which some condition monitoring applications were implemented to solve, and the chosen condition monitoring applications were not in all cases compatible with each other. Thus, it was found that improper investigations of the characteristics of failures caused inadequate applications of technologies. Within the railway sector, there is definitely no shortage of the initiative to provide technical solutions to solve problems. Hence, there is probably no major problem in finding a possible solution to obtaining information about the health of technical systems. The problem may be more related to understanding the problem which monitoring technologies are to be applied to, in this case the problem of improving punctuality.

The licentiate thesis provided some insights into the capabilities of condition monitoring technologies. However, it was made apparent that merely applying technologies to manage single failure modes was insufficient for improving the punctuality. Hence, further research should not focus on the exploration of condition monitoring technology itself. Instead, further research should focus on what kind of condition information could support punctuality improvements. This research is presented in the appended papers and summarised below.

### **3.3 Paper 1**

Granström, R. & Söderholm, P. (2005). Punctuality measurements' effect on the maintenance process: a study of train delay statistics for the Swedish railway. Published in the proceedings of the 8<sup>th</sup> international conference and exhibition of Railway Engineering, 29<sup>th</sup>-30<sup>th</sup> June 2005, London, UK.

#### **Background**

The paper is based on a study of train delay statistics which was performed in order to identify which items (e.g. track, signals, turnouts or contact wires) in the infrastructure system had the greatest impact on punctuality and train delays. This study was intended to identify critical items within the infrastructure system that should be focused on in the remaining part of the research.

#### **Research question**

This paper relates to the following research question:

RQ 2. How can necessary system condition information be identified?

#### **Methodology**

This study is deductive in nature, as it explores the chain of events from system-level train delays to subsystem-level faults (e.g. the loss of function of track and contact wire). The data collection is based on archival data and informal interviews. The sources of evidence are derived from TFÖR (Banverket's train delay reporting system), OFELIA (Banverket's failure/fault report system) and discussions with people involved in train delay encoding and failure/fault reporting.

#### **Findings**

Within the study, comparisons between train delay statistics and failure reports revealed that delay statistics were not providing a representative picture of the influence of different items on train delays. Train delay reporting procedures were identified as the cause of the unrepresentative statistics. Hence, reporting procedures could result in the encoding of train delays being correlated to the symptoms of faults rather than the causes of faults. For example, contact wire faults, which were reported as the causes of most train delay time (compared with all the other infrastructure items), were in many cases caused by faults of the rolling stock's pantograph. However, the pantographs' contribution to train delays was not revealed in the delay statistics, since the train delays were attributed to contact wire faults rather than pantograph faults.

The paper highlights the risk of misguided maintenance and punctuality improvement efforts when using statistics that do not represent the root causes of faults. The paper also illustrates how the maintenance effort required by the infrastructure manager is affected by the maintenance effort conducted by traffic operators (and vice versa). From the study it was seen that effective punctuality improvements cannot be achieved by solely considering improvements of the infrastructure maintenance. Hence, improvements of punctuality through maintenance must, when interaction between systems is involved (e.g. at the interfaces between the wheel and the rail and between the contact wire and the pantograph), emanate from a holistic railway system perspective, where both the infrastructure and the rolling stock are considered jointly.

### **3.4 Paper 2**

Granström, R. & Söderholm, P. (2008). Condition Monitoring of Railway Wheels and No Fault Found Problems. Accepted for publication in international journal of COMADEM.

#### **Background**

The study on which this paper is based was initiated by Banverket. The purpose of the study was to assess the cause of the high number of No-Fault-Found (NFF) events connected to a wheel impact detection system. Defective railway wheels can cause severe damages to both track and vehicle items, which in the worst case scenario can lead to derailments with extensive losses. Banverket uses wheel impact detection systems to support the prevention of railway damages and their related losses, through the recognition of wheel defects and the generation of alarms. Wheel impact detection systems are used by Banverket as go/no-go devices, which provide the operators of the rolling stock with signals showing whether they can proceed (go) or whether they must stop to perform corrective maintenance actions (no-go). In the case of no-go signals, train delays emerge. These delays concern not only the train that triggered the alarm, but also other traffic that may be delayed by the stopping train.

The study was used by the author as a means to acquire more hands-on knowledge considering condition monitoring technologies and their use on both a national and international level.

#### **Research question**

This paper relates to the following research question:

- RQ 1. How can information about the condition of technical systems support the stakeholders within the Swedish railway in improving punctuality by means of more effective and efficient maintenance?

#### **Methodology**

The study combines experiences from the study initiated by Banverket with international experiences from wheel impact detection systems. The wheel impact detection study was performed in order to assess the reliability of the monitoring system. Hence, this study is inductive in its use of subsystem (wheel) data to explore the system operation. The data collection is both qualitative and quantitative. The sources of evidence are system data, archival records and document studies.

#### **Findings**

Wheel impact alarms are always followed by a manual inspection of the wheel by the train driver. The study revealed that all the alarms generated by the system were valid. Hence, the limitations of the manual inspections by train drivers were likely to be the cause of the NFF events. The study illustrates the necessity of considering testability requirements and ensuring that different test levels are coordinated when implementing new condition monitoring technologies. This test coordination is crucial in order to avoid No-Fault-Found (NFF) events, which can erode any potential benefits of the technological solution. Hence, when implementing new test technologies (e.g. condition monitoring technologies), their impact

on existing tests, included in both the technical system and its support system, must be considered and an adjustment of applied test strategies should be performed.

Utilizing the detection systems as go/no-go devices may be sufficient to fulfil the infrastructure manager's objectives (the prevention of railway damages and their related losses). However, the international experiences from the utilization of other wheel impact detector systems indicate that these detector systems also can be used as devices to support condition-based maintenance of the rolling stock. The same information as that used to provide traffic operators with go/no-go signals can also be used as a means to predict and plan rolling stock maintenance. Hence, a more proactive utilization of wheel impact detection systems would improve punctuality, since vehicles can be maintained before triggering no-go signals (enabling scheduled overhaul) and before causing corrective maintenance activities to be performed on the infrastructure (due to failure interactions). A more proactive utilization would also help to serve the combined business objectives of both the infrastructure manager and the traffic operators, since excessive degradation of bound capital (money invested in infrastructure and rolling stock, e.g. track, sleepers, wheel sets, and bearings) can be reduced. However, a more thorough utilization of the wheel impact detection systems requires more extensive cooperation between different stakeholders, i.e. the infrastructure manager and the operators. This cooperation would make the utilization of the systems more complex than it is today. Furthermore, it is not easy to identify the stakeholder that should take the responsibility of pursuing this kind of development. However, such development should lie within the common interest of the stakeholders. The reason for this is that both the effectiveness (doing the right things) and the efficiency (doing the things right) of their combined enterprise will determine the enterprise value for the end customer (i.e. how well the taxpayers' money is spent and how much the public and industry have to pay for freight charges and tickets). Hence, wisely applied condition monitoring technologies can contribute to the effectiveness and efficiency of the stakeholders concerned, which in turn will determine the competitiveness of the railway in relation to other means of transportation.

### **3.5 Paper 3**

Granström, R., Söderholm, P., & Kumar, U. (2008). A system and stakeholder view of maintenance for punctuality improvement. Accepted for publication in international Journal of Quality in Maintenance Engineering (JQME).

#### **Background**

In 2004 Banverket changed their train delay reporting procedures in order to obtain statistics that more accurately represent the root causes of faults. Statistical studies conducted on train delays showed that the top three infrastructure subsystems causing most train delay time are the contact wire, track and turnout. These subsystems are in direct physical contact with the rolling stock. Furthermore, the highest railway life-cycle cost is related to the wheel/rail interface. The functions, degradation rates and maintenance needs of these subsystems (the contact wire, track and turnout) are strongly dependent on the condition of the rolling stock and hence the maintenance effort conducted on the rolling stock. Furthermore, the experience from the licentiate thesis and Paper 2 indicated, for example, that detector systems can be used in order to support condition-based maintenance of rolling stock, which, if effectively executed, will have a positive effect on the degradation rate and thus the need for maintenance and the functions of the rail. However, even though knowledge of the use of

detector system data, for example, to support condition-based maintenance of rolling stock has been available for some time, little progress seems to have been made in using such data. Hence, it became clear that knowledge of how condition monitoring technologies can support the maintenance of the system is by itself not a natural solution to the problem of improving punctuality. The problem is also stakeholder-related. In other words, condition monitoring technologies will not be applied to support punctuality improvements by means of more effective and efficient maintenance unless the stakeholders find it rational to do so. Therefore, from this point on, the stakeholders' perspectives on the problem were also included in the research. In order to obtain an overall view of the problem, it became interesting to explore whether the railway context motivates stakeholders to improve punctuality by means of more effective and efficient maintenance; in addition to exploring how condition information can be used to support punctuality improvements within the railway context.

The purpose of Paper 3, which is a conceptual paper, is to describe the implications and possibilities of improvement of railway punctuality by means of more effective and efficient maintenance, considering technical systems and stakeholder interrelations within a Swedish railway context. This paper describes how availability performance measures (e.g. train delay performance, illustrated in Paper 1) and performance measures derived from condition monitoring technologies (e.g. detector systems, described in Paper 2) can support improvements of punctuality within the context which the technical and stakeholder systems of the railway sector are bound to interact within.

### **Research questions**

This paper relates to the following research questions:

RQ 1. How can information about the condition of technical systems support the stakeholders within the Swedish railway in improving punctuality by means of more effective and efficient maintenance?

RQ 2. How can necessary system condition information be identified?

### **Methodology**

A generic system lifecycle model is derived from national and international standards to illustrate how important stakeholder requirements for system services (e.g. punctuality of transportation) are affected by central processes in the lifecycles of the technical systems (i.e. the rolling stock and infrastructure). This system lifecycle model supports an exploration of how the fulfilment of the infrastructure manager's performance objectives is affected by interrelationships between infrastructure maintenance contractors and traffic operators. These interrelationships are used to highlight the impact of the railway context on maintenance and the role of maintenance in punctuality improvement throughout the railway system's lifecycle.

### **Findings**

The fulfilment of required improvements of the railway system's performance can be jeopardized if the stakeholders' interrelationships are neglected. The study proposes the use of incentives in combination with adequate performance measures (derived from both availability performance measures and condition monitoring technologies) to stimulate the stakeholders to put adequate efforts into the technical systems' lifecycle processes. This should



facilitate an alignment of the technical systems' performance objectives with the profit goals of the stakeholders. In other words, the paper illustrates how availability performance measures and condition monitoring performance measures can be used as management tools to enable and enforce fulfilment of availability and interaction objectives from stakeholders.

### **3.6 Paper 4**

Granström, R. (2008). A system and stakeholder approach for the identification of condition information: a case study for the Swedish railway. Accepted for publication in: *International Journal of Rail and Rapid Transit*.

#### **Background**

Paper 3 considered the use of both availability performance measures and performance measures derived from condition monitoring technologies as management tools to enable and enforce performance enhancement activities from stakeholders. For further research upon availability performance measures, see e.g. Nyström's (2008) and Åhrén's (2008) overviews of applicable availability indicators within a railway context.

Paper 4 is based on a case study which in essence explores the same problem as that explored in Paper 3. However, it is a more detailed exploration of subsystems' and stakeholders' interrelations, and is intended to provide validity for the reasoning in Paper 3. Paper 4 is provided to widen the perspective of the utilization of condition monitoring technologies, as it incorporates both a system and a stakeholder perspective on the identification of information needs. Hence, it explores why information is needed and what information the stakeholders need in order to enable adequate maintenance and punctuality improvement efforts. The paper is a continuation of Papers 1, 2 and 3 in terms of technical system and stakeholder interrelations and the utilization of condition monitoring technologies as tools to support system performance enhancement activities performed by stakeholders. Paper 2 provided an illustration of how condition monitoring technologies that are primarily applied to serve the infrastructure manager's objectives can provide a greater value if information can be more effectively utilized by traffic operators. However, applying a monitoring solution to manage a single failure mode (e.g. wheel flats) will not be sufficient to manage the variety of failure modes that can cause failure interactions, loss of system functions and train delays. The maintenance-related punctuality problem that is under scrutiny in this paper is related to the contact wire/pantograph interface. This interface is chosen since the contact wire is the most critical infrastructure subsystem from a punctuality perspective. The purpose of this paper is to identify the stakeholders' need for system condition information in order to improve railway punctuality. The paper provides a holistic formulation of maintenance-related punctuality problems within the interface between the contact wire and the pantograph. From the identified problem formulation, the information needed to support the maintenance of technical functions can be identified. The incorporated system and stakeholder perspective adds a dimension to the description of what information is needed and why it is needed. The system and stakeholder perspective on the assessment of the information need can serve as decision support when acquiring new condition monitoring technologies. Based on the problem formulation, this perspective can also serve as an illustration of how information is to be used to improve punctuality.

## **Research questions**

This paper relates to the following research questions:

- RQ 1. How can information about the condition of technical systems support the stakeholders within the Swedish railway in improving punctuality by means of more effective and efficient maintenance?
- RQ 2. How can necessary system condition information be identified?

## **Methodology**

The first part of the study was a deductive exploration of contact wire fault statistics and train delay statistics. This part of the study was performed to obtain a perception of the problems related to the contact wire/pantograph interface. However, due to the observed inability of the statistics to represent the causes of faults (due to the difficulty of reporting root causes, e.g. the problems observed in Paper 1), the deductive approach could not be taken further. Hence, an inductive approach was applied as a complement. To formulate the problem description for the contact wire/pantograph system, a Failure Mode and Effects Analysis (FMEA) was applied. Other examples of inductive methodologies are: Preliminary Hazard Analysis (PHA), Hazard and Operability Studies (HAZOP), Functional Failure Analysis (FFA) and What-If (a brainstorming exercise). FMEA is, however, a well-established and structured approach which has been proven useful for the purpose of identifying relevant condition monitoring information, see Söderholm (2005). To include the stakeholders' perspectives on the need for system condition information, the subsequent part of the study involved informal interviews with contact wire and pantograph experts. During the interviews, the interviewees had the chance to reflect on the results from the FMEA effort. Additional information from the interviewees was then incorporated into the study.

## **Findings**

The study resulted in the identification of seven contact wire failure modes and four pantograph failure modes that must be managed in order that the system may provide its required service. In addition, the presently used condition monitoring technologies and the information needed to control the failure modes were also identified. The study illustrates how the maintenance effort conducted by one maintenance contractor can affect another contractor's required maintenance effort through failure interactions with rolling stock. Hence, these illustrations are used to describe why the symbiosis between the stakeholders must be acknowledged in order to improve punctuality. The illustrations are also useful for the explanation of why incentives are needed to stimulate stakeholders and why condition information is needed in order to assess stakeholders' ability to control failure modes. The study also presents how the same information can be used by different stakeholders to cope with their different responsibilities, which is useful to consider when acquiring condition monitoring technologies. For example, the same information can be used by:

- Banverket; to assess whether the operators and contractors are performing adequately to prevent the occurrence of failure modes.
- The operators and contractors; to assess the degradation of their respective systems, in order to assess when and where maintenance is to be performed to prevent failures.
- Banverket; to obtain adequate decision support for future modifications and reconstructions of the infrastructure system.

- Banverket; to generate decision support for their process of constructing regulations or constructing contracts with economic incentives.

The contribution of the paper, in addition to the attempt to construct a holistic problem formulation of the contact wire/pantograph interface and apply the stakeholder perspective on the information needed, is the exploration of the methodology used within the study. It is believed that the methodology is applicable to the rail/wheel interface, as well as to other stakeholder and subsystem interfaces.

### **3.7 Paper 5**

Granström, R. (2008). Scientific maintenance management for improved railway punctuality. *Submitted for publication.*

#### **Background**

As described in Papers 1-4, availability performance measures and interaction performance measures (derived from condition monitoring technologies) can contribute to the control of stakeholder interrelations and the support of maintenance of the technical system in order to stimulate and enable system performance improvements. Hence, these papers all illustrate how information can be used in order to support punctuality improvement. However, experiences from the licentiate thesis indicated that, without a structured approach to the application and utilization of condition monitoring technologies, there is a risk that potential benefits of the technological solutions will be lost. For example, condition information may not be utilized or maintenance efforts may be ill directed due to, for example, erroneous maintenance task thresholds, failure modes not considered, the measurement of wrong parameters or the inability to transform information into adequate maintenance tasks.

Based on the findings of Papers 1-4, together with experiences from the licentiate thesis, the final research question was formulated as: “How can stakeholder interrelations and the introduction and utilization of condition monitoring technologies be managed to improve punctuality?” Knowing that the effort required to obtain any conclusive answer to this question would require a whole PhD thesis by itself, this paper could be considered as a source of inspiration for further research within the field. The paper provides a possible scenario in which stakeholder interrelations and the introduction and utilization of condition monitoring technologies can be managed to improve punctuality.

The paper adds a historical perspective on contemporary railway maintenance management through the application of a management methodology that was launched almost 100 years ago. Taylor’s Scientific Management is within this paper used to provide this historical perspective. Even though no attempt is being made to advocate that Scientific Management is the ultimate approach to managing railway maintenance, there are still many similarities between the problems facing contemporary railway management and the problems facing Taylor at the time for the development of Scientific Management. Hence, these similarities encouraged the development of this paper, which can be used as a source of inspiration to seek already known remedies to known problems instead of trying to invent new remedies. A wide use of performance measures was developed during the Scientific Management movement. Even though contemporary condition monitoring technologies can provide performance measures unheard of at the beginning of the 20<sup>th</sup> century, illustrations seek to show that

methods that were developed at that time for introducing and utilizing performance measures can perhaps still be valid within a modern context.

### **Research questions**

This paper relates to the following research questions:

RQ 1. How can information about the condition of technical systems support the stakeholders within the Swedish railway in improving punctuality by means of more effective and efficient maintenance?

RQ 3. How can stakeholder interrelations and the introduction and utilization of condition monitoring technologies be managed to improve punctuality?

### **Methodology**

The principal-agent problem is used to connect objectives, performance measures and incentives with railway maintenance requirements, with a focus on the role of condition monitoring. An implementation and utilization approach to condition monitoring to manage stakeholder actions and thereby the fulfilment of the overall railway objectives is also outlined. This approach is influenced by theories of Scientific Management and a generic maintenance process. Empirical material is collected from the Swedish railway through archival analysis, interviews and document studies.

### **Findings**

There are a number of obstacles to the performance of railway maintenance, e.g. different stakeholders with heterogeneous interests and responsibilities, as well as a lack of appropriate decision information. A Scientific Maintenance Management approach can be supported by accurate and objective decision information derived from condition monitoring technologies. This approach supports an alignment of separate stakeholder objectives with the maintenance requirements of the technical systems. These system requirements must be fulfilled to enable effective and efficient maintenance management, and thereby improved railway punctuality.

## 4 Conclusions

*The purpose of this research has been to explore and describe how information about the condition of technical systems can support stakeholders within the Swedish railway in improving punctuality by means of more effective and efficient maintenance. In this chapter the discussions will summarise some conclusions that may be drawn from the performed research. Since the research questions were formulated to support the fulfilment of the research purpose, the conclusions relate to the stated research questions.*

### 4.1 Research question 1

The first research question was formulated as: “How can information about the condition of technical systems support the stakeholders within the Swedish railway in improving punctuality by means of more effective and efficient maintenance?”

The punctuality of the railway system is dependent on a combination of required functions that simultaneously must be provided by different stakeholders. In this thesis three primary stakeholders have been considered: the infrastructure manager, the infrastructure maintenance contractors and the traffic operators. All the papers appended in the thesis illustrate the symbiosis between these stakeholders, as well as between the two railway subsystems, the infrastructure and the rolling stock.

For the railway system to deliver the right quality of the transportation service to freight and passenger customers (with regard to the quality dimension of punctuality), the following considered stakeholders must contribute some efforts to establish a successful triad:

- The infrastructure manager bears the overall responsibility for the functions of the railway system. Hence, the infrastructure manager must provide the infrastructure maintenance contractors and the traffic operators with an operational environment that enables and stimulates them to provide the required functions of their respective subsystems (i.e. the infrastructure and rolling stock respectively).
- The contractors and the operators must provide an operational availability of their respective subsystems that supports an operational environment that allows them to perform scheduled activities in accordance with the agreed timetable.
- The contractors and operators must also ensure a required interaction between their respective subsystems, i.e. the rolling stock and the infrastructure. This will support an operational environment where the required functions are achieved and the degradation of bound capital (money invested in contact wires, rails, turnouts, wheels and pantographs, for example) is both predictable and acceptable.

The information required for the assessment of the infrastructure manager’s, contractors’ and operators’ ability to support a satisfactory operational environment is: availability performance measures and condition information. The condition information represents the health of items within the wheel/rail and the contact wire/pantograph interfaces. See Papers 2-5.

The railway context can affect the operators’ and contractors’ motivation to provide subsystems with the required functions (see Papers 3-5). An unwanted context may emerge if necessary requirements are lacking or stated requirements are ambiguous, if it is difficult to as-

sess the fulfilment of stated requirements, or when there are no financial implications linked to the fulfilment of stated requirements (see Papers 3, 4). In such an unwanted context, it can become a competitive disadvantage for profit-driven entities (contractors and operators) to provide functions in accordance with the infrastructure manager's objectives when competing with other entities that do not provide functions that fulfil the objectives (Paper 3).

The following are proposals as to how information about the technical systems' condition can contribute to a desired context by providing ways to support the stakeholders in improving punctuality by means of more effective and efficient maintenance within the railway context:

- The infrastructure manager can use availability performance measures and condition information (representing the health of items within the wheel/rail and contact wire/pantograph interfaces) to assess whether the operators and contractors are being provided with an operational environment where their respective subsystems can deliver the required functions. The same information can be used to assess the fulfilment of requirements made on the maintenance contractors and traffic operators. In addition, incentives connected to the fulfilment of requirements can be used to align the profit goals of the stakeholders with Banverket's punctuality objectives. Hence, these incentives can serve as a motivation for operators and contractors to provide the required functions. In addition, the infrastructure manager can also combine the condition information with other information, e.g. from failure reports or economic systems, to generate decision support for modifications of the infrastructure system or for adjusting rewards or penalties related to the performance of the other stakeholders.
- The contractors and operators can use the same condition information as Banverket uses to assess their performance to support the planning and forecasting of necessary maintenance of the infrastructure and the rolling stock (the only difference being the information's level of detail), see Paper 4. The information can be used to support all the activities in every phase of the maintenance process, see Paper 5.

## **4.2 Research question 2**

The second research question of this research was formulated as: "How can necessary system condition information be identified?"

Within the research presented in this thesis, one systematic approach to identifying necessary condition information has been applied. This approach can be described as a process consisting of a number of phases and activities that are supported by appropriate methodologies and tools. A more detailed description of this process can be found in Chapter 3 (*Research Process*). In this section the activities are briefly summarised in relation to Papers 3 and 4. The activities related to Paper 3 can be described as:

- Identifying what to accomplish, i.e. improving punctuality by means of more effective and efficient maintenance.
- Identifying the subsystems that cause most train delay time. This can be accomplished through studies of train delay statistics. However, train delay statistics can be deceptive, by providing a measure of the symptom rather than the disease (see Paper

1). Therefore, it is necessary to obtain an understanding of what the statistics represent and how they are gathered, in order to estimate the validity of the statistics and to avoid bad decisions. Reports of fault causes can facilitate the validation process, see Papers 1 and 4.

- Identifying the stakeholders that affect the required functions of the identified subsystems through maintenance activities. This can be accomplished by investigating the railway context and thereby identifying those responsible for the respective assets. In this research, three stakeholders were identified, i.e. infrastructure maintenance contractors, traffic operators and the infrastructure manager (involved in the contracting of infrastructure maintenance).
- Identifying what the respective stakeholders must provide to enable the system to support the delivery of the right quality of service (e.g. the punctuality of the railway transportation service). Here the system lifecycle model (which is based on national and international standards) is useful in serving as a structure for the identification of what the stakeholders must provide (Paper 3). For example, a maintenance contractor must (in the system utilization and support phase) provide the functions that are required to achieve the desired operational availability and proper interaction with the rolling stock. An operator must (in the system utilization and support phase) provide the functions that are required to achieve the desired operational availability and proper interaction with the infrastructure. The infrastructure manager must assure that the contractors and operators provide the required functions of their respective subsystems. In addition, the infrastructure manager must assure that proper maintenance is sufficient for providing the required functions of the infrastructure. If proper maintenance is not adequate, modifications or procurement of new infrastructure items is necessary. In the same way, if the proper maintenance of the rolling stock is not adequate to provide the required functions, modifications or procurement of new items is necessary. This is one reason why the lifecycle view is valuable.
- Identifying information that is relevant to assessing whether the contractors and operators provide the required functions during the systems' utilization and support phase. Since the stakeholders must provide the functions that are required for the achievement of the desired operational availability and interaction behaviour, it is measures that reflect these two aspects that should be obtained (Paper 3 and Paper 4).
- Identifying the contractors' and operators' motivation for providing the required functions. This involves taking into consideration the rules of the game within the railway context. One fundamental factor that has driven the deregulation of the Swedish railway is the fact that both the contractors and the operators are profit-driven entities. Hence, a rational behaviour for these entities is to adapt their activities to the context so that they generate profit. If the entities cannot generate profit, or achieve competitive advantages, by providing the required functions, a rational behaviour may be not to provide the required functions.
- Identifying how the identified information can be used to support punctuality improvements within the railway context. Once again, the rules of the game should be acknowledged. Hence, to enable the contractors and operators to generate profit by providing the required functions, economic incentives connected to the fulfilment of requirements are needed. The fulfilment of stated requirements can be assessed by utilizing the identified information.

Paper 3 primarily considered the use of two types of information, i.e. measures of availability performance and interaction behaviour. For further research on issues related to the identification of relevant availability performance measures, see Nyström (2008) and Åhrén (2008). A further exploration of the identification of necessary condition information can be found in Paper 4. Within Paper 4, a similar set of activities as that described in Paper 3 was applied to identifying the necessary condition information. The activities related to Paper 4 can be described as:

- Identifying what to accomplish, i.e. reducing train delays related to the contact wire. In order to identify what to accomplish more specifically, the required functions of the system must be acknowledged. The main required function of the contact wire is to transfer electric energy properly from the infrastructure to the rolling stock.
- Identifying the primary causes of contact wire faults and their effect on train delays. This can be accomplished by linking fault data to train delay data. This linkage supports the identification of the main causes of train delay time related to the contact wire. This analysis showed that pantograph faults caused 40 percent of the contact wire faults. However, due to difficulties in identifying the root causes of faults (e.g. due to problems observed in Papers 1 and 4), this approach only provides a general perception of the problem.
- Identifying the stakeholders who affect the required functions of the contact wire. As in Paper 3, the identified stakeholders were: the infrastructure maintenance contractors, the traffic operators and the infrastructure manager.
- Identifying what the stakeholders must provide to ensure that the required function of the contact wire is fulfilled. This can be accomplished by considering what item functions must be sustained to transfer electric energy properly from the infrastructure to the rolling stock. Failure Mode and Effects Analysis (FMEA) is a methodology that can be used for this identification.
- Identifying the condition information that is necessary to assess the stakeholders' ability to provide the required functions. This can be accomplished in the FMEA by an identification of the information that is necessary to assess the absence of required functions (i.e. failure modes).
- Identifying what condition information the stakeholders need to provide the required functions. This can be accomplished by complementing the FMEA through interviews with experts involved in the maintenance of the contact wire and pantographs.
- Identifying how the interrelations of the subsystems (the contact wire and pantograph) and the stakeholders affect the operators' and contractors' motivation to provide the required functions. Causal maps derived from the FMEA can be used to illustrate the subsystems' and stakeholders' interrelations. It was shown that, even though a contractor may prevent existing failure modes, this does not guarantee that the contractor will be able to provide the required contact wire function. The reason for this is that the contractors' ability to succeed is affected by both the operators' and the other contractors' maintenance efforts.
- Identifying how the information can be used to support the stakeholders in providing the required functions, e.g. a proper transferral of electric energy from the infrastructure to the rolling stock. As in Paper 3, the rules of the game and the responsibilities of the stakeholders must be acknowledged. Hence, financial implications linked to the fulfilment of requirements (the requirements for controlling failure modes) are necessary to motivate the operators and contractors to provide the required functions



and to allow them to benefit economically from excelling in their maintenance practices. Furthermore, the contractors and operators can use the same information to facilitate the application of condition-based maintenance of the infrastructure and rolling stock respectively.

### 4.3 Research question 3

The third research question was formulated as: “How can stakeholder interrelations and the introduction and utilization of condition monitoring technologies be managed to improve punctuality?”

A possible scenario in which stakeholder interrelations and the introduction and utilization of condition monitoring technologies can be managed is presented in Paper 5. The proposed structure is based on the four principles of Scientific Management, which are related to a generic maintenance process, see Figure 2.

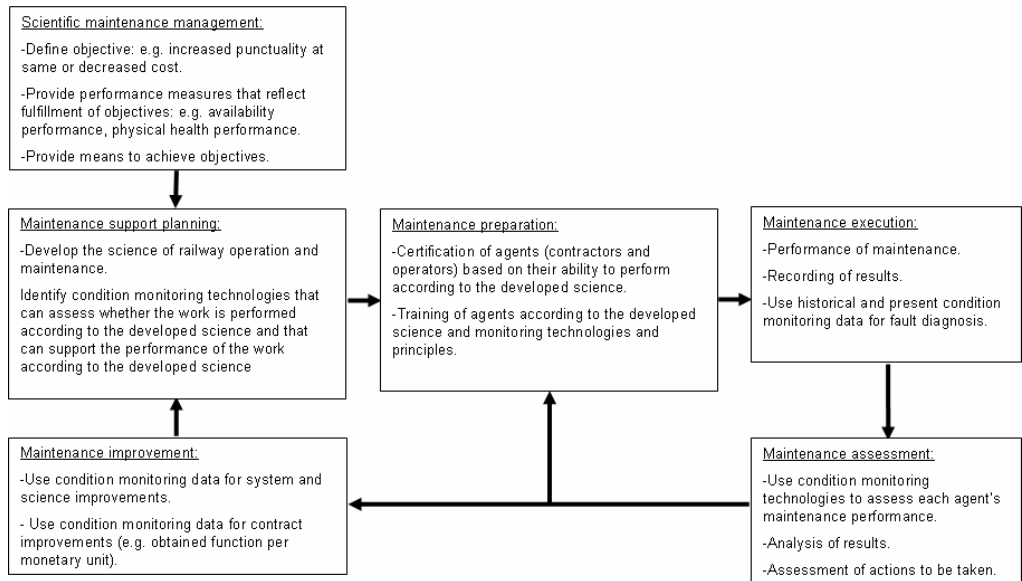


Figure 2. A generic maintenance process inspired by IEC 60300-3-14 (2004) and adapted to structure an introduction of condition monitoring technologies and subsequent stakeholder actions required to obtain railway objectives.

Figure 2 illustrates an adaptation of a generic maintenance process provided in IEC 60300-3-14 (2004). The process is applied in order to structure an introduction and utilization of condition monitoring technologies. The four principles of Scientific Management are subsequently applied within the process and adapted to suit a modern railway context:

1. Developing the science of operation and maintenance of railways, which is connected to the maintenance support planning phase, see Figure 2. This entails scientific investiga-

tions of aspects such as the degradation behaviour of items within the system. This science should consider the rolling stock and the infrastructure jointly.

2. Careful selection and subsequent training of infrastructure maintenance contractors and traffic operators according to the developed science, which is connected to the maintenance preparation phase, see Figure 2. The selection will involve a certification of the contractors' and operators' ability to provide the desired quality level of the services, e.g. the ability to provide the desired level effectively (the right quality of work) and efficiently (within the provided time frames).
3. Bringing the science and the selected contractors and operators together, which is related to the maintenance preparation phase, see Figure 3. This involves rigorous cooperation between the infrastructure manager, the operators and the contractors to ensure that all the work is being carried out according to the principles of the developed science. One example of this cooperation is the infrastructure manager's support to and training of operators and contractors. Contractors and operators who are able to perform according to the developed science should be substantially rewarded for their efforts.
4. An almost equal division of the work and responsibility between managers and workmen. This means that the managers apply the developed Scientific Management principles to plan the work and that the workmen perform it. On an organizational level and in a railway context, this can be compared with a situation where the infrastructure manager performs the maintenance support planning phase and the other operators and contractors perform the maintenance preparation and maintenance execution phases.

## 5 Discussion and further research

*This chapter includes a discussion about the contributions, limitations and validity of the performed research. In addition, some proposals for further research are incorporated. The discussion is divided into two subsections. Section 5.1 is related to the problem domain, i.e. how the research contributions can be generalized. Section 5.2 is related to the application area, i.e. the railway sector.*

### 5.1 Problem domain

Within this thesis, the degree of punctuality is determined by a combination of required functions that are delivered by three different stakeholders. Throughout the research process, the problem to be solved has increased in complexity. Initially, the research covered aspects of punctuality, condition monitoring technologies and infrastructure items. However, over time the research evolved to cover a wider problem area including punctuality, condition monitoring, the infrastructure, the rolling stock, the interaction between the rolling stock and the infrastructure, stakeholders, stakeholders' interrelations, requirements, incentives and management. Simultaneously, as the complexity of the problems increased, the problems to be solved seemed to become more general and fundamental.

In relation to this, one statement within Scientific Management (Taylor, 1911) has especially caught the attention of the present author: "It is useless to assign a task unless at the same time the adequate measures are taken to enforce its accomplishment." The provision of means for accomplishing tasks can be related to the phenomenon studied in this research, which makes some aspects interesting to consider. For example, it might be the case that the considered stakeholders are not provided with sufficient means to accomplish their tasks. The infrastructure maintenance contractors and traffic operators might not be provided with an operational environment where they can provide the required functions. Furthermore, the operator entities and contractor entities are profit-driven and might perhaps not be sufficiently rewarded for their efforts to provide the required functions. It might also be the case that the infrastructure manager's stated requirements do not provide a satisfactory operational environment even when fulfilled. Furthermore, the infrastructure manager might be unable to assess the operators' and contractors' ability to fulfil the stated requirements.

These uncertainties and doubts emerged while communicating with people within the Swedish railway sector. It was even questioned if Banverket could impose the necessary requirements on other stakeholders, e.g. the traffic operators. One reason why Banverket might be unable to impose necessary requirements on some stakeholders is often claimed to be that these requirements by themselves can affect the competition and interoperability among profit-driven entities. If Banverket were unable to impose the necessary requirements on other stakeholders, this might be due to the fact that Banverket is not provided with the means to achieve its objectives. Therefore, the competitive system, whose purpose is to reduce the waste of both human labour and natural resources, might actually be a subsidiser of waste. Hence, the competitive system might not be providing the means to achieve the objectives.

It might be useful to contemplate the above discussion by considering William Edwards Deming's discussion about the appreciation for a system (Deming, 1982, 1993). According

to Deming, the appreciation for a system involves an understanding of how interactions (i.e. feedback) between the elements of a system can result in internal restrictions that force the system to behave as a single organism that automatically seeks a steady state. It is this steady state that determines the output (e.g. the punctuality level) of the system rather than the individual elements. Thus, it is the structure of the organization, rather than the employees alone, which holds the key to improving the quality of output.

The fundamental problem at hand seems to be that in order to obtain any effective improvements, efforts must focus both on the technical systems' need for maintenance as well as on the organizational structure. Papers 1-4 appended in this thesis have been used to gain an understanding of the problem of improving punctuality through maintenance. Rather late in the research process (the autumn of 2007), through the guidance of a guest lecturer at the Division of Operation and Maintenance Engineering, it came to the author's attention that there is a concept called agency theory. This theory has a great resemblance to the problems being described in Paper 3. At this point, the research really started to become interesting. The reason was that the theory offered the opportunity to describe the railway specific problem as a problem of a much more general character. Agency theory research focuses on the optimal contractual relationships, behaviour versus outcome, between the principal and the agent (Ackere, 1993), e.g. between Banverket (the principal) and the contractor (the agent). Examples of issues included in agency theory are:

- Moral hazard. Agents can act opportunistically, due to information asymmetry between the principal and the agent. Moral hazard refers to a lack of agent effort. The agent does not make the effort agreed upon because the objectives of the two parties are different and the principal cannot assess the actual level of effort that the agent has expended.
- Monitoring can be used by the principal to counteract the moral hazard problem. For example, the principal can monitor the contractor's ability to control failure modes (Paper 4). Hence, monitoring provides information about the agent's actual actions.
- Incentives can be used by the principal to reward the agent for performing acts that are useful to the principal. In this way, it is possible to align the interests of the agent with the interests of the principal.
- Contracts that are designed so that they consider issues like those discussed above are a challenge that lies at the heart of the principal-agent relationship.

Even though time was scarce, an effort was made to incorporate elements of the agency theory in Paper 5. As such, Papers 1-4 of this thesis can perhaps be regarded as complementary perspectives on principal-agent problems, through the description of how the relations between the principal and the agent can impair the technical system's required functions. Papers 3 and 5 can also be regarded as approaches to solving principal-agent problems. Therefore, the approaches used in this thesis can hopefully also serve as an inspiration for further research to create complementary perspectives on and solutions to principal-agent problems.

The studies of available empirical information in this thesis can perhaps be regarded as generic. Punctuality has been the application area for which information has been studied to obtain improvements. When considering what the underlying problem of punctuality improvement actually is, it is realised that punctuality is only an example of a more generic problem. If the delimitations of the research were to be stripped away, the studies of infor-

mation could perhaps be relevant to other studies related to improvements of, for example, safety, cost and environmental impact. Hence, the underlying problem is highly related to agency theory, where the fundamental problem is not only related to the identification of what can and should be accomplished in terms of work, but also related to the provision of the means for stakeholders to accomplish their responsibilities, considering the rules of the game, e.g. those that governments stipulate through deregulation and the introduction of competition among agents. Hence, the problem is related to the provision of an environment where competing agents can fulfil their assigned tasks at the same time as they can obtain sufficient profits and competitive advantages by providing the required services. Even though there may be other solution approaches to controlling agents so that they may act in the best interests of the principal, this thesis has proposed the use of condition information to overcome some of the moral hazard problems that can arise due to the information asymmetries between agents and principals. Within the railway, the use of condition information could be particularly useful, since the agents need the same information to execute their required tasks successfully. Hence, the information would be used both to provide the means to accomplish the required tasks, and to control the principal-agent relationships.

The work presented in this thesis has pursued the purpose of the research, which was to explore and describe how information about the condition of technical systems can support stakeholders within the Swedish railway in improving punctuality by means of more effective and efficient maintenance. Empirical and theoretical materials have been studied as a means both to gain an understanding of the difficulties involved with punctuality improvements and to support the improvement of punctuality. Empirical data have been collected through interviews, observations, measurements, workshops and databases. The analyses have been performed through developed lifecycle and process models, as well as explorative data analysis and Failure Mode and Effects Analysis (FMEA). The studies have been performed in close interaction with persons who have expertise in different fields, which supported the data collection and analysis with both input and review. Hence, the validity of the results of the performed studies has been strengthened.

The performed studies have mostly considered a Swedish railway context. Hence, it can be difficult to generalize the results to other railway contexts. However, it is believed that the applied study approaches can be relevant both to other railway contexts and to other industries, as well as other fields of research. Further research could explore how modelling the interrelationships of the technical and stakeholder systems can be applicable to businesses where multiple organizations are dependent on each other to succeed in their individual tasks, since the competitiveness and the price of the end product (goods, a service or any combination thereof) are determined by the success of their combined efforts. Here, the primary industries are those that are dependent on capital-intensive and complex technical systems with a long lifecycle, e.g. aviation, power generation and distribution, pulp and paper, and steel and mining.

## **5.2 Application area**

The three main subsystems that cause train delay time within the Swedish infrastructure system are the contact wire, tracks and turnouts. These subsystems are in direct physical contact with the rolling stock. Hence, their degradation rates and functions are heavily dependent on the condition of the rolling stock's wheels, bogies and pantographs. These subsystem interfaces (i.e. the wheel/rail and contact wire/pantograph interfaces) are also the organizational interfaces between the infrastructure manager, maintenance contractors and traffic operators. However, even though these organizational interfaces may be convenient from some aspects, they may be far from optimal when considering punctuality aspects. Hence, it would perhaps be beneficial to separate the interfaces between organizational responsibilities and the critical interfaces of the technical systems from each other. For example, it would perhaps be better if Banverket owned the wheels, bogies and pantographs of the rolling stock, and then the interfaces between the organizations would instead be located to the roof and the floor of the carriages, which are less dynamic (Lagnebäck, 2007). This separation of interfaces would not change the required maintenance effort. However, a joint consideration of both rolling stock and infrastructure maintenance would probably be facilitated. It may even be the case that a joint consideration of rolling stock and infrastructure maintenance would be best facilitated within a single-organization system. This may be one reason why some railways (e.g. the British) have reversed the efforts of deregulation.

This research has to a great extent been focused on creating a scenario in which condition information is used to support punctuality improvements. However, before condition information can be used effectively to support improvements of punctuality, a great deal of further research is required. As shown in this thesis, condition information can be used to assess the fulfilment of requirements made on railway stakeholders, at the same time as it can be used to support stakeholders in fulfilling requirements.

Further research is required to assess what requirements for system functions must be fulfilled in order that stakeholders may provide the required system services; for example assessment of the availability levels that must be provided, and assessment of the physical tolerances which wheels/rails and contact wires/pantographs should operate within to guarantee the required availability at a minimal cost. Concerning the physical tolerances, the formation of requirements is a matter of assessing the physical boundaries which materials should be allowed to degrade within. This is closely related to what in Paper 5 is described as the qualitative development of the science of operation and maintenance (see Paper 5). This could, for example, be facilitated through a design-of-experiments approach, where high-resolution sensor technologies would be used to record the behaviour of, for example, the contact wires and pantographs in a real operating environment (e.g. on the Iron Ore Line in northern Sweden and Norway). Examples of parameters to record are the horizontal and vertical displacement of the contact wire, the carbon slipper condition (see Paper 4) and climate factors, such as the temperature and air humidity. Data obtained from these recordings could be used to create mathematical degradation models, which could be used for prognostic purposes. Hence, prognostic information derived from the mathematical models could be used to assess the time frames within which maintenance has to be carried out to guarantee the functions of the system. These mathematical models are necessary to determine the physical degradation boundaries, and therefore also to determine what requirements to impose on stakeholders. Further research is also required to identify measurement methods that can be used

to assess the stakeholders' ability to fulfil requirements for system functions; for example identification of the condition monitoring methods that can reflect the operators' and contractors' ability to provide wheels and rails within the prescribed physical tolerances (see, Paper 2 and Paper 4). Mathematical models will here also be essential to determine the monitoring effort required in a real operating context. Hence, they can provide indications of how often, for example, contact wire monitoring has to be performed and what measurement resolution and measurement frequency monitoring systems should provide. Further research is also necessary to evaluate how condition data should be stored and distributed, and how the data should be transformed into information which can act as decision support for maintenance planning and execution. This is closely related to what in Paper 5 is described as the quantitative development of the science of operation and maintenance (see Paper 5). These aspects are essential to consider in the condition monitoring procurement process.

Further research is also needed in order to assess how, for example, availability and interaction performance measures should be related to financial implications, in order to align the interests of, for example, the contractors and operators with those of Banverket. Hence, further research is required to evaluate different contractual models depending on the ability to monitor performance.

In order that condition monitoring applications may reach their full potential, a more comprehensive mapping of the stakeholders and their information need is required. For example, Banverket uses consultancy agencies for constructing new infrastructure systems or for making modifications in existing infrastructure systems (see Paper 4). Hence, further research could explore how Banverket could use condition data and mathematical modelling to create information useful for their formation of requirements for consultancy agencies. It could also be useful to explore how infrastructure consultancy agencies and manufacturers of rolling stock items could benefit from monitoring data. Hence, such data could, through the creation of mathematical models, provide them with information for the modification process of existing items and for the development of new items. Further research will probably be necessary to explore how subcontracting within traffic operation entities (i.e. when leasing rolling stock or using subcontractors to maintain the rolling stock) should be dealt with, when forming the requirements to be made on traffic operators during the operation and support phase.

Further research could also in greater detail explore if the proposed methodology involving the use of FMEA, with complementary perspectives derived from interviews with experts in the field (used in Paper 4), could be applicable in the identification of information that is relevant to controlling the interfaces between the wheel and the rail and between the wheel and the turnout.

Monitoring is expensive. Hence, further research will be required to identify ways to judge the cost-effectiveness of monitoring actions. Consequently, research is required to assess the costs for monitoring in comparison with the benefits obtained from monitoring. Perhaps a common cost-benefit analysis would help to facilitate this through a study performed from a Life Cycle Cost (LCC) perspective; for example a study of the cost for monitoring in comparison with the profits gained from the reduction of excessive degradation of bound capital.

An additional area of further research could be the exploration of how requirements imposed in the system operation and support phase, in combination with more effective and efficient

maintenance of the transportation system, could decrease the systems' environmental impact; for example to explore the environmental effect from decreased degradation of materials. This would be a broader perspective where the effectiveness of monitoring actions would be evaluated from a sustainability perspective, instead of only an LCC-perspective. One example could be to utilize a Life Cycle Analysis (LCA) approach. LCA offers a broader lifecycle perspective than that provided in the ISO/IEC 15288 (2003) standard. LCA is a tool for the analysis of the environmental burden of products at all stages in their lifecycle, from the extraction of natural resources, through the production of materials, product parts and the product itself, and the use of the product, to the handling of the product after its discard, either by reuse, recycling or final disposal (in effect, therefore, 'from the cradle to the grave') see Guinée (2002).

However, even though the waste of energy and natural resources may be reduced through both transferring transports from road to rail and through more effective and efficient maintenance, from a sustainable development perspective this will only be a drop in the ocean. In the view of the present author, our environmental problems are related to our consumption of both natural resources and services, especially our consumption of resources and services provided from remote locations. Therefore, in order to make a real environmental impact, we need to reduce our consumption of natural resources and services. Hence, further research should be focused on exploring how to reduce our needs for transportation. In other words, further research should investigate how we can reduce our consumption of natural resources, and how we can produce and consume where we live, or live and consume where we produce.



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## **APPENDED PAPERS**



# Paper 1





# **PUNCTUALITY MEASUREMENTS EFFECT ON THE MAINTENANCE PROCESS –A STUDY OF TRAIN DELAY STATISTICS FOR THE SWEDISH RAILWAY**

Rikard Granström, Peter Söderholm

Division of Operation and Maintenance Engineering  
Luleå Railway Research Centre  
Luleå University of Technology  
SE-971 87 Luleå Sweden  
rikard.granstrom@ltu.se, peter.soderholm@ltu.se

## **ABSTRACT**

Governmental regulations state that the Swedish national railway administrator Banverket has an overall responsibility for train punctuality, independent of whether train delays are caused by Banverket or the train operating companies. Banverket is responsible for the functioning of the railway system as a whole, but can with own maintenance and reinvestment activities only affect the infrastructure. Conflicts derive from the two stakeholders' different roles and interests. In order to effectively forecast maintenance needs and costs of the infrastructure, Banverket want that the infrastructure's deterioration caused by the rolling stock should be both as small and as predictable as possible. However, the train operating companies look at the same situation from the other point of view, with a focus on their rolling stock. The interrelationship between the two stakeholder roles and their combined maintenance process is complex, since it is difficult to pinpoint the responsibility for low performance of the whole transport system and separate assets. One essential approach, in order to monitor low performance linked to responsible stakeholder roles and causes is to follow up the two measures punctuality and train delays.

This paper explores the characteristics of existing train delay statistics and describes risks when maintenance efforts and design of incentives for improved railway operation is based on statistics that does not reflect the root-causes of problems.

**Keywords:** Maintenance, railway, punctuality, statistics, incentive, risk, delay, train delay

## **INTRODUCTION**

For current Swedish railway operation, with the separation of infrastructural management (Banverket) and train operation it is essential to be able to pinpoint the main problem areas and the main problem owners that are causing delays to the transportation system. This clarification intends to e.g. guide effective maintenance efforts and prevent sub-optimization of areas where the over all affect might be negligible (Nyström & Kumar, 2003). From the infrastructure manager's point of view, it is essential that the deterioration of the infrastructure is highly predictable in order to enable effective maintenance of the infrastructure. Banverket cannot affect the maintenance of the rolling stock and its contribution to the infrastructure's deterioration through own maintenance activities. However, Banverket can create

regulations stating requirements upon the conditions of the rolling stock (conditions affecting the degradation of the infrastructure) and also create economic incentives which motivate operators to provide rolling stock within prescribed conditional limits. This paper explores existing train delay statistics in terms of how it reflects the two stakeholder roles' influence on punctuality. The paper also discuss how the statistics fulfills requirements of relevant information for maintenance and what the consequences might be when decisions are based on information that is revealing symptoms rather than root causes.

## PUNCTUALITY AND DELAYS

Next to safety, punctuality is Banverket's most important goal area (Fahlen & Jonsson, 2005). According to the Swedish national encyclopedia the one who is punctual 'keeps exactly to agreed time'. From this definition punctual is an execution of an agreement at a specific time. Within railway this agreement is synonymous with the timetable, where the timetable is the agreement that describes where and at what time a specific transport is to be located. The timetable is an agreement between the train operators and the infrastructural manager. Punctuality is acknowledged as a key performance indicator (Åhren, 2004) which to some extent indicates to what extent the transportation system as a whole (e.g. infrastructure, rolling stock, and traffic control) manages to deliver transports on time according to the timetable. Punctuality is usually calculated by dividing the number of punctual trains by the total number of trains and presented as the percentage of punctual trains (Olsson & Haugland, 2004). Banverkets definition of punctual is; 'arrival at the end station within plus/minus five minutes'. Swedish punctuality is calculated in the manner explained by Olsson & Haugland (2004), it should be noted that canceled trains are not included in punctuality statistics. Rudnicki (1997) defines punctuality as 'a feature consisting in that a redefined vehicle arrives, departs or passes at a predefined point at a predefined time'. This definition comes close to describing how Swedish train delay statistics work.

Train delay statistics are used in order to gain an understanding of what is causing unpunctuality on the Swedish railway. Banverket uses different approaches such as database systems and collaborative work, such as PULS (punctuality through collaboration between operators and Banverket) (Fahlen & Jonsson, 2005), for the follow up of train delays. The most central database system for encoding of causes of train delays and train delay follow up is TFÖR (train delay system). TFÖR registers the train's correlation to the timetable and retrieves the train delay information from train traffic control system's track circuit indications. The delays are manually encoded by the traffic controllers. The traffic controllers are supposed to register a delay cause when the extra-delay is more than five minutes. The extra-delay is the change in delay between two stations, this means that if a train is extra-delayed 3 minutes between two stations and additional four minutes between the next two stations the train is in fact seven minutes of the time table but is not regarded as delayed and is therefore not coded. The reason for this somewhat tolerant definition of extra-delay is to limit the work of encoding and analyzing delay data.

The TFÖR system contains some ninety-seven different codes for train delay encoding. The codes are gathered due to their belonging into six main areas (problem owners) which are:

- **Planned maintenance and renewal works:** Planned maintenance and renewal works that consumes more time than is agreed on in the timetable.
- **Traffic-control-codes:** Train delays that can be correlated to the traffic control centers operative work.

- **Operators-codes:** Delays that can be correlated to the traffic operators activities such as: train driver missing, late departure from freight terminal, inspection of wagons, shunting, and so on.
- **Vehicle-codes:** Delays due to failures or lack of performance of the rolling materiel. Motive power or carriage damages, e.g. pantograph, hot-box and dragging-brakes detector alarms, brake malfunctions, and wheel-damages.
- **Infrastructure-codes:** Codes to identify delays caused by signaling, track, electrification and telecommunications.
- **Others:** Covers what is left out, such as sabotage, environmental obstacles (e.g. snow, ice, and trees), illness, and other causes not defined by the ninety-seven prescribed codes.

For follow-up of failures and damages to the infrastructure Banverket uses the failure report system 0FELIA. TFÖR data can be linked to 0FELIA data. This link provides opportunities to gain more precise information of the underlying causes of delays. Extra-delays in TFÖR with the failure code infrastructure are matched with failures registered in 0FELIA. This is done manually by the train traffic controllers. A failure can be reported by train-drivers, train dispatchers, different traffic operators, repairmen, Banverkets inspection personnel, entrepreneurs or private persons.

## METHOD

The materiel presented in this paper is based upon a database analysis of train-delay statistics from the TFÖR system, for the period of January 2001 to December 2004. TFÖR can link primary and secondary delays depending on what type or types of delays that is of interest. This link makes it possible to separate or seek relations between delays that have emerged on primary causes (e.g. failures related to turnouts, rail, pantographs, and wheels) with delays emerged from secondary causes (delays caused by other delayed traffic). It is important to be able to trace the chain of events caused by a failure in order to see its total consequences. In this paper the ‘total primary caused relationship’ is used, which is the relationship Banverket uses when presenting monthly delay statistics (Johansson, 2005). Total primary caused relation is defined as ‘a primary reported extra-delay added with secondary derived extra-delays’. For example, a ten minutes primary reported extra-delay causes twenty five minutes on another train and the own train secondary. The twenty five minutes are connected to the own train and reported failure code.

The study started with an examination of infrastructural and rolling stock failures influence on punctuality. This initial study showed that available delay-statistics did not provide realistic information on the contribution to delays from the infrastructure or the rolling stock. Therefore, the study focused on exploring the true meaning of the statistics, in order to understand how the statistics comes to reflect causes of delays. Chosen statistics for the study was train-delays related to the pantograph to overhead-wire interface and the wheel to rail interface, since these interfaces are the physical contact points between the rolling stock and the infrastructure. 0FELIA data provided by Analysgruppen (analysis group, formation of competence for statistical analysis at Banverket northern region) for the period 2001-2003 was used in order to identify what the main root causes of failure were for respective infrastructural component (Pettersson, 2004). How TFÖR in terms of train-delay statistics reflect what is derived from the 0FELIA data was explained by how the operative work at the train traffic-control-centre with encoding of delays was carried out. This was illustrated by a simple process mapping (Mizuno, 1988) illustrating the consecutive activities or chain of events leading to encoding of train delays of failures within the interface between the pantograph and the overhead-wire or the interface between the wheel and the rail.

## RESULTS

The distribution per problem owner (according to available statistics) is described in Figure 1.

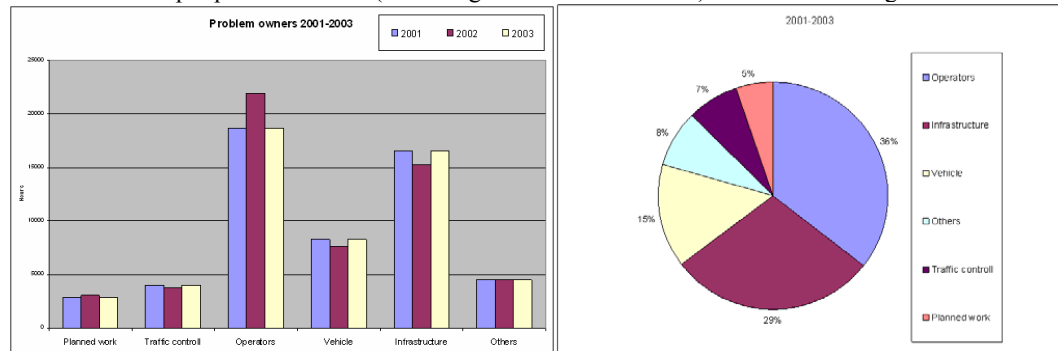


Figure 1. TFÖR distribution of train-delays/problem owner for the period 2001-2003 (whole of Sweden).

As can be seen in Figure 1 (left graph) the train delay contribution per problem owner (planned work, traffic control, operators, vehicle, infrastructure and others) show relatively small fluctuations over the years. Figure 1 (right graph) shows a mean value of respective problem owners influence on punctuality for the period 2001-2003. The reported causes of delays related to the infrastructure and vehicles are illustrated in Figure 2.

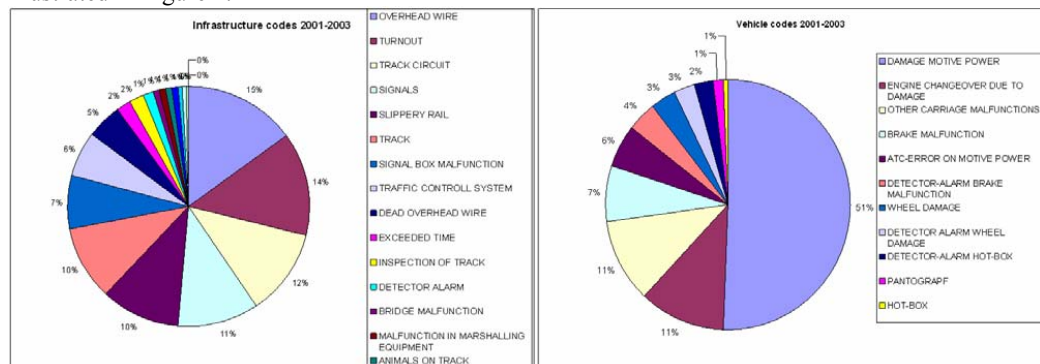


Figure 2. The distribution of reported causes of infrastructural related delays (left), and distribution of vehicle related delays (right).

The cumulative number of train delay hours for the Swedish railway reaches somewhere around 70,000 hours/year. Interesting to observe in this case is that according to the statistics the overhead wire contributes with 15% of the infrastructural related delays in correlation to the pantograph which contributes with 1% of the vehicle related delays. When calculating their respective influence on the 70,000 hours you find that the overhead-wire causes 3,045 delay hours ( $70,000 \cdot 0.29 \cdot 0.15$ ) to the system and the pantograph 105 hours ( $70,000 \cdot 0.15 \cdot 0.01$ ). One can in this case draw the conclusion that the influence of the pantograph is insignificant. However this does not correspond to the results presented by the analysis groups (Banverket Northern Track) in their study of overhead-wires. Their study shows that the pantograph is the most dominant cause for overhead-wire failures. The reason to why this is not visible

in the statistics is due to the encoding of relationships between delays. A possible combination of events leading to this result is described in Figure 3. Overhead-wire failures are not many in numbers but when the overhead-wire is torn down it causes long delays (2-6 hours), which causes a lot of disturbances for other traffic.

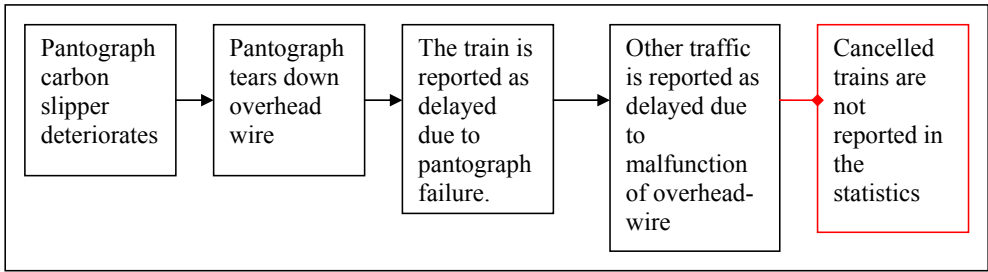


Figure 3. The chain of events leading to underestimation of the pantographs influence on punctuality.

The same type of relationship can be shown for the relationship between wheel and rail, see Figure 4.

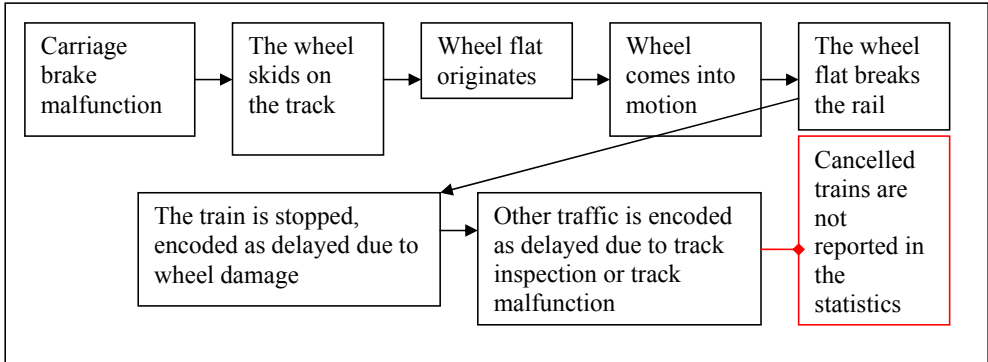


Figure 4. The chain of events leading to underestimation of the wheels influence on punctuality.

The same kind of problem with the encoding of root causes is also apparent in this case, the causing train is encoded as delayed due to wheel damage while other traffic is encoded as delayed due to track malfunction or track inspection. The analysis groups study on rail shows that wheel damages is one of the most dominant factors contributing to rail malfunction and hence related delays. Still according to the statistics the rail account for 2,030 (70,000\*0.29\*0.10) delay hours and the wheel damages 315 (70,000\*0.15\*0.03) hours.

At the moment work is in progress at Banverket in order to improve the encoding of statistics, so that it better describes the relationship between delays and root causes. In 2004 new demands were introduced stating that the total consequences of failures were to be better related to the identified initial failure cause, this is illustrated in Figure 5.

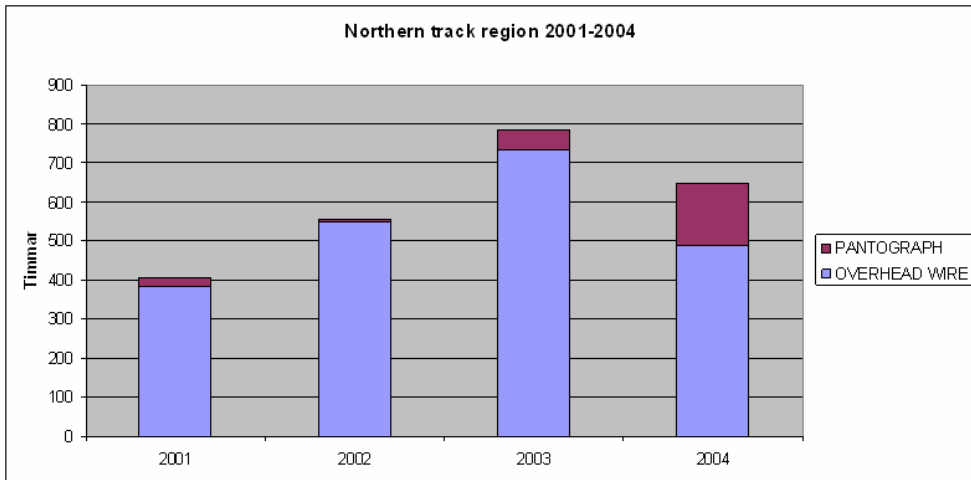


Figure 5. Figure shows how the train delay relationship between the pantograph to overhead-wire has changed during the years 2001- 2004.

Figure 5 illustrates a remarkable change when Banverket set out to improve the reporting of statistics in order to enhance the correlation between delays and root-causes. During the years 2001- 2003 the pantograph responded for some 1-6% of the pantograph to overhead wire delays. With a changed, more representative statistics, there was an increase to 25% during 2004. It is obvious that there was a scope for improvement of the reporting of statistics.

## DISCUSSION

What are the consequences of relying upon information that does not correspond to root cause? Imagine that you are suffering from dehydration; you go to the doctor and complain about a headache, the doctor without further observation provides you with aspirin. With the statistics provided the maintenance process like the doctor can be misled to take preventive measures treating symptoms instead of the disease. From the previous discussions the following risks derived from the follow-up of train-delays have been identified:

- Risk of appointing wrong problem owner as responsible. In the case with the pantograph to overhead wire it is obvious that Banverket is provided with a larger influence on the train delays than they actually account for.
- Risk of prioritizing maintenance within areas where the total punctuality improvement potential is less than can be estimated from the statistics. This implies that wrong information act as a base for prioritizing of maintenance, prioritizing that probably would look different if one could derive the root-causes of the delays. For example Banverket grinds the track, exchanges it or welds it in stead of asserting pressure on the operators to perform better maintenance on the rolling stock.
- Risk of not being able to create effective incentives due to the unawareness of some parameters. Once again the interface between the pantograph to overhead wire. The statistics shows that 3,045

delay hours is caused by the overhead wire, while only 105 hours is caused by the pantograph. Based on this information there is no interest to, within the incentive contracts, highlight the importance of the quality of the pantographs.

- Risk of not being able to perform proactive maintenance. The pantograph has a great influence on the function of the overhead-wire, but seems (according to the statistics) to have little effect on punctuality. As shown, train delay statistics can provide a more or less accurate picture of the causes of train delays. The delays are in many cases a consequence of deterioration of respective parties assets. If some assets influence on punctuality is underestimated, there is an obvious possibility of neglecting its importance. To achieve proactive maintenance the maintenance process cannot rely upon historical data that is influenced by a variety of conditions of the rolling materiel, especially when the influence is neglected. For predetermined maintenance with fixed time intervals this implies that maintenance intervals are calculated upon basis of belief that the consequences of the influence from the rolling stock is as negligible so that it does not affect the deterioration rate that determines the maintenance intervals.
- Risk of lost confidence in the follow-up statistics. It is in many cases obvious that the statistics does not reflect the true frequencies of causes to delays, which should influence the maintenance process. If confidence in the statistics is lost what is then there to rely on?

## CONCLUSION

The accuracy of information is of absolute importance in order to enable good decisions for focus of effective punctuality improvement measures. Punctuality statistics can obviously be improved to a certain extent, but it will never be a precision tool. If a pantograph is damaged by an overhead wire failure, and the faulty pantograph tears down the overhead wire in another location, it will be very difficult to determine the root cause and include it, instead of the symptom, in the statistics. No matter how precise the punctuality statistics may be it can only serve the purpose of identifying the main contributing factors to unpunctuality. In order to create effective incentives for enforcement of improved interaction (between rolling stock and infrastructure) other information is needed. Information that can assess and be used to enforce that the operating conditions of the railway are such that both Banverket and the traffic operators can provide their required services.

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## Paper 2



# Condition Monitoring of Railway Wheels and No Fault Found Problems

Rikard Granström<sup>1</sup> and Peter Söderholm<sup>2</sup>

<sup>1</sup> Division of Operation and Maintenance Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden. Phone: +46 (0)920 49 21 45. E-mail: rikard.granstrom@ltu.se

<sup>2</sup> Division of Operation and Maintenance Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden. Phone: +46 (0)920 49 20 77. E-mail: [peter.soderholm@ltu.se](mailto:peter.soderholm@ltu.se)



**Rikard Granström Lic.Eng.** has been active as a signalling engineer within the railway sector since 2001. Rikard received his B.Sc. in Electronics Engineering in 2001 and his Licentiate in Engineering degree in Operation & Maintenance Engineering in 2005. Rikard's main research interest is in the area of condition-based maintenance and railway punctuality.



**Dr. Peter Söderholm** is a senior lecturer at the Division of Operation & Maintenance Engineering at Luleå University of Technology. Peter received his M.Sc. in Mechanical Engineering in 2001, his Licentiate in Engineering degree in Quality Technology & Management in 2003, and his Ph.D. in Operation & Maintenance Engineering in 2005. Peter is active at the Centre for Maintenance and Industrial Services (C-MIS) at the University and is a member of the Swedish National Committee for IEC TC56: Dependability. Peter is currently performing research related to ICT (Information & Communication Technology) application within maintenance. The main area for study and application is the military aerospace industry.

## ABSTRACT

Defective railway wheels can cause severe damages to both track and vehicle items, which in the worst case scenario can lead to derailments with extensive losses. Wheel impact detection systems are intended to support the prevention of railway damages and their related losses, through the recognition of wheel defects and the generation of alarms. When a wheel impact detection system was being commissioned in Sweden, the commissioning study showed that the detection system was reliable, i.e. it was not generating any false alarms. However, during operation some of the system's alarms resulted in No-Fault-Found (NFF) events at subsequent manual inspections performed by train drivers to assess the severity of damages. Hence, a verification study was launched to determine if the cause of the NFF events was false alarms generated by the detection system, or the inability of subsequent manual inspection to replicate the detection system's test result. The verification study was expected to support an exclusion of the manual inspection, which was perceived to be the cause of the NFF events. However, an exclusion of the manual inspection would require the wheel impact detection system to be highly reliable, since it would be the sole support for decisions about appropriate operation and maintenance actions at an alarm. This study presents experiences from the verification study and links these to international experiences illustrating how wheel impact detection systems can support continuous assessment of the wheel condition and related condition-based maintenance efforts. The experiences highlight the importance of data accuracy and appropriate information management, to achieve the potential benefits and avoid the drawbacks of condition monitoring.

**KEYWORDS:** Maintenance, Condition Monitoring, Railway, No Fault Found (NFF), information management.

# 1 INTRODUCTION

Rail industry records show that, for common railway signalling assets, the occurrence of No-Fault-Found (NFF) events is as high as 50% [1]. The impact of NFF events can be measured as the proportion of the repair budget that is wasted by not finding the root cause of faults [2]. NFF events increase the burden on the supply and maintenance system, which can be measured in terms of an increased volume of spare parts inventories, increased pipeline time, and increased cost of work and manpower [3,4,5,6,7]. Hence, NFF events result in a loss of profits through unnecessary maintenance actions and delays [8].

The NFF phenomenon may be described as illustrated in Figure 1. At any test level, a fault may be recognized and localized to a unit. However, when the unit is tested at a subsequent test level, the recognition or localization of the fault may be unsuccessful. This situation can occur for a number of reasons. One possibility is that, having correctly recognized and probably localized the fault at the preceding level, attempts to replicate the test results at the subsequent level are unsuccessful. Another possibility is the fault being incorrectly recognized or localized at the preceding level.

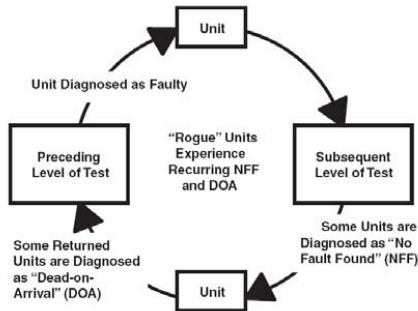


Figure 1. The No-Fault-Found (NFF) and Dead-on-Arrival (DOA) phenomena. A unit that experiences a recurring combination of NFF and DOA phenomena is sometimes called a “rogue” unit [9].

A unit can also be classified as Dead-on-Arrival (DOA) when being returned to the preceding test level from a subsequent test level at which an NFF event has occurred. Units that are recurrently classified as NFF and DOA are sometimes called “rogue” units. The NFF phenomenon has a negative impact on

critical system stakeholder requirements, such as system safety, dependability, and life cycle costs. Hence, it is essential to prevent the causes of NFF events and reduce their consequences, in order to increase stakeholder satisfaction. However, in order to achieve this desirable situation, it is necessary to identify the problem owners and root causes of NFF events [9].

In this paper, the “preceding level of test” concerns tests using wheel impact detection systems, while the “subsequent level of test” concerns manual inspection. One major purpose of wheel impact detection systems is to recognize out-of-round wheel defects, e.g. wheel flats. The primary cause of wheel flats is that the braking force is too high in comparison to the available friction between the wheel and the rail [10,11,12]. This situation results in unintentional sliding (without rolling) of the wheel on the rail. As material is worn off a wheel, flats are created, which, depending on the size, can cause severe damage to the infrastructure when the affected wheel comes into rolling motion. The wheel flat situation can be caused by poorly adjusted, frozen, or defective brakes. In Sweden, the majority of wheel flats appear during winter due to snow and low temperatures. Wheel flats, or other types of out-of-roundness, cause severe damages to both track and vehicle components, such as rails, switches, sleepers, insulated joints, wheel sets, wagon axles and bearings [13,14,15,16,17]. The purpose of a wheel impact detection system is to prevent infrastructure damage caused by increased stress applied to the rail from irregularities of the wheel surface.

In January 2000, a commissioning study was performed in order to assess the reliability of one of the wheel impact detection systems installed on the Iron Ore Line in northern Sweden [18]. Wheel impact detection systems are used by Banverket (the Swedish Rail Administration) as go/no-go devices, which provide the operators of the rolling stock with signals showing whether they can proceed (go) or whether they must stop and take corrective maintenance actions (no-go). The purpose of the study was to assess the detection system’s measurement accuracy (the “preceding level of test”, see Figure 1) by means of manual inspections (the “subsequent level of test”, see

Figure 1) of the wheels, before the system was to become operational. A detection system alarm is, according to Swedish regulations, always followed by a subsequent test (manual inspection by the train driver), where the train driver is the one who determines the severity of the damage and takes decisions about subsequent actions (proceeding, or stopping to perform corrective maintenance activities). The commissioning study showed that the detection system provided satisfactory data quality, without generating any false alarms. However, when the detection system became operational, some of the alarms produced by the system resulted in NFF events at subsequent manual inspections by train drivers. These NFF events could have been caused either by false alarms generated by the detection system, or by the inability of the subsequent test (manual inspection) to verify the detection system's alarms. Subsequently, Banverket launched a verification study [19]. Like the commissioning study, the verification study was intended to assess if manual inspections could replicate the detection system's test results or not. The result of the study was expected to serve as a momentum for an exclusion of the subsequent manual inspections by train drivers, which were perceived to be the cause of the NFF events. However, an exclusion of the manual inspections would require the system to be highly reliable, since a decision regarding operation and maintenance would then solely be based on the detection system's test results. Another positive effect of excluding manual inspections is that the delays caused by manual inspections can be avoided. These are primarily the delays to the train that has triggered an alarm, and secondarily the delays imposed on other traffic and caused by the occupation of sidings used for assessment of the damages. (These sidings would normally be used when trains are meeting each other on the track.)

## 2 STUDY APPROACH

The purpose of the study was to identify the cause of the unsatisfactory high number of reported NFF events related to the wheel impact detection system. The wheel impact detection system located between Kiruna Station and Krokvik Station on the Iron Ore Line in northern Sweden was selected for the purpose of the study. The study was designed to allow the train drivers and the Train Traffic Control

Centre (TTCC) personnel to operate under as normal conditions as possible. For subsequent inspection of wheel damages, northbound trains were stopped at Krokvik Station and southbound trains were stopped at Kiruna Station. When trains were stopped (due to an alarm, at the "preceding level of test", see Figure 1), the personnel participating in the study met the train driver and took part in the damage verification (the "subsequent level of test", see Figure 1). The wheels that were indicated as faulty by the detection system were marked, a picture of the damage (or damages) was taken and the carriage numbers were noted down. In some cases, a wheel profile (mini-proof) measurement of the wheel surface was also made. The train driver still had to make the final judgement of the severity of the damage and decide what kind of actions were to be taken. No prefabricated wheel damages were used during the study. The only modification, compared to normal operating conditions, was that the threshold for low level alarms (B level alarms) was lowered (in order to retrieve more data during the test). The high level alarms (E level alarms) were unchanged compared to normal operation (A and C level alarms are also available but were not utilized in the study) [19].

## 3 THE STUDIED WHEEL IMPACT DETECTION SYSTEM

The studied wheel impact detection system measures the vertical impact force that the wheel applies to the rail as the train passes the detector. The force is measured by 80 strain gauges mounted between the sleepers along a distance of 7.785 metres. This distance allows two measurements of each wheel to be performed. The system uses 20 measurement channels (10 channels per track with four strain gauges per channel). As the studied detection system is shorter than 20 metres, it cannot detect all the wheel damages due to the harmonic motion ( $\lambda=20\text{m}$ ) of the train during operation. Depending on the harmonic motion, the size of the damage, the wheel diameter and where on the wheel the damage is located, there is a possibility that the damage may not be recognized by the detection system. The probability of recognizing a wheel damage is approximately between 80 and 85% for an iron ore train. However, the studied application is perceived to be adequate for its purpose. The detection system recognizes irregularities, such

as wheel flats, and sends alarms according to prescribed criteria when the damaged wheel creates increased force (above the prescribed thresholds) on the rail. In addition, the detection system records the time and date of train passage, the train speed, the train length, the number of locomotives and carriages, the number of axles, and the metric tonnages.

The detection system provides three types of alarms (see Figure 2):

- Peak alarm: the actual force applied on the rail (most useful for monitoring loaded carriages and locomotives).
- Dynamic alarm: corresponds to the peak force minus the average load (most suitable for monitoring semi-loaded carriages).
- Ratio alarm: equals the peak force divided by the average load (most useful for monitoring unloaded carriages).

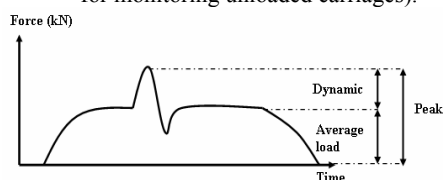


Figure 2. Alarm illustration.

The detection system normally operates at two different levels for each alarm: the high level (alarm level E) and the low level (alarm level B), see Table 1.

Type Of alarm	Alarm level	Normal Value (kN)	Study Value (kN)
Peak	Low (B)	290	191
Peak	High (E)	320	320
Dynamic	Low (B)	155	71
Dynamic	High (E)	190	190
Ratio	Low (B)	4.2	2.3
Ratio	High (E)	5.2	5.2

Table 1. Configuration of alarm levels for normal operation and during the performed study.

### 3.1 Alarm Scenarios

When a detection system indicates a damaged wheel, a report is sent to the TTCC. The report contains information about the type of alarm, the alarm level and where on the train the damage is located (the axle number and the left or right side). This information is then relayed to the train driver, who has to stop the train at the next upcoming station. The train

driver then has to inspect the damage manually in order to assess its severity. If the train driver makes the judgement that the damage falls in the category of prescribed damage criteria stated by the traffic safety instructions [20], the following actions are performed. If the length of the defect is 40-60 mm, or if there is a material build-up with a height smaller than 1 mm, the train is allowed to proceed to a station agreed upon by the traffic operator and the infrastructure manager together (the nearest workshop). If the temperature is lower than -10 degrees Celsius, the train speed is restricted to a maximum of 10 km/h. At higher temperatures, there are no restrictions other than the stipulation that the speed interval 15 - 45 km/h should be avoided, since the risk of inflicting damage on the rails is largest at these speeds. If the length of the damage is longer than 60 mm, or if the height of a material build-up is higher than 1 mm, the train can go to the nearest station at a maximum speed of 10 km/h. In such cases, it is common to detach faulty carriages from the train and leave them at the station for on-site corrective activities. In some cases a severe wheel damage (>60mm) calls for an inspection of the track [20], since there is an obvious risk that the wheel flat may have damaged the rail to the extent that a derailment can occur. This has a huge impact on train delays, since no traffic can be allowed to run or all traffic is restricted to a speed less than 30 km/h until the track is verified and in some cases also restored to an operational condition.

Even a minor damage can cause a large number of traffic disturbances due to the manual inspection of the wheel. Imagine an alarm indicated on one of the last carriages of an iron ore train. This causes a 450-metre one-way walk for the train driver in order to reach the indicated wheel. If the driver is fortunate, it will be possible to locate the damage and verify it at once. If the driver is unfortunate, the damage may be hidden towards the rail or between the brake pads or covered by some protective shield. In such a case, the train driver will have to mark the position of the wheel, go back to the locomotive, pull the train, and hopefully be able to turn the damaged wheel into a position where the damage can be revealed. Then the driver will once again have to go back and try to verify the alarm. During the damage identification, this train will be delayed, as well as other traffic that will not be

able to utilize the station fully when trains are meeting each other, since the train that experienced the alarm is occupying one of the sidings.

#### 4 STUDY ANALYSIS AND RESULTS

During the study, 18 out of 145 trains (12%) were the objects of detector alarms, 30 axles were the objects of alarms and a total of 48 alarms were produced by the detection system. The result of the study showed that all of the 11 peak alarms could be verified. Regarding the dynamic alarms, 18 out of 19 alarms were verified (95%), while 14 out of 18 (78%) ratio alarms were verified. An analysis of the alarms that could not be verified may give an indication of the number of possible false alarms. The one dynamic alarm that was not verified was most likely a result of start-up problems during the initiation of the study. Furthermore, it could be established that one of the ratio alarms was not correctly verified because the train operator had attached a number of additional carriages to the train set before the train was reached by the personnel participating in the study, which caused the study team to measure the wrong carriage. The remaining three ratio alarms that were not verified may have been caused, for example, by irregularities of the running surfaces (see Figure 3) or out-of-roundness defects, which can be extremely difficult to assess visually.

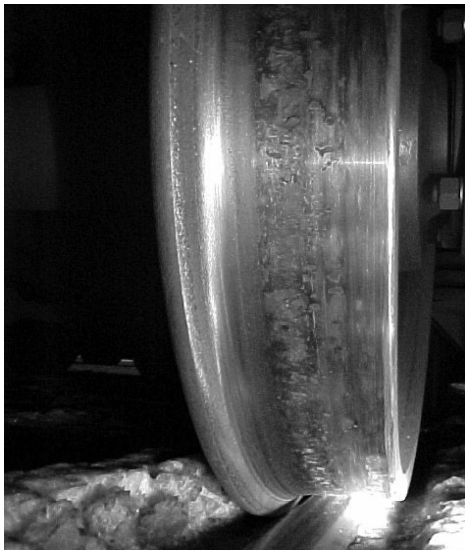


Figure 3. Surface damages or possible out-of-roundness.

Previous experience from another wheel impact detection system on the Iron Ore Line showed that wheels that experienced out-of-roundness defects were the reason for unverifiable detector alarms. The performed study also showed that the damages related to verified ratio alarms were small (see Figure 3) in relation to the traffic safety instructions [20]. This, together with the fact that the detection system at normal alarm levels would not have produced any alarms, indicated that the detection system did not produce any false alarms at normal operating alarm levels. Hence, the analysis of the results of the study showed that the detection system's reliability was satisfactory for Banverket's use.

During the study, it was observed that it may be quite difficult to verify correct detector alarms by visual inspections. This difficulty is illustrated in Figure 4, which shows a small part of a damage that is revealed between the brake pads. In Figure 5, the difficulty is illustrated by a damage that is partially hidden towards the rail.



Figure 4. Damage identified between the brake pads (wheel seen to the right).

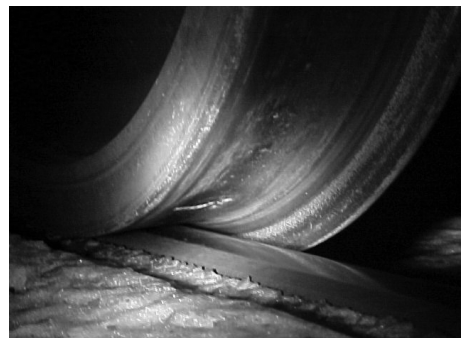


Figure 5. Damage partially hidden towards rail.

The main result from the verification study was that, after years of continuous operation, the system did not produce alarms for fault-free wheels at normal alarm levels, i.e. no false alarms were generated. This result, combined with that of the commissioning study [18], showed that the detection system's reliability was good enough to consider a cancellation of manual inspections. One could also consider the possibility of complementing the existing traffic safety instructions, in order to allow operation and maintenance decisions to be based upon the actual forces applied on the rail, which are derived from wheel impact detectors. It was also identified that it is possible to lower the peak and dynamic alarm levels, since fairly large damages (as defined by the traffic safety instructions) had been observed on wheels that would not indicate alarms at normal alarm levels.

It was during the study observed (as illustrated by Figures 4 and 5) how difficult it can be to identify damages manually. It is very likely that, even though a train driver follows the correct procedures for damage identification, he/she will not be able to identify the damage, and will therefore report the damage as NFF (i.e. a false alarm by the detection system). Furthermore, high impact forces can be caused by wheel flats, as well as by out-of-roundness, which can be almost impossible to verify by visual inspections. Hence NFF events are very likely to be caused by the inadequacy of the manual inspections (the "subsequent level of test", Figure 1).

## **5 GO/NO-GO OR CONDITION-BASED MAINTENANCE**

Utilizing the detection system as a go/no-go system may be sufficient for the infrastructure manager. However, other experiences from wheel impact detection systems indicate that, once a wheel defect occurs, the severity of impacts will increase over time [21, 22, 23, 24]. There is also a synergy effect between wheel impacts and bearing defects. Wheel defects shorten the bearing fatigue life, which can lead to premature bearing failure [25, 26, 27, 28]. In the UK wheel impact detection systems were originally perceived to be an aid for removing vehicles that failed to meet Railway Group standard limits [29]. However, it was recognised that the actual data 'owner' should have been the train operator, as early

recognition of deterioration was perceived to be a better use of the systems [29]. Further, experiences from the InteRRIS system (the Integrated Railway Remote Information System) show how the integration of information from multiple detection systems and vehicle identification systems, e.g. Radio Frequency Identification (RFID), can help make wayside detector system results sharable between infrastructure managers and car owners [21]. The integrated wayside detector network can feed all the train data collected at multiple detector sites into one composite data system [21]. This can enable a correlation of increasing wheel impacts with, for example, increased roller bearing temperatures (derived from hot box detection systems, used for monitoring bearings) or increased acoustic emissions (derived from acoustic emission detectors, also used for monitoring bearings). In turn the data on each wagon (and locomotive) can exist in the information system as a discrete "vehicle health record" [21]. The health record for a particular freight wagon can contain all the recent detector data gathered for that wagon. The health record also creates the basis for generating repair tasks or work orders for the preventive or predictive repair or replacement of components [21]. Hence, the same data that the infrastructure manager uses to remove faulty vehicles from operation can be used by the traffic operators to support condition-based maintenance on their vehicles.

An impact detection study that was performed later, initiated by Banverket, examined the possibility of excluding the manual inspections for E (high level) peak alarms. Hence, if a carriage was damaged and triggered a high level peak alarm, the carriage had, independent of any inspection of the damage by the train driver, to be left at the next station (for corrective activities). During this study, the other alarms were treated as under normal conditions. Prior to the study, Banverket had declared that it was important to obtain feedback from the traffic operators if fault-free carriages had been left on the track. The results from the study showed that there had been almost no feedback from the traffic operators. Banverket interpreted the lack of feedback as a satisfactory result, since none of the traffic operators had been complaining. This study will be expanded with high level dynamic and ratio alarms deciding whether the train operators



(independent of any inspection by the train driver) should take their carriages to the nearest workshop for repair. The carriages will not be allowed to leave the workshop before they have been restored to an acceptable working condition.

Banverket is obviously progressing in their use of wheel impact detection systems, but as they make progress, traffic operators are not being provided with more than go/no-go signals. Perhaps it would be more advantageous for Banverket and the traffic operators to form a cooperative study where data from different impact detection systems would be integrated and linked to vehicle identification data. This would allow Banverket to perform continuous verification of the detector system functions (without interfering with traffic), since systematic deviations in load measurements from a single detector could indicate detector malfunctions. This could also provide traffic operators with useful information for their condition-based maintenance activities. A further extended usage of impact detector system information could also be valuable for the assessment of infrastructure degradation. The accumulated metric tonnage is one important factor for assessing the degradation of infrastructure assets [39, 31]. It is a difficult task for Banverket to get hold of accumulated tonnage figures from the traffic operating companies, since they regard them as trade secrets [32]. However, tonnage figures can be extracted from the wheel impact detection systems at present, but this function is not used. Moreover, the impact detector systems can also be used to identify overloading of carriages and whether loads are unevenly distributed on carriages.

## 6 CONCLUSIONS

Detector alarms are, in accordance with the existing traffic safety instructions, triggered at a threshold where the damaged wheel is likely to cause immediate damage to the infrastructure, even though much damage may already have been inflicted. If a measurement methodology is sufficient, it is obviously better to make operation or maintenance decisions based on the actual forces applied to the rail rather than on the size of the identified wheel damages. As a comment on the criteria of the present traffic safety instructions, Johansson [12] states that the peak contact force is deter-

mined by the depth of the flat rather than by its length and size. Furthermore, the study showed that the wheel impact detection system's alarms were able to provide valid data for determining whether to give operators no-go signals (or signals telling them to go to a specified station), without any additional manual inspection. However, it must be considered that there always is a risk of not retrieving valid go signals (i.e. not recognizing existing wheel defects).

The performed study showed that NFF events were likely to be caused by inadequate manual inspections (the "subsequent level of test", Figure 1), and that the manual inspections could be excluded. However, this does not provide a guarantee that the detection system will deliver accurate data on any given occasion. It is necessary to perform continuous verification activities on the detection systems in order to assess their delivery of correct information. However, system testing, as performed in the study, is costly and it interferes with traffic (being likely to cause train delays). In other words, it would be beneficial for traffic operators, passengers, and the infrastructure manager if the detector system function could be verified more automatically and continuously.

## 7 DISCUSSION

The study presented in this paper shows that it is essential to consider testability requirements and ensure that different test levels are coordinated when implementing new condition monitoring technologies. This test coordination is crucial in order to avoid No-Fault-Found (NFF) events, which can erode any potential benefits of the technological solution. NFF problems can be avoided if the preceding monitoring methodology is more reliable than the system which it monitors, and if the monitoring methodology subsequently used to recognize and localize the failure is at least as reliable as the preceding monitoring methodology. Hence, when implementing new test technologies (e.g. condition monitoring technologies), their impact on existing tests, included in both the technical system and its support system, must be considered and an adjustment of the applied test strategies should be performed.

International experiences from the utilization of detection systems show that there are

benefits to be obtained if the information from the systems can be utilised in other ways than only to serve the infrastructure manager's objectives. With a more integrated approach (integrating detector system data with vehicle information) the infrastructure manager can avoid manual inspections (and related NFF events) and still continuously assess the monitoring system's measurement accuracy. From the perspective of the transport system, i.e. the infrastructure and the rolling stock, it is obvious that a proactive utilisation of detector system data could prevent undesirable stoppages (primary delays), as well as secondary delays (delays to other traffic caused by the primary delays). Furthermore, the proactive utilisation of such data could also serve the business objectives of both the operators and the infrastructure manager. The reason for this is that the operators could transfer corrective maintenance into preventive maintenance. At the same time, the infrastructure manager could more efficiently prolong the infrastructure asset's life by preventing damages to the infrastructure, which would also reduce the need for expensive corrective maintenance and reinvestments.

However, a more thorough utilisation of wheel impact detection systems requires more extensive cooperation between different stakeholders, i.e. the infrastructure manager and the traffic operators. This cooperation will make the utilisation of the systems more complex than it is today. Furthermore, it is not easy to identify the stakeholder that should take the responsibility of pursuing this kind of development. However, such development should lie within the stakeholders' common interest. The reason for this is that both the effectiveness (doing the right things) and the efficiency (doing the things right) of their combined enterprise will determine the enterprise value for the end customer (i.e. how well the tax payers' money is spent and how much the public and industry have to pay for traffic charges and tickets). Hence, wisely applied condition monitoring technologies can contribute to the effectiveness and efficiency of the stakeholders concerned, which in turn will determine the competitiveness of the railway in relation to other means of transportation.

## 8 ACKNOWLEDGEMENTS

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# Paper 3



## **A system and stakeholder view of maintenance for punctuality improvement**

Rikard Granström, Peter Söderholm and Uday Kumar, Luleå University of technology

### **Purpose**

The purpose of this paper is to describe implications and possibilities of improvement of railway punctuality by means of more effective and efficient maintenance, considering technical systems and stakeholder interrelations within a Swedish railway context.

### **Approach**

A generic system lifecycle model based on national and international standards is used to illustrate how important stakeholder requirements for system services (e.g. punctuality of transportation) are affected by central processes in the lifecycles of technical systems (i.e. rolling stock and infrastructure). This system lifecycle model supports an exploration of how the fulfilment of the infrastructure manager's performance objectives is affected by the interrelationships between the infrastructure maintenance contractors and the traffic operators. These interrelationships are used to highlight the railway context's impact on maintenance and its role in punctuality improvement throughout the railway system's lifecycle.

### **Findings**

The fulfilment of required improvements of the railway system's performance can be jeopardized if stakeholders' interrelationships are neglected. The primary considered stakeholders are the infrastructure manager, infrastructure maintenance contractors and traffic operators. The study proposes the use of incentives in combination with adequate performance measures (derived from both availability performance measures and condition monitoring technologies) to stimulate the stakeholders to make adequate efforts to enhance the technical systems' lifecycle processes. This should facilitate an alignment of the technical system's performance objectives with the profit goals of the stakeholders

### **Research implications**

The presented study supports further research about punctuality improvement of the railway system by means of more effective and efficient maintenance.

### **Originality/value**

There is a limited amount of published literature describing how maintenance can support punctuality improvement in the context in which the technical and stakeholder systems of the railway sector are bound to interact. Hence, it is believed that this paper makes a contribution in this respect.

### **Practical implications**

The modelling of the interrelationships of the technical and stakeholder systems can be applicable to businesses where multiple organizations are dependent on each other to succeed in their individual tasks, since the competitiveness and the price of the end product (goods, service or any combination thereof) are determined by the success of their combined efforts. The most relevant industries are those that are dependent on capital-intensive and complex technical systems with a long lifecycle, e.g. railways, aviation, power generation and distribution, pulp and paper, and steel and mining.

**Keywords**

Punctuality, maintenance, stakeholders, incentives, railway, system view, lifecycle

**Paper type**

Conceptual paper

**Introduction**

Some aspects of punctuality and maintenance within different railway contexts can be found in the contemporary literature, e.g. Knowles (1998), Gibbons (2004), Vickerman (2004), Marsden & Bonsall (2005), Espling (2007) and Stenbeck (2007). However, the literature seems scarce which holistically describes how punctuality improvement can be supported by maintenance in the context in which the technical and stakeholder systems of the railway sector are bound to interact. The purpose of this paper is to describe the implications and possibilities of improvement of railway punctuality by means of more effective and efficient maintenance, considering technical systems' and stakeholders' interrelations within a Swedish railway context.

**Changing railway environment and Condition-Based Maintenance**

There is a social need and a political will to transfer a significant portion of transportation services from roads to rail (European Commission, 2001). Hence, the railway traffic in Sweden is increasing (Banverket, 2006), which is having a direct impact on both the maintenance and the punctuality of the transportation service. The punctuality is being affected, since an increasingly crowded track (due to increased capacity utilization) is making the impact of infrastructure and rolling stock failures on train delays and knock-on train delays (trains that are delayed due to other delayed trains) more severe (due to reduced slack in the timetable). The increased capacity utilization of the infrastructure is also causing it to deteriorate at a greater pace, which is increasing the demand for maintenance and reinvestment to retain and restore the required functions of the railway system. Simultaneously, as the need for maintenance is increasing, there is less time for executing it due to the increased traffic. In addition, the infrastructure maintenance budget is more or less fixed (Banverket, 2004, 2005, 2006). Hence, in this new situation with increasing requirements and utilization levels with the same available resources, the effectiveness and efficiency of necessary maintenance have to be improved to retain and restore the required functions of the infrastructure. Hence, it is a delicate task to balance the maintenance efforts to achieve the required punctuality, safety and dependability with limited resources. This situation is resulting in new requirements for the prediction of degradation and necessary maintenance concerning both the infrastructure and the rolling stock, to avoid unplanned corrective maintenance and allow timely performed preventive and corrective maintenance. At the same time, different studies show that 70-90 percent of complex systems fail prematurely after maintenance execution, see e.g. Broberg (1973), Nowlan & Heap (1978), Moubrey (1997), Allen (2005) and Reason & Hobbs (2003). Hence, from this point of view also, excessive maintenance execution should be reduced to avoid maintenance-induced errors. Therefore, Condition-Based Maintenance (CBM) is in many cases favourable compared to predetermined time-based maintenance, which entails the risk of excessive maintenance execution. However, the successful implementation of CBM requires that appropriate functions at appropriate indenture levels of the technical system should be monitored and that tests at different maintenance echelons within the maintenance organization should be integrated in order to avoid testability deficiencies like No-Fault-Find (NFF) events; see e.g. Granström & Söderholm (2006) and Söderholm (2007a). NFF



events constitute a critical testability deficiency within the automotive, aviation and railway industries that has a strong negative impact on critical requirements such as dependability, safety and cost (Söderholm, 2007a). Hence, to improve punctuality, the Swedish railway has identified a need for more effective (doing the right things) and more efficient (doing the things right) CBM (LTUa, 2005). Based on the challenging scenario described above, Banverket (the Swedish Rail Administration) has initiated research projects to explore how more effective and efficient maintenance can contribute to punctuality improvements within the railway sector through the application of supporting condition monitoring technologies (LTUa, 2005) and enhanced availability performance measures (LTUb, 2005).

### **Railway stakeholders, systems and their interrelationships**

The member states of the European Union (EU) must, according to Council Directive 91/440, separate the management of infrastructure and that of rolling stock. Further, the directive states that, in order to render railway transport efficient and competitive as compared with other modes of transportation, the member states must guarantee that railway undertakings are afforded the status of independent operators behaving in a commercial manner and adapting to market needs. The application of the directive differs between the EU member states (Improverail, 2002). Even though the Swedish application model differs in detail, it can be considered representative of other EU railways. Hence, the following description of railway stakeholders, systems and their interrelationships can to some extent be generalised to other European railway contexts. Furthermore, the descriptions can perhaps also be generalised to other industries, for example power generation and distribution, in which the ownership and management of the systems have been separated.

The Swedish railway sector is partly deregulated, which means that private entities are allowed to compete for contracts to perform infrastructure maintenance. This also applies to the rolling stock operation, where private entities are allowed to traffic the rail network. In Sweden, 80 percent of the railway network is owned by the Swedish Government (Banverket, 2006). The Government controls the infrastructure and most of the Swedish railway sector through Banverket. Banverket's main objectives, stated in the governmental transport policy objectives, are to ensure system safety, cost-effectiveness, reliability of service and sustainability, for example in terms of environmental impact and longevity of transportation provision for the public and industry. Governmental requirements state that Banverket has a sector responsibility for the railway, which means that it has an overall responsibility for the whole railway (Banverket, 2006). This implies that Banverket should monitor and actively pursue development throughout the railway sector. Hence, Banverket has the responsibility for improving punctuality, among other things (Ericsson et al., 2002). The fundamental purpose of exposing railway stakeholders to competition is to obtain more railway service per monetary unit (Espling, 2007, Stenbeck, 2007). The belief is that this will spur methodological and technological development to lead by gradual stages to a maximization of the prosperity of society (Laffont, 1994). According to Banverket's objectives, maximization of prosperity results from achieving the required system functions of the transportation service at the lowest cost. This means controlling the operation and maintenance to assure that the required functions are obtained, at the same time as the degradation of the bound capital in rolling stock and infrastructure is optimized to generate the lowest system lifecycle cost (LCC). Banverket can affect stakeholder behaviour within the railway sector through requirements manifested in regulations or contracts, some of which have economic incentives attached (Ericsson et al., 2002). The most common principles of contracting are prescriptive or performance contracting, in which the arm's-length and partnering approaches are utilized (Olsson & Espling, 2004; Espling & Olsson, 2004b).

When considering the interrelationships between the different railway stakeholders, it is of importance to understand their responsibilities for different parts of the railway system and the boundaries between these parts. The reason is that this understanding will facilitate an analysis of their behaviour and rationale. Furthermore, from a punctuality improvement perspective it is interesting to see how different technical systems contribute to train delays. Considering the infrastructure, the top five subsystems causing most train delay time due to the absence of required functions in Sweden during 2004-2006 were: the track (2,391 hours/year), contact wire (2,123 hours/year), turnouts (1,988 hours/year), signal boxes and section blocks (1,588 hours/year) and the positioning system (603 hours/year). Figure 1 illustrates the average delay per failure in relation to the frequency of failures for these subsystems during the years 2004-2006. Contact wire failures and track failures are most critical in terms of the failure consequence measured as the delay/failure. In the case of a contact wire failure (a contact wire torn down, or a power supply malfunction) or a track failure (broken rail), the train traffic cannot be resumed until the failure has been rectified. Contact wire failure can occur anywhere along the track, whereas turnout failures usually occur close to a station. As such the time required to fix a contact wire failure will be much longer than that required to fix a turnout failure. For the track, turnout, signal and section block and positioning systems, the traffic can be restored, i.e. with reduced speed or capacity, before the failure is rectified, if the failure recognition and localization process has confirmed that operation will not endanger safety. For example, turnouts can be locked in one position, allowing traffic to pass only one way throughout the turnout, which allows traffic to pass at the expense of reduced station capacity. In the case of train delay caused by, for example, a contact wire failure or a safety-critical track failure (e.g. a rail break), the time to rectification is generally quite long (e.g. 4 to 10 hours). In response, train traffic controllers start cancelling trains in order to reduce the spread of knock-on delays. However, since cancelled trains are not included in the statistics, the full consequences of these failures are underestimated.

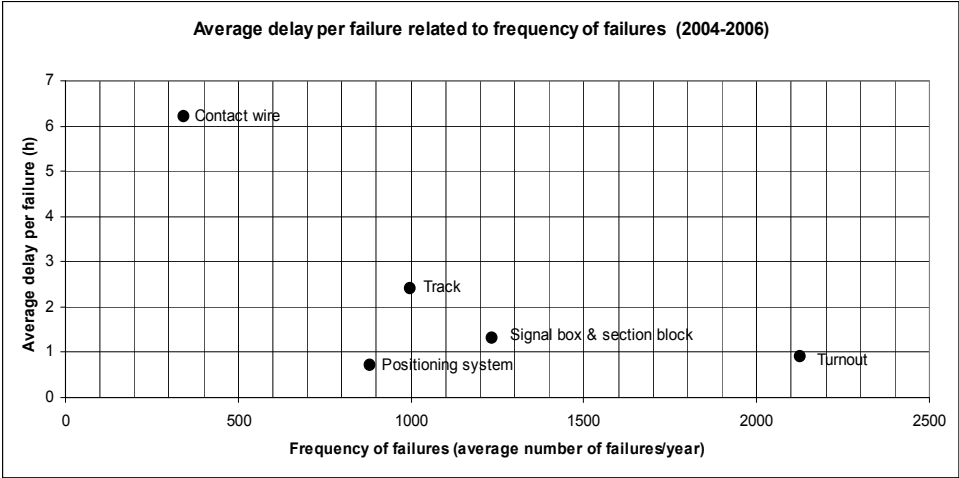


Figure 1. Average delay per failure related to frequency of failures for the top five infrastructure systems causing most train delay time during 2004-2006.

Interesting to observe is the fact that the top three infrastructure subsystems that cause most train delay time are in direct physical contact with the rolling stock. Close to 40 percent of contact wire failures are caused by rolling stock pantograph failures (Granström, 2008). Furthermore, the highest railway LCC is related to the wheel/rail interface (Larsson, 2005).

The functions, degradation rates and maintenance needs of contact wires, turnouts and tracks are strongly dependent on the condition of the interacting rolling stock's wheels and pantographs, and vice versa (Mutton, 1982; Sukhov, 1999; Samuels et al., 2003; Nissen et al., 2007). An increasing awareness of this fact has encouraged the development of technologies that can monitor critical parameters of the infrastructure and rolling stock interaction (Esveld, 2001; Ruplal, 2003; Granström, 2005; Granström & Söderholm, 2006; Lagneback, 2007).

In accordance with the infrastructure manager's objectives, maintenance contractors and traffic operators derive a common, long-term benefit from providing a punctual and cost-effective transportation service, since this determines their competitiveness compared to other means of transportation. The railway punctuality target level is determined on a subjective basis, and political performance objectives thus evolve into a desired overall punctuality level. Even though the level of the punctuality target is selected on subjective grounds, it constitutes an objective foundation for how the lifecycle processes of the railway system are to be managed to achieve punctuality objectives cost-effectively. However, what is most cost-effective for the railway system (the infrastructure and rolling stock combined) in the long run is not necessarily that which generates the most revenue for operators and contractors in the short term.

From a maintenance point of view, the technical prerequisites for punctuality are met when both the rolling stock and the infrastructure subsystems provide the required functions on predetermined occasions and for predetermined durations. The Swedish railway system can be regarded as a series system (Blischke & Murthy, 2000; Rausand & Høyland, 2004), since most of the Swedish railway is constructed with single-line track without much redundancy. Hence, both the infrastructure and the rolling stock must provide adequate service in order to maintain safely a defined level of traffic at a given time. This means that the punctuality is dependent on a combination of technical functions that are simultaneously delivered by different organizations. The interdependence between the infrastructure manager, infrastructure maintenance contractors and traffic operators creates inter-firm relations (Mohr & Spekman, 1994; Gulati, 1995; Gulati & Gargiulo, 1999), due to the interactions between their respective technical systems. Within inter-firm relations, it is common to be exposed to the risks of opportunistic behaviour, which can come to affect the success of the combined enterprises (Gulati, 1995; Park & Russo, 1996; Hagen & Choe, 1998). Within the railway context, such risks may stem from different operational perspectives. Depending on how contracts are formulated, maintenance contractors' operational perspectives of five to seven years are short, compared to the infrastructure manager's longer perspectives, e.g. more than 40 years (Espling, 2004). Risks can arise when a contractor becomes aware that their contract is not going to be renewed. To increase the profit, a contractor may in such a case be willing to cut the costs for maintenance, by not performing adequate maintenance during the last stretch of the five year contract. Such opportunistic behaviour is possible since the effects on system performance caused by decreased maintenance are not immediate (Brealey & Myers, 2003; Vickerman, 2004). In this way the maintenance entrepreneur can maintain the technical function of the infrastructure for the remaining part of the contract, and increase the profit at the expense of the infrastructure manager and the succeeding contractor, who will take over a degraded system that requires more extensive maintenance or reinvestment efforts. One method applied by the infrastructure manager to reduce the risk of such behaviour is to wait as long as possible before notifying contractors as to whether their contracts will be renewed.

Opportunistic behaviour from stakeholders involved within the railway may put the achievement of the prosperity for society and the competitiveness objectives of their joint

system at risk. Therefore, this paper seeks to find answers to the question of whether the railway context motivates the stakeholders to improve punctuality by means of more effective and efficient maintenance, and, in accordance with LTU (2005a, 2005b), to describe how condition monitoring applications and availability performance measures can provide means to support punctuality improvements within the railway context.

### **Definitions and assumptions**

A stakeholder is a party having a right, share or claim in a system or in its possession of characteristics that meet the party's needs and expectations (ISO/IEC 15288, 2003). Examples of stakeholders throughout a system's lifecycle are users, developers, maintainers, disposers, acquirer and supplier organizations, regulatory bodies and members of society (ISO/IEC 15288, 2003).

In this paper, five stakeholders are considered:

- Infrastructure maintenance contractors, responsible for maintaining the infrastructure assets.
- Traffic operators, responsible for operating and maintaining the rolling stock.
- The infrastructure manager (Banverket), with the mission to pursue actively a cost-effective and reliable transportation service.
- Customers (members of the public and industry), who indicate the railway's competitiveness towards other means of transportation by their willingness to pay for the service of the railway system.
- The Government, which stipulates the foundation of the railway context (e.g. competition among actors within the railway sector).

The infrastructure manager, the infrastructure maintenance contractors and the traffic operators are considered as the three primary stakeholders. The reason for this is that these stakeholders are the ones that, through requirements and their own activities, affect the system lifecycle processes. Three types of stakeholder relations are examined: those between operators, between contractors and between operators and contractors. These relations are associated with the infrastructure manager's overall objectives of the cost-effectiveness and quality of the transportation service.

Discussions about the opportunistic behaviour of stakeholders will in this paper be conducted from society's perspective, which is reflected by the infrastructure manager's objectives. Accordingly, any stakeholder's behaviour is regarded as opportunistic if the stakeholder profits from activities that do not correspond to the infrastructure manager's overall objectives of cost-effectiveness and quality of service. However, the authors are fully aware that what can be regarded as opportunistic behaviour in this paper can be regarded as rational behaviour from other perspectives.

Punctuality is acknowledged as a key performance indicator within the railway sector (Åhrén, 2005), which to some extent characterizes the ability of the railway system to deliver transports on time according to the timetable. Punctuality is usually calculated by dividing the number of punctual trains by the total number of trains, and the result is then presented as the percentage of punctual trains (Olsson & Haugland, 2004; Nyström, 2005; Nyström, 2008). The Swedish railway sector's definition of punctual is "arrival at the end station at a time which is plus/minus five minutes from the timetable". In summary, punctuality should be treated as the extent to which an event takes place when agreed (Nyström, 2008).

Closely related to punctuality is availability performance, which is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided (IEV 191-02-05). This ability depends on the combined aspects of the reliability performance, the maintainability performance and the maintenance support performance (IEV 191-02-05). Operational availability is the probability that an item, when used under stated conditions in an actual operational environment, will operate satisfactorily when required to do so (Blanchard, 1992). Maintenance is the combination of all the technical and administrative actions, including supervision action, intended to retain an item in, or restore it to, a state in which it can perform a required function (IEV 191-07-01). The stakeholders' ability to provide the required functions will in this paper be discussed further primarily in terms of availability.

The introduction has considered aspects of postponed effects of reduced maintenance in the contract termination phase. Further presented scenarios primarily consider effects of reduced maintenance during the contract periods.

### **System lifecycle model**

A technical system's need for maintenance is more or less decided during the design and manufacturing stages for a specific function or performance (Blanchard & Fabrycky, 1998; Goffin, 2000; Blanchard, 2001; Markeset & Kumar, 2003). The technical systems that surround us, and which we are dependent on, also tend to increase in complexity (Juran & Godfrey, 1999). These complex technical systems often have a rather long life (White & Edwards, 1995; Sandberg & Strömberg, 1999). For example, several railway items have life lengths beyond 40 years (Espling, 2004). One example is turnouts, which are known to have operational lives of up to 40 years. During this life, the requirements for the system services will change due to technical development, and changes in the needs of stakeholders, the operational environment, laws and regulations (Bohner & Arnold, 1996; North et al., 1998; Juran, 1992; Kotonya & Sommerville, 1998; Herzwurm & Schockert, 2003). To maintain a high level of stakeholder satisfaction, throughout the system's lifecycle, the organizations responsible for the systems have to respond to changes in requirements through continuous improvement (North et al., 1998; Juran, 1992; Kotonya & Sommerville, 1998; Herzwurm & Schockert, 2003; Liyange and Kumar, 2003). Many complex technical systems of today are also critical ones with stringent requirements for safety, reliability, maintainability, and security, e.g. the railway, aircraft, nuclear power plants, and spacecraft. For many complex technical systems, the requirements for a lower cost of operation and support throughout the system's lifecycle have also grown in importance (Moubray, 1997; Sommerville & Sawyer, 1997; Cini & Griffith, 1999; Sandberg & Strömberg, 1999; Schmidt, 2001).

The lifecycle of a system can be described in terms of different phases and processes. Examples of typical lifecycle phases are: conception, development, acquisition, utilization, support and retirement. Examples of processes related to these phases are: operation, maintenance and modification. Selected sets of these processes can be applied throughout the lifecycle for managing the phases of a system's lifecycle. This is accomplished through the involvement of all the stakeholders with the ultimate goal of achieving customer satisfaction (ISO/IEC 15288, 2003). The processes illustrated in Figure 2 represent fundamental processes of a technical system's lifecycle, in which the railway stakeholders can contribute to improving the punctuality of the railway system.

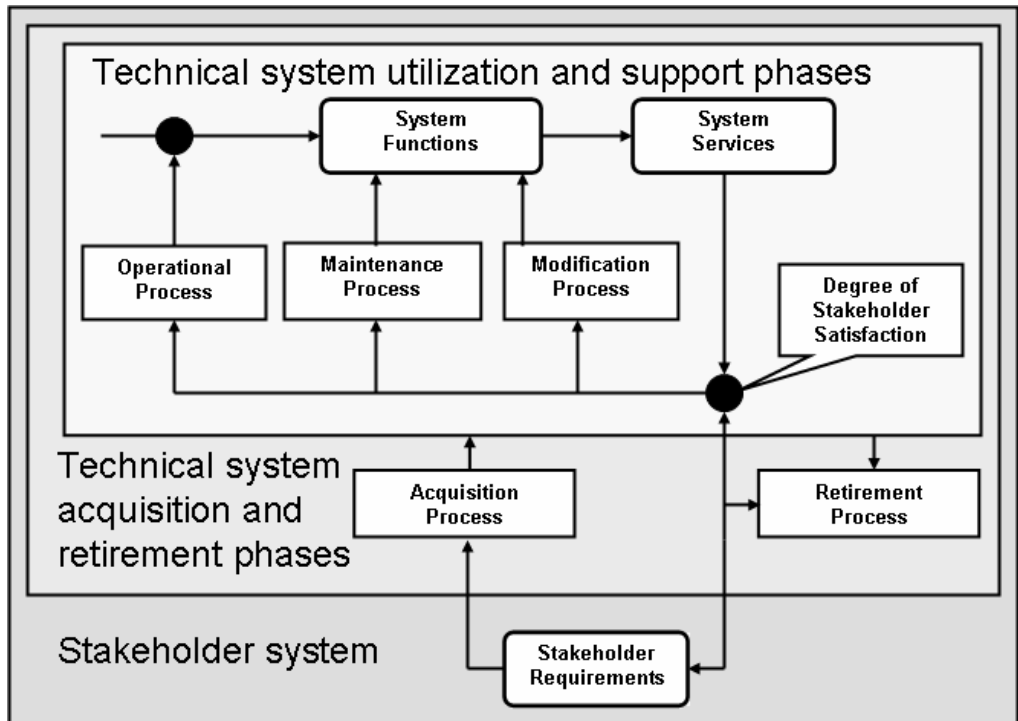


Figure 2. Generic system lifecycle model (adapted from ISO/IEC 15288, 2003; Söderholm et al., 2007b; and SS 441 05 05, 2000) illustrating how processes central to a system's lifecycle are affected by the requirements of stakeholders.

The system utilization and support phases and the system acquisition and retirement phases are an adaptation from ISO/IEC 15288 (2003), illustrating central processes in the technical system's lifecycle. The stakeholder system, which influences the utilization and support stages of the technical system, is adapted from Söderholm et al. (2007b) and SS 441 05 05 (2000). The system acquisition and retirement phases represent non-operational phases within the system lifecycle, i.e. before and after the utilization and support phases. Within the stakeholder system, the requirements stipulate the prerequisites for system utilization and support and system acquisition and retirement, as a function of stakeholder requirements and stakeholder satisfaction. A gap between the delivered system services and the stakeholder requirements motivates corresponding actions in appropriate processes, in order to achieve stakeholder satisfaction. A system design may become obsolete due to degradation or changes in stakeholder requirements (Söderholm, 2005), which can initiate a modification process or a system retirement process and, if required, a system acquisition process.

### Stakeholders within the railway system's lifecycle

The infrastructure manager has the overall responsibility for the quality of the transportation service of the railway. The infrastructure manager can affect the modification, acquisition, retirement and operational processes (see Figure 2) of the infrastructure. The operational process is affected through the infrastructure manager's train traffic control centres, e.g. through the rerouting of trains when disturbances occur and the remote operation of turnouts and the electric power supply. The infrastructure maintenance process and all the processes of the rolling stock that influence the railway transportation service are affected through

requirements directed towards maintenance contractors and operators. The infrastructure manager has three activities at its disposal to support an operational environment in which a cost-effective and punctual transportation service can be obtained. Firstly, the infrastructure manager must keep track of its own system lifecycle processes. Secondly, the infrastructure manager must ensure that operators and contractors align their activities by keeping to the timetable and thereby enabling them to perform scheduled activities. Thirdly, the infrastructure manager must ensure that the interaction between the rolling stock and the infrastructure enables the achievement of the required quality level of the transportation service and an acceptable degradation of bound capital. Hence, in order that the infrastructure manager may achieve the desired quality level of the transportation service, operators and contractors must provide the required functions, in terms of availability and interaction, of their respective systems.

Infrastructure maintenance contractors can ensure the required functions of the infrastructure system through their efforts within the infrastructure maintenance process. Since maintenance contractors generally are not responsible for the other processes within the infrastructure system's lifecycle, e.g. the modification and acquisition processes (see Figure 2), it is assumed that the infrastructure systems are not expected to perform beyond their capabilities. In other words, correctly performed maintenance allows the required infrastructure system functions to be realized. If these functions are not realized, the infrastructure manager must take action through applying the appropriate processes (Figure 2).

Traffic operators can ensure the required functions of the rolling stock primarily through their efforts within the rolling stock's operational and maintenance processes (see Figure 2). If these efforts are not sufficient, or if the rolling stock is no longer economically viable to operate and maintain (judged by the traffic operator), actions through appropriate processes must be taken (see Figure 2).

As described earlier, the infrastructure manager can support the fulfilment of the desired quality levels of the transportation service through its own activities and through requirements for availability and interaction made on operators and contractors. However, the non-existence of requirements, insufficiencies in requirements or the inability to assess the fulfilment of requirements can jeopardize the fulfilment of the objectives. Consequently, in the absence of adequate requirements, or in the absence of the ability to assess the fulfilment of requirements, operators or contractors can let their subjective desires state their own availability and interaction objectives. Even though it is not being claimed in this paper that maintenance contractors or traffic operators are generally unwilling to conduct adequate efforts in their respective lifecycle processes (due to the possible insufficiencies of the infrastructure manager's requirements or the inability to assess the fulfilment of requirements), a further exploration of stakeholder interrelations is presented below with the intention of demonstrating how stakeholders and the railway transportation service can be affected by the opportunistic behaviour of involved stakeholders.

### **Operator interrelations**

For the traffic operators the operation and maintenance effort, and the effectiveness of the efforts made to improve their assets will reflect the operational availability of their assets (Blanchard, 1992; Hawkins, 2004). An illustration of this relationship can be seen in Figure 3. Figure 3 illustrates, by simple marginal cost reasoning, how the operation and maintenance efforts made by operator A or operator B will impact on the respective assets' operational

availability levels. The operational availability level determined by the performed operation and maintenance effort is the level which their rolling stock will operate in accordance with.

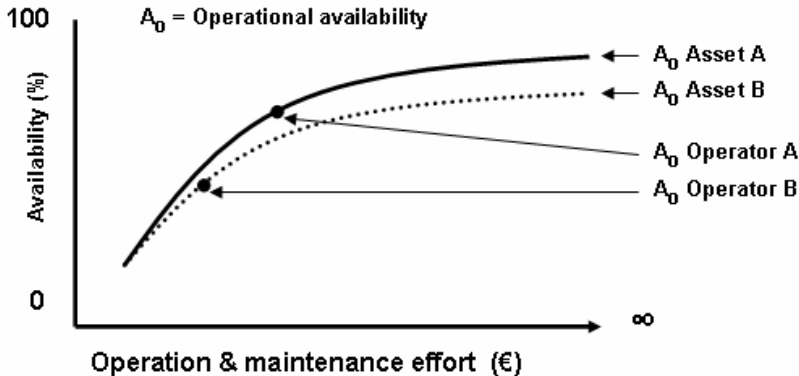


Figure 3. Illustration of relationship between rolling stock operation & maintenance effort and availability for the two cases Operator A with Asset A and Operator B with Asset B.

The provided level of operational availability can be affected by competition between different operators. This is due to the fact that the customers of their services may not be willing to pay for the extra availability from operator A, if they can obtain an acceptable service at a lower cost from operator B, see Figure 3. This would seem a fair deal within other transportation modes, e.g. transportation by road or ship. However, an interesting aspect of this is that, even though a customer may be willing to pay for the extra availability provided by operator A, it cannot be taken for granted that the operator will be able to provide a more reliable service because of knock-on delays caused by operator B's less reliable service. In other words, this creates a situation where operator A's ability to succeed in its tasks is affected by operator B's operation and maintenance effort. If operator A provides an availability level in accordance with the infrastructure manager's objectives and operator B does not, the situation creates a competitive disadvantage for operator A, if operator A is not compensated for the disruptions, or if operator B is not penalized in some way for the traffic disruptions caused. Further, such a scenario can also evolve into a situation where operator A reduces its efforts and operational availability in order to stay competitive.

This reasoning also applies to the system modification, acquisition and retirement processes (Figure 2) of the rolling stock. If there is no incentive for operator A to modify or acquire rolling stock to achieve a higher operational availability level (as illustrated by asset A in Figure 3) than that provided by operator B, due to an inability to exploit it, it is likely that cheaper material with lower performance characteristics will be acquired rather than more expensive and reliable rolling stock; or that rolling stock with excessively poor performance characteristics in relation to the infrastructure manager's objectives will be left in service.

In order to improve the collective availability of all the operators' rolling stock, it is important to find incentives that make it beneficial for the operators to put enough effort into both their utilization and support phases and their acquirement and retirement phases (see Figure 2). This will reduce the probability of causing sub-optimisation and failure to achieve the desired punctuality objectives due to the opportunistic behaviour of the operators.



### Contractor interrelations

To describe the situation for the infrastructure maintenance contractors, a similar line of reasoning as in the case of the operators is utilized, see Figure 4. For reasons of simplicity, it is assumed that, even though contractor  $\alpha$  and  $\beta$  are not operational on the same track sections, their respective assets share the same operational availability characteristics. This simplification is made due to the fact that the contractors generally cannot influence more than the maintenance process (see Figure 2). As in the case of operator interrelations, the contractors' maintenance efforts and the effectiveness of the efforts made on their assets will reflect the operational availability of their assets (Blanchard, 1992; Hawkins, 2004).

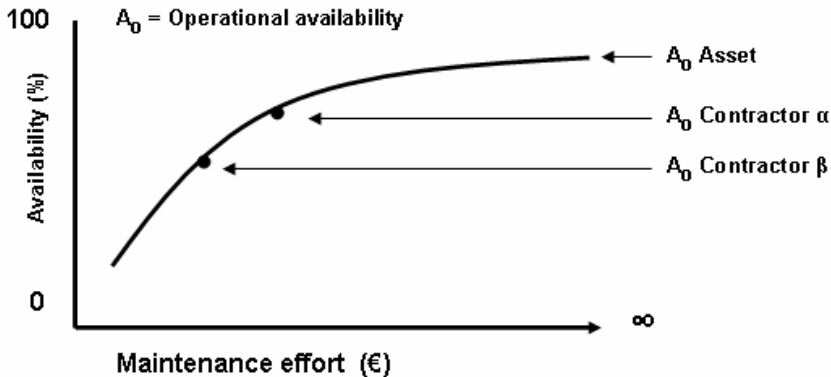


Figure 4. Illustration of relationship between infrastructure maintenance effort and availability.

Consider the scenario with two maintenance contractors where contractor  $\alpha$  is performing sufficient maintenance to fulfil the infrastructure manager's availability objectives and where contractor  $\beta$  is not (Figure 4). In this case the provided level of operational availability can be affected by competition between different maintenance contractors. This is due to the risk of opportunistic behaviour in the contracting period, whereby contractor  $\beta$ , in order to receive the contract, may be willing to offer a lower tender with the intention of cutting the costs for maintenance at the expense of the system functionality. If contractor  $\alpha$  does not receive any special benefits for efforts conducted to cope with the infrastructure manager's availability objectives, or if contractor  $\beta$  is not penalized for the unsatisfactory availability level provided, this will create a competitive disadvantage for contractor  $\alpha$ . Further, such a scenario can also evolve into a situation where contractor  $\alpha$  also lowers its tenders at the expense of the system functionality in order to be able to stay competitive.

In order to improve the collective availability of the whole infrastructure, it is important to find incentives that make it beneficial for contractors to put enough effort into their maintenance processes. The aim of this is to minimize the probability of not achieving the desired punctuality objectives due to opportunistic behaviour from the maintenance contractors involved.

### Operator and contractor interrelations

Figure 5 shows a triad model that illustrates the interrelation between the three stakeholders: traffic operators, infrastructure management (infrastructure manager and infrastructure maintenance contractors) and customers. The interrelationships between the three stakeholders are manifested by the cost as a function of the maintenance efforts in the two separate processes of infrastructure and rolling stock maintenance, at the two physical

interfaces between the wheel and the rail, and between the contact wire and the pantograph, as well as the resulting cost of the stakeholders' combined efforts within these interfaces. On the left hand side, the figure illustrates how a low rolling stock maintenance effort resulting in increased degradation of the infrastructure must be compensated by a high infrastructure maintenance effort to deliver the required functions of the rail or contact wire subsystems. On the right hand side, the figure illustrates how a low infrastructure maintenance effort resulting in increased rolling stock degradation must be countered by a high rolling stock maintenance effort to enable the required functions of the wheel or the pantograph subsystems. The accelerated increase in the cost on both sides is due to the increased amount of necessary corrective maintenance and the cost related to the accelerated erosion of bound capital, i.e. the subsystems' useful life is shortened at a greater pace, which means that reinvestments (the acquisition process, see Figure 2) must be initiated sooner than anticipated. For example, wheel flats can cause increased rail degradation and corrective maintenance activities on the rail. Wheel flats appear when a wheel slides on the rail (Lonsdale, 2003; Johansson, 2005). Wheel flats can be caused by poorly adjusted or defective brakes (Esveld, 2001; Johansson, 2005). Severe cases of wheel flats can damage the rail to the extent that it is no longer safe to operate on. Such cases significantly impact on train delays, since this calls for immediate track inspection and corrective maintenance activities, e.g. welding and replacement of rail. Catastrophic consequences of wheel flats are derailments with extensive losses.

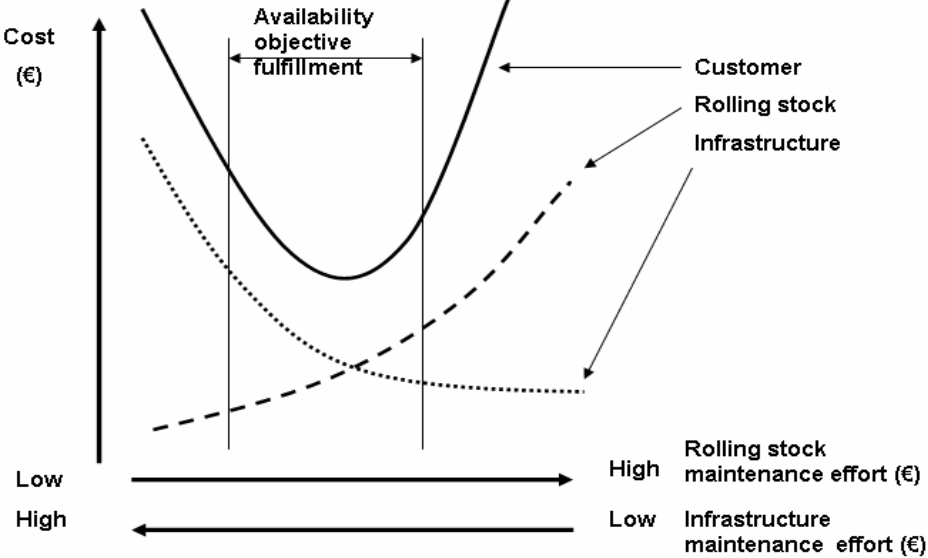


Figure 5. Triad model of interrelation between traffic operators, infrastructure management and customers, at the two physical interfaces between the wheel and rail, and between the contact wire and pantograph.

As previously illustrated, the three subsystems contact wires, tracks and turnouts are the largest causes of train delay time of all the infrastructure subsystems. The customer cost curve in Figure 5 is related to the price that the customer must pay in terms of freight charges, ticket prices or taxes for the combined efforts within the contact wire/pantograph and rail/wheel interfaces, which somewhat simplified is the summarization of the cost curves related to the rolling stock and the infrastructure. This cost curve is an adaptation of the Taguchi loss function; see Taguchi (1987) and Bendell et al. (1989).

Within Figure 5 it is assumed that the required availability can be achieved throughout the figure. However, beyond certain points of rolling stock interaction or infrastructure interaction, it will be impossible for the infrastructure management and traffic operators respectively to provide the required subsystem functions. This may be due to budget constraints. For example, an infrastructure maintenance contractor cannot afford to have multiple track repair crews dispatched along the track 24 hours a day 365 days a year. Hence, in a real context, with limited monetary resources, the required availability of the subsystem functions can only be obtained within a certain interval. The interval labelled “availability objective fulfilment” in Figure 5 can be described as the interval where the interactions between the rolling stock and infrastructure is such, that excessive degradation of bound capital is avoided, and where the available resources are sufficient for enabling the required availability of the subsystem functions. Beyond the boundaries of this interval punctuality is inevitably sacrificed.

In order to stimulate the stakeholders to provide services within the availability objective fulfilment interval (Figure 5), and to avoid a situation where an operator or contractor reduces its required efforts to achieve competitive advantages, incentives are needed. The aim of such incentives is to reduce the risk of excessive degradation of bound capital and to provide the operators and contractors with an operational environment in which maintenance activities are sufficient to enable the desired availability of the wheel/rail and contact wire/pantograph system functions.

### **Incentives for improved railway operation**

Consider the scenario with two operators where operator A is putting adequate effort into improving its operation and maintenance processes (to satisfy the infrastructure manager’s availability and interaction objectives) and operator B is not. If operator A does not receive any benefits for its efforts, or if operator B is not penalized in any way, a situation with negative competitiveness for operator A can emerge. Operator B will also influence the maintenance contractors’ ability to perform their tasks due to interference with scheduled maintenance activities and due to the increased amount of maintenance that the contractors have to perform, due to failure interactions such as wheel flats. Hence, the maintenance contractors must be compensated for the increase in the required efforts and costs. Since a part of the Swedish infrastructure maintenance budget is subsidized by track access charges (Notisum, 2006), a reasonable compensation would perhaps be that operator B would be penalized with a higher track access charge than operator A. These charges should be based on availability performance and interaction performance measures. This approach with differentiated charges would compensate the maintenance contractors for the increase in the required maintenance efforts, and simultaneously it could diminish operator B’s competitive advantage. A contractor that is not fulfilling the objectives of availability and interaction is interfering with both the operators’ and the other contractors’ scheduled activities and causing increased costs in terms of increased maintenance efforts and increased reinvestment needs as regards the rolling stock. Performance contracts including penalties or bonuses which are based on availability performance and interaction performance measures can be used to stimulate contractors to excel in their maintenance practices.

In order to achieve a situation where operators and maintenance contractors strive towards Banverket’s objective of punctuality at a minimum cost (ticket prices, freight charges, and taxes) for the customer, there is a need for incentives that make it profitable for the maintenance contractors and operators to put adequate effort into their respective lifecycle processes (Figure 2). However, the assessments of the individual stakeholder’s availability

and interaction performances that are deterministic input for the control of rewards or penalties within previously proposed incentive contracts (track access charges and performance contracts) must be assessed on objective grounds in order to avoid conflict-of-interest issues.

### **Availability and interaction performance measures**

In Sweden the punctuality measure is based on the arrival at the end station. This means that a train may be delayed according to the timetable on large portions of the route and thereby cause knock-on delays, but still be on time at the end station. Further, since this punctuality measure is a system performance indicator, it cannot be used to extract the individual performance of contractors or operators. Hence, the defined punctuality is not a good availability performance measure. A better performance measure for operators and contractors could be based on a connection between train delays and the absence of required rolling stock or infrastructure functions. However, the spread of train delays is determined by factors such as the time of day (capacity utilization), the localization on the network, and when the traffic controllers start to cancel traffic. Therefore, train delays correlated to the absence of an asset's required functions may not be a fully suitable performance measure either. One time-related measure that can be objectively determined is the time period for the absence of a required function (the absence having been caused by the stakeholder responsible); i.e. measuring the duration of the absence of a required function, not the effect of the loss of the required function. By measuring the absence time of required functions, the performance of operators and contractors can be measured on equal terms. However, operators and contractors cannot themselves determine their own availability performances. Hence, it is necessary that an independent third party evaluation should make such a judgement objectively, to avoid conflicts of interests (ECORYS, 2006). In the case of the Swedish railway, the train traffic control centres could act as this third party. One major reason is that they are already managing failure reporting and the train delay systems.

The train operator cannot, from an incentive contract perspective, be the party that decides if their rolling stock is operating within the availability objective fulfilment interval, see Figure 5. The same situation also applies to the maintenance contractors and their infrastructure assets. These issues must also be determined upon objective grounds. To assure proper degradation of the transportation system, the infrastructure manager can use condition monitoring technologies to assess continuously the interaction performances of both operators and contractors. For example, the infrastructure manager can use wheel impact detection systems, wheel profile monitoring systems and pantograph monitoring systems to assess the health of the rolling stock. The condition monitoring information can, in addition, be used to support condition-based maintenance of the rolling stock and infrastructure assets.

### **Concluding remarks**

Deregulation of the railway can be an effective way to cut costs for separate entities. However, it can also cause sub-optimization, whereby the overall system services may be jeopardized. In all the three examined relations (between operators and contractors, between operators, and between contractors), risks of opportunistic behaviour were exposed. This opportunistic behaviour is caused by the railway context and can have a negative impact on the stakeholders' willingness to improve punctuality by means of more effective and efficient maintenance. Hence, the stakeholder relations have to be acknowledged to create useful incentives for the alignment of the separate stakeholders' business requirements with the technical system's maintenance requirements.

With a total system lifecycle view, the stakeholders of the railway sector have a great deal to gain from the perception that they share important problems and that their separate maintenance processes sometimes should be seen as one, even though they are separated into different organizations. In this way, sub-optimization of infrastructure or rolling stock maintenance can be avoided to achieve optimal maintenance for the railway transportation system. Improvement work should emanate from a common view that considers the end customers' needs. Hence, how well the infrastructure manager (Banverket), the infrastructure maintenance contractors and the traffic operators jointly can control their separate and combined maintenance processes will determine the competitiveness of their shared enterprise.

Incentives that are related to adequate information derived from condition monitoring applications and availability performance measures can be used to provide means for stakeholders within the railway context to improve punctuality by maintenance efforts. These incentives should consider a total system lifecycle perspective and encourage stakeholders to make adequate efforts in their respective lifecycle processes to enable the optimization of the combined function of both the infrastructure and the rolling stock systems. In the future, the development of such incentives could motivate the railway industry to produce systems that cope better with the requirements of the separate and the combined maintenance processes. Hence, both the rolling stock and the infrastructure would be to a greater extent designed to cope with the shared objectives.

To manage railway maintenance efficiently, it is necessary to control the technical system. However, to achieve effective railway maintenance management in a partly deregulated environment, it is also necessary to control the business system. Hence, to achieve a desired service at a minimum cost within the railway sector, it is necessary to align the technical system's performance objectives with the profit goals of stakeholders.

Further research is required to assess what requirements for system functions must be fulfilled in order that stakeholders may provide the required system services. Such research should, for example, assess the availability levels that must be provided and what physical tolerances wheels and rails should operate within. Further research is also required to identify measurement methods that can be used to assess the stakeholders' ability to fulfil requirements for system functions. For example, such research should identify condition monitoring methods that can reflect the ability of operators and contractors to provide wheels and rails within prescribed physical tolerances. Further research will also be required to assess how economic incentives are to be related to the fulfilment of requirements.

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# Paper 4



# **A system and stakeholder approach for the identification of condition information: a case study for the Swedish railway**

**Rikard Granström**  
**Division of Operation and Maintenance Engineering**  
**Luleå University of Technology**  
**SE-97187 Luleå Sweden**

## **Abstract**

The purpose of this paper is to identify stakeholders' need for system condition information in order to improve railway punctuality. The paper provides a holistic formulation of maintenance-related punctuality problems within the interface between the contact wire and the pantograph. From the identified problem formulation, the information needed to support the maintenance of technical functions can be identified. The incorporated system and stakeholder perspective adds a dimension to the explanation of what information is needed and why it is needed. The system and stakeholder perspective on the assessment of the information need can serve as decision support when acquiring new condition monitoring technologies. Based on the problem formulation, this perspective can also serve as an illustration of how information is to be used to improve punctuality. In order to identify stakeholders' need for system condition information, a failure mode and effects analysis (FMEA) approach was used. The FMEA is complemented with information derived from informal interviews performed with a variety of experts working with issues related to contact wires and pantographs. The applied methodology can be useful for conducting further research studies on other stakeholder and engineering interfaces, such as the wheel/rail interface.

## **Keywords**

Maintenance, information, system, stakeholder, railway, contact wire, pantograph

## **1 INTRODUCTION**

The Swedish railway sector is partly deregulated, which means that private entities are allowed to compete for contracts to perform infrastructure maintenance on the rail network. This also applies to rolling stock operation, where private entities are allowed to perform traffic operation on the rail network. In Sweden, 80 percent of the railway network is owned by the Swedish Government [1]. The Government controls the infrastructure and most of the Swedish railway sector through Banverket (the Swedish Rail Administration). Banverket's main objectives, stated in the governmental transport policy objectives, are to ensure system safety, cost-effectiveness, reliability of service and sustainability, for example in terms of environmental impact and longevity of transportation provision for the public and industry. Governmental requirements state that Banverket has a sector responsibility for the railway, which means that it has an overall responsibility for the whole railway. This implies that Banverket should monitor and actively pursue development throughout the whole railway sector [1]. Hence, the responsibility for improving punctuality, among other things, lies with Banverket [2]. This government agency can affect the behaviour of stakeholders (operators and infrastructure maintenance contractors) within the railway sector by creating regulations or constructing contracts, some of which have economic incentives attached [2].

Being responsible for the overall functioning of the transportation system, Banverket must also monitor the behaviour of stakeholders who affect the functions of the system. Infrastructure maintenance contractors are responsible for the functions of the infrastructure and the traffic operators are responsible for the functions of the rolling stock. Therefore, it is important to consider what kind of information infrastructure maintenance contractors and operators need respectively in order to control the condition and degradation of their respective subsystem functions. It is also important to consider what kind of information Banverket needs in order to assess objectively the effectiveness (doing the right things) and the efficiency (doing the things right) of the maintenance work performed by the various stakeholders.

Banverket has initiated studies to explore how the punctuality of the railway system can be improved by applications of condition monitoring technologies [3]. To execute condition-based maintenance successfully, it is necessary to have control of both the technical health and the degradation behaviour of items [4, 5]. One of the main purposes of using condition monitoring technologies is to allow system health information to serve as decision support for effective and efficient maintenance management. At present there are numerous different technologies available for monitoring the condition of railway systems [6, 7, 8]. There is definitely no shortage of initiatives from industry to provide condition monitoring solutions to solve maintenance-related problems. Hence, finding a possible solution to the task of obtaining health information about the functions of technical systems is unlikely to be a major problem. The problem may be more related to finding a proper solution. A proper solution does not necessarily focus on what can be measured, but rather on the kind of information needed. This can be illustrated by problems related to low testability and insufficient integration of different maintenance echelons, e.g. No-Fault-Found (NFF) events [9, 10]. A proper solution is rather a solution that can provide the decision support required for effective and efficient maintenance management. From such a perspective, there arises a need for critical assessment of the technology itself and, primarily, the characteristics of the problem that is to be solved.

The maintenance-related punctuality problem that is under scrutiny in this paper concerns the contact wire/pantograph system interface. A holistic problem formulation for the system is established to identify information that is relevant to controlling the technical health and degradation of the system. Moreover, the problem formulation is relevant to understanding why the information is needed. The aim of the study is therefore to use the problem formulation as a guideline for identification of the need for information from both a system and a stakeholder perspective. It is important to ascertain what information Banverket, the infrastructure maintenance contractors and the traffic operators need to fulfil their respective responsibilities, and to understand why that information is needed. This can act as input data that can help identify what kind of condition monitoring solutions can provide the decision support required for effective and efficient maintenance management. It can also help to illustrate how the same information is useful from different stakeholder perspectives (which is worth considering when acquiring condition monitoring solutions), as well as helping to estimate the improvement potential of applying condition monitoring solutions.

The contribution of this paper, in addition to the attempt to construct a holistic problem formulation of the contact wire/pantograph interface and to apply the stakeholder perspective to the information needed, is the exploration of the methodology used within the study. This methodology may perhaps be applicable to the rail/wheel interface or, for that matter, to other interaction-dependent engineering systems.

The outline of the remaining part of this paper is as follows. In Section 2 the studied contact wire/pantograph system and its stakeholders are introduced. In Section 3 the research approach applied is presented and justified. Section 4 contains the analysis and results of the performed study. This section is first divided into subsections dealing with the contact wire and pantograph subsystems respectively, and then into subsections treating the modes, causes and effects of failures. In addition, the currently applied condition monitoring methods and the perspectives of the stakeholders are presented, with an emphasis on related information requirements. Section 5 contains a discussion about the results of the study, and Section 6 gives some concluding remarks.

## 2 THE STUDIED SYSTEM AND ITS STAKEHOLDERS

Electric energy for the Swedish railways is supplied at high voltage to feeder substations, where the voltage is reduced to a suitable level (15kV 16.7 Hz) and fed to the railway contact wire system to be used by locomotives and trains. On railways, the electric current passes from the contact wire via the rolling stock's pantograph to the locomotive (see Figure 1), where the energy is used by electric motors and fed to the earthed rails, which are part of the return circuit. Hence, the overall purpose of the contact wire/pantograph system is to transfer electric energy properly from the infrastructure to the rolling stock. Therefore, certain behavioural characteristics of both the infrastructure and the rolling stock must be guaranteed in order to achieve this overall purpose. In other words, certain demands on specific functions of both the infrastructure and the rolling stock must be met in order to achieve a proper transfer of electric energy.

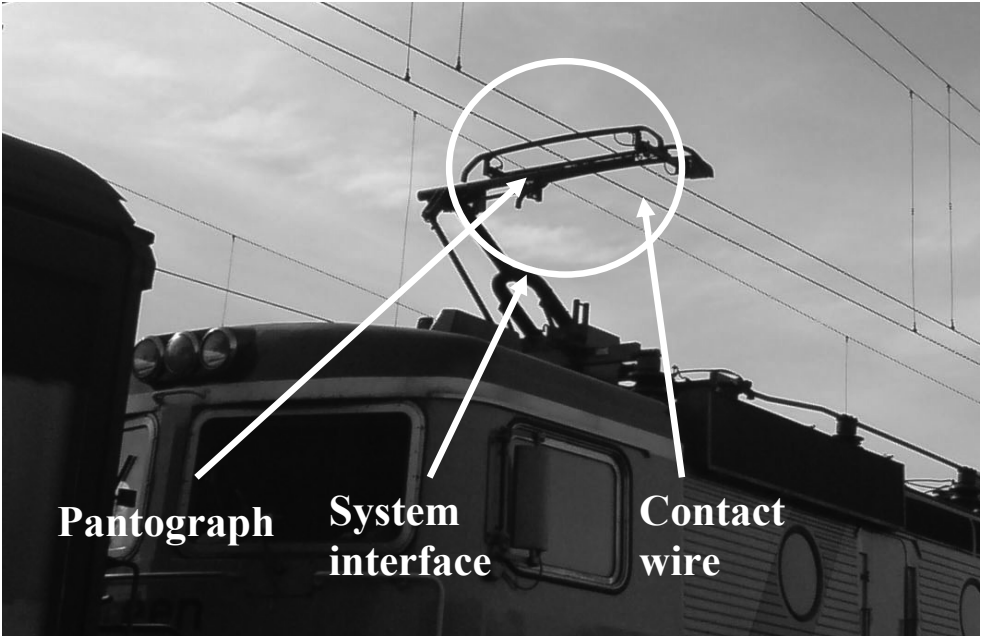


Figure 1. *The contact wire, the pantograph and their critical system interface.*

Table 1 illustrates the top five reasons for infrastructure-related train delays in Sweden during 2004-2006 (these figures are approximately the same every year).

NO.	Subsystem Years 2004 – 2006	Delay attributed to infrastructure (%)	Delay attributed to infrastructure (h)	Number of train delays	Average delay attributed to each failure (h)
1	Track	20%	7,173	2,995	2.4
2	Contact wire	18%	6,370	1,030	6.2
3	Turnout	17%	5,963	6,383	0.9
4	Signal box and section block	13%	4,764	3,703	1.3
5	Positioning system	5%	1,808	2,646	0.7

*Table 1. Top five causes of infrastructure-related train delays, 2004 – 2006. Data collected from Banverket's TFÖR (train-delay registration) system.*

Contact wire and track failures take turns at being the dominant infrastructure subsystems causing the most train delay time. Contact wire failures happen less often than turnout failures, but when they do occur, they tend to block traffic for quite some time (6.2 h on average, see Table 1). Turnouts contribute the most train delays, but the average delay per fault for turnouts is quite low (0.9 hours on average) compared to that for the contact wire. One interesting observation is the number of train delays attributed to each asset. If assumed that the time that it takes from the system fault recognition to the initiation of a corrective maintenance action is similar for both the contact wire and the turnout, this would imply that the time impact from the maintenance identification to the maintenance initiation is six times greater for turnouts than for the contact wire. However, contact wire still causes the most train delay time, so it can be concluded that contact wire faults are far more critical than turnout faults.

When large traffic disruptions occur, Banverket starts cancelling trains in order to reduce knock-on delays (trains that are delayed due to other delayed trains) on the network. Cancelled trains are not reported in any delay statistics. Hence, the total effect of large traffic disruptions will never be apparent in the delay statistics. Therefore, the influence on train delays from failures on track or contact wires is underestimated to a higher degree in the delay statistics than the corresponding influence from other subsystem failures. Banverket has no exact time limit for deciding when to start cancelling trains. This is instead determined by the traffic controllers on a case-to-case basis. Nor is there any correlation made between the number of cancelled trains and the causes of delays, so it is impossible to estimate exactly how many trains are cancelled due to each subsystem failure respectively.

In order that the infrastructure maintenance contractors may forecast effectively the need for preventive maintenance, the contractors depend on the deterioration caused to the infrastructure by the rolling stock being as predictable as possible, and small enough to enable adequate response time. However, the train operators adopt a similar strategy when focusing on their rolling stock. The interrelationship between the stakeholder roles and the physical interaction of their assets (through the wheel/rail and pantograph/contact wire interfaces) is complex, since it is difficult to pinpoint the causes of failure interactions within the interfaces. Related examples can be found throughout the railway sector, where the increased strength of rail causes reduced serviceability of wheels, or where the increased hardness of wheels causes reduced serviceability of rail [11, 12].

Figure 2 is an illustration of train delays related to the top thirty reported causes of contact wire failure.



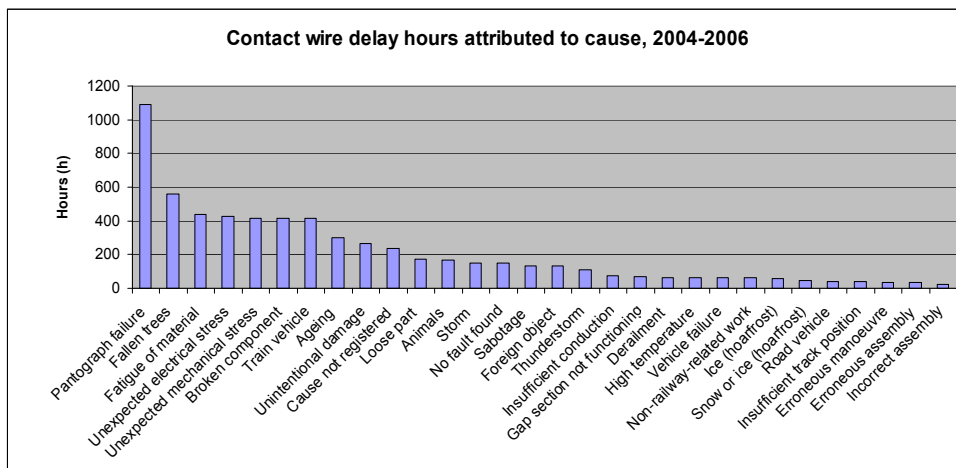


Figure 2. Illustration of the top thirty causes of train delay time related to the contact wire system. Data collected from Banverket's failure/fault report system Ofelia.

According to failure statistics (Figure 2), failures of the rolling stock's pantograph are responsible for nearly 20 percent of contact wire-related train delays. The real delay contribution from pantograph failure is (according to Banverket experts) estimated to be somewhere around 40 percent. This is, however, not visible in the statistics, being hidden behind causes such as train vehicle, unexpected mechanical stress, fatigue of material, and cause not registered, which also contain an influence from pantograph failures.

### 3 APPROACH

As a first step to enforce punctuality improvement (given the responsibility bestowed on Banverket by the Swedish Government), a set of control indicators must be identified. These are indicators that assess whether the stakeholders (operators and contractors) manage to deliver adequate system functions (functions required to enable adequate train operation). Consequently, a focus of this paper is to identify what condition information is needed in order to monitor the health of the functions delivered by the maintenance effort of the respective stakeholders. To highlight the necessity of acquiring knowledge of the subsystem conditions, the paper also focuses on describing why information is needed from different stakeholder perspectives.

A fault is in this paper considered at the system level, and, therefore, a train delay is a fault. A failure is regarded as a subsystem function which has deviated from its prescribed performance criterion, but has not yet caused a system fault.

The systems' functions and interactions are explored using qualitative data analysis [13]. The Failure Mode and Effects Analysis (FMEA) methodology [4, 14, 15] is used to explore the problem inductively from the component level via the subsystem failure mode to the system level fault. This approach is chosen due to the study's focus on inductively exploring functions and information for failure mode identification and failure mode localization [4, 5, 16] concerning the contact wire/pantograph system, rather than on deductively studying them through, e.g., fault tree analyses [17].

The FMEA relating to the contact wire and the pantograph functions contained (according to the guidelines in IEC 60812) an expert assessment of what kind of subsystem functions the respective systems are to deliver (to assure a proper power conduction), the possible causes of absence of function, the local effect (of absence of function), the end-item effect (train delay), the applied methods for detection of failure, the present fault-prevention provisions and, finally, the information needed to control the health of each identified function respectively.

Some delimitations were used in the FMEA study. The study does not regard the functions of the power supply to the contact wire system. The pantograph functions that are considered are only those functions whose absence can cause damage to the contact wire. It was also assumed that the systems are not expected to perform beyond what they are designed to do. In other words, it is assumed that proper maintenance is sufficient to assure a proper system function. Consequently, design changes to cope with deviating performance requirements were not dealt with to any extent. Moreover, only functions whose absence could propagate into a system fault (train delay) were considered, i.e. the end item effect is the same for all the identified failure modes.

Even though the study was not conducted as an FMECA (Failure Mode, Effect and Criticality Analysis), some effort was made to retrieve a priority ranking of the identified failure modes and to assess the detectability of the failure modes by the currently applied condition monitoring methods. FMECA is an extension of FMEA to include a criticality assessment of the failure modes and thereby allows a prioritization of countermeasures [15]. The two major criticality assessment approaches that normally are utilized in FMECA applications are based on the criticality matrix or the Risk Priority Number (RPN) [15]. However, in some cases the necessary information is not available and it becomes necessary to revert to a simpler form of a non-numeric FMEA [14, 15, 18]. In this study no relevant historical data is available. Hence, no analytical methodologies, such as Fault Tree Analysis (FTA) and Event Tree Analysis (ETA), or simulations could be used to estimate the frequencies of unwanted events [19]. However, for the purpose of the present FMEA, it is believed that expert judgement is sufficient and that a Delphi-influenced approach [20] is appropriate to elicit the experts' estimates of failure mode prioritization and the failure modes' degree of detectability. Regarding the priority ranking estimation, it is believed that a criticality matrix approach (considering a combined estimate of severity and probability) is sufficient to render a priority ranking of failure modes (see, e.g., IEC.60300-3-9 [19]), especially when considering the inconsistency of RPN (see, Kmenta & Ishii [18] for a thorough discussion about the limitations of RPN). To extend the performed FMEA by further pursuing the estimation of the severity and of the probability of identified failure modes, a more formal FMECA could be applicable. This could be carried out by applying the Analytic Hierarchy Process (AHP) or some other methodology for pair-wise comparison, as described by Saaty [21]. Another possibility would be to apply the expected cost approach in a scenario-based FMEA, as presented by Kmenta & Ishii [18].

The study was conducted in four parts. The first part of the study was a deductive exploration of contact wire failures and train delay statistics, much of which has already been presented in the introduction of this paper. This part of the study was performed to obtain an initial problem formulation for the forthcoming parts of the study. The second part of the study was the FMEA effort, which was performed at Banverket's headquarters. The FMEA study was conducted in cooperation with three contact wire experts with several years of experience of working with contact wire systems. The FMEA study formulated the baseline problem description for the contact wire/pantograph system.

In order to include the stakeholders' perspectives, the third part of the study involved informal interviews with infrastructure managers, infrastructure maintenance contractors, traffic operators, pantograph experts, rolling stock workshop staff and personnel operating Banverket's measuring wagon (STRIX). Some of the interviewees (pantograph experts and traffic operators) were identified during an annual pantograph expert meeting at Banverket's headquarters (which the author attended). Other interviewees were selected based on recommendations from Banverket and the traffic operators (infrastructure managers, maintenance contractors, rolling stock workshop staff and STRIX personnel). During these interviews, the interviewees had the chance to reflect on the results from the FMEA problem formulation created by the Banverket experts. The interviewees were also requested to declare how present maintenance practices were conducted. Additional information from the interviewees was incorporated into the study. The fourth part of the study is an analysis of the information retrieved, which is presented below.

## **4 ANALYSIS AND RESULTS**

To provide a structured description of the complex problem connected with the contact wire/pantograph interface, this section is divided into two parts. The first part (Section 4.1) provides a system perspective by giving a description of contact wire and pantograph failure modes and the methods that are applied to monitor these failure modes. This section gives a perception of what kind of information is needed to gain control of the failure modes. The second part (Section 4.2) adds the stakeholders' perspective on the problem (described in Section 4.1) to illustrate why the information is needed.

### **4.1 System perspective**

This section provides first a description of contact wire failure modes and the methods that are applied to monitoring these. Subsequently, the pantograph is dealt with in a similar manner. Finally, a priority ranking of the identified failure modes is presented, together with an assessment of the failure modes' degree of detectability using the applied condition monitoring methods.

#### *4.1.1 Contact wire failure modes, effects and causes*

The identified contact wire failure causes and failure modes, the local effects, the end item effects and how they are inter-related are illustrated by the causal map in Figure 3. The descriptions of the Failure Modes (FM), Failure Effects (FE) and possible Failure Causes (FC) are subsequently presented.

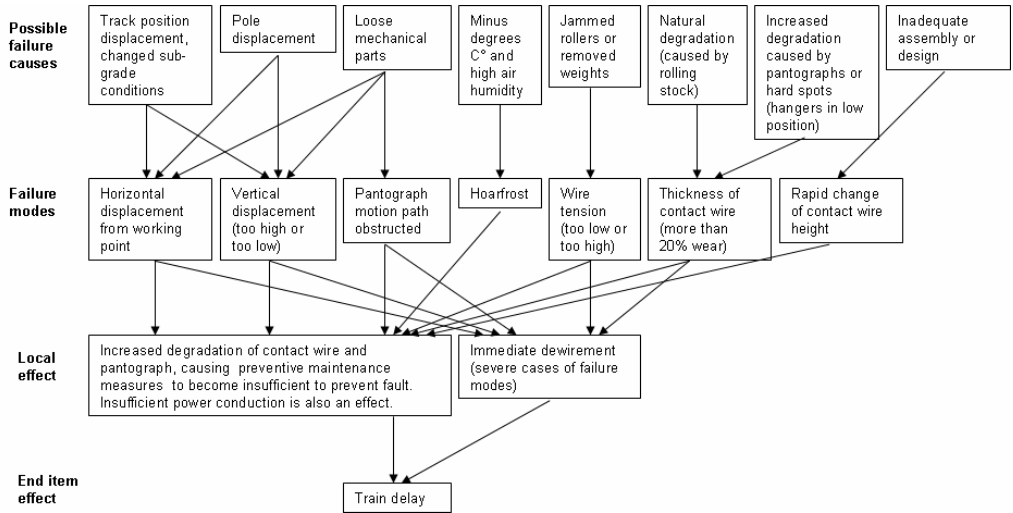


Figure 3. Causal map of identified contact wire failure causes and failure modes, the local effects, the end item effects and how they are inter-related.

FM (Horizontal displacement from the working point): The contact wire must stay within the prescribed horizontal distances from the centre of the track. This is necessary to avoid the contact wire reaching beyond the span of the pantograph's carbon slipper. The contact wire position must still fluctuate in relation to the centre of the track in order to enable an even degradation of the pantograph's carbon slipper. FE: If the contact wire position is out of tolerance, this can cause damage to the pantograph and, in a worst-case scenario, immediate dewirement (when the pantograph mounts the contact wire and tears it down). There is also a risk of insufficient power conduction (which can cause sparks and luminous arcs and damage both the contact wire and the pantograph). FC: Possible causes of loss of function are: displacement of the poles holding the contact wire; damage to or loosening of mechanical parts; or a change in the track position. One usual cause of displacement of the contact wire is non-coordination between contact wire adjustment actions and tamping actions performed on the track. Thus, the track position is changed, but the contact wire position is not adjusted accordingly.

FM (Vertical displacement from the working point): The contact wire must stay below the prescribed highest vertical distances from the top of the rail. It must also stay above the prescribed lowest vertical distances from the top of the rail. FE: If the vertical position is too high, the pantograph cannot reach the contact wire. This causes a luminous arch, which can cause burn damages to the pantograph (damaging the carbon slipper and the glue holding it to the aluminium profile) and the contact wire or, in a worst-case scenario, immediate dewirement. If the vertical position is too low, there is a risk of damage to the pantograph's carbon slipper, immediate dewirement and/or luminous arcs being discharged towards vehicles and cargo (which can be damaging to both the contact wire and the rest of the rolling stock). FC: Possible causes of high vertical displacement can be either pole displacement or low rails due to changed sub-grade conditions. Possible causes of low vertical displacement can be a high track position due to changed sub-grade conditions, low wire tension or loose mechanical parts.

FM: (Pantograph motion path obstructed): The motion path of the pantograph must be free from obstacles in the infrastructure. FE: If the motion path is not free from obstacles, the pantograph will smash into misplaced infrastructure objects, causing damage to both the pantograph and the infrastructure. Severe cases can lead to immediate dewirement. FC: Possible causes can be loose or misplaced mechanical parts.

FM (Hoarfrost). FE: If hoarfrost appears on the contact wire, the power conduction will be negatively affected. Hoarfrost causes luminous arcs between the contact wire and the pantograph, thus causing heavy degradation of the pantograph. The contact wire will also degrade more quickly. FC: The cause of hoarfrost is below-zero temperatures combined with high air humidity, and hoarfrost is especially common in the northern parts of Sweden during September, October and November.

FM (The contact wire tension is either too high or too low): The contact wire must have a certain tension to withstand the pressure from the pantograph properly, preventing the pantograph from smashing into infrastructure objects. The tension of the wire is determined by the permitted maximum train speed: the faster the trains the higher the tension. This is to prevent dynamic motions (which can damage the system) between the contact wire and the pantograph. Tension weights are attached to the contact wire to ensure the proper wire tension. FE: If the wire tension is too high, the contact wire may snap. If the tension is too low, the contact wire position will be too low in relation to the top of the rail, thus increasing the risk of luminous arcs at the cantilevers (holding the contact wire). This also increases the risk of dynamic behaviour and bad power conduction. FC: The cause of insufficient wire tension can be that the rollers from which the tension weights hang are jammed, or that the weights have been removed.

FM (Too thin a contact wire): The contact wire must not (according to specifications) be degraded by more than 20 percent of its original dimensions if it is to withstand the forces that are applied to it. FE: If the wire thickness is too low, the wire is likely to snap. FC: Single-point wear could be caused by trains standing still or hard spots (hangers in a low position, causing accelerated motion of the pantograph, causing in turn increased degradation of the contact wire and the pantograph's carbon slipper). Increased degradation can also be caused by pantograph failure (a damaged carbon slipper, too high or too low a lift pressure, or incorrect dynamic motion).

FM (Rapid change of the contact wire height): If the contact wire height changes too rapidly, it is likely to cause accelerated vertical motion of the pantograph. FE: Accelerated pantograph motion causes increased degradation of the contact wire and the pantograph's carbon slipper. FC: Inadequate design or assembly might be the cause.

The only identified compensating provision against faults is to equip trains with double pantographs, so that, if one gets damaged, the other one can be used. A compensating provision against the hoarfrost failure mode can be to use a thicker carbon slipper, which can lessen the effects of hoarfrost. Further, a method for removing hoarfrost is to use the first pantograph (not electrically connected) on the train as an ice scraper. This is a method that was used in the past, but is no longer permitted under Banverket regulations. However, according to the interviewed traffic operators, there are just as many luminous arcs formed at the third pantograph as at the first when there is hoarfrost and when triple-headed locomotives are being used to haul heavy cargo.

#### 4.1.2 Applied methods for contact wire failure mode identification

The applied methods for the detection of contact wire failure and the information needed to gain control of the failure modes are presented in the causal map in Figure 4. The additional information required to gain better control of the respective failure modes, compared to the present-day situation, is represented by the information gap.

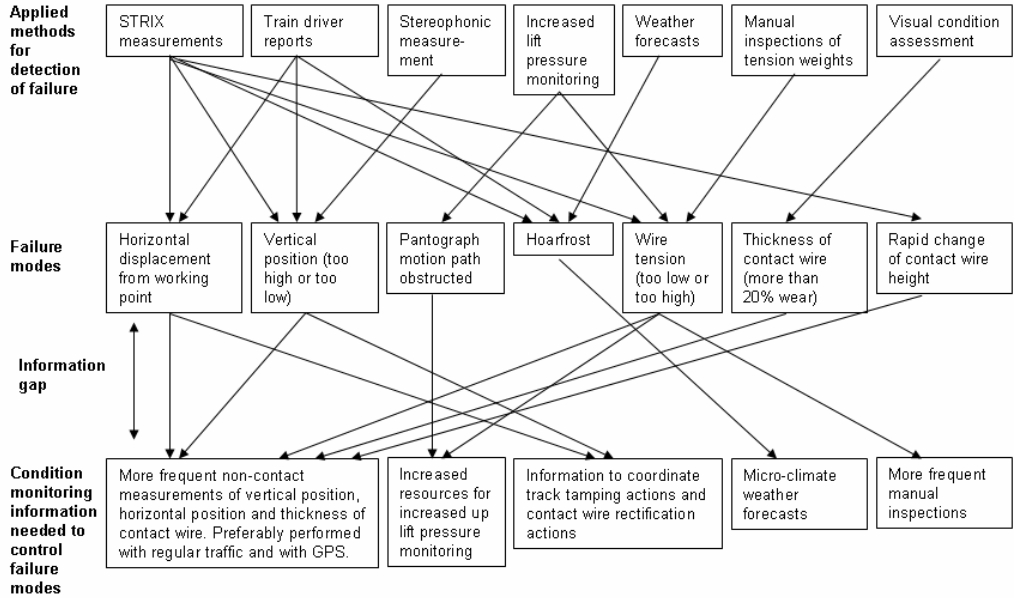


Figure 4. Causal map of applied condition monitoring methods for detecting contact wire failure modes and the information needed to gain control of the failure modes

STRIX is Banverket's measurement wagon. The STRIX pantograph is in physical contact with the contact wire and measures the horizontal and vertical displacement of the contact wire (by use of accelerometers and strain gauges). In this way it also records the dynamic behaviour of the pantograph's contact with the contact wire. Therefore, the measurements are influenced by the behaviour of the STRIX pantograph. According to Banverket experts, the accuracy of STRIX measurements is questionable. STRIX also takes video recordings of the infrastructure. However, these videos are rarely used for failure identification purposes. STRIX measurements are performed on most of Banverket's track structure (sidings at stations are excluded). STRIX is to perform at least two measurements per track section per year. The measurements are performed between March and November (the period from December to February being devoted to maintenance and upgrades of the system). It is interesting to observe that most of the problems relating to the contact wire and pantograph appear between November and March (when no measurements are made). Predetermined inspections and maintenance in the northern track region are performed on the contact wire system every third and sixth year (more rigorous inspection). In between these predetermined occasions, STRIX is the primary source of failure identification. If STRIX measurements indicate that the contact wire is out of tolerance, a work order is sent to the maintenance contractor to correct the problem. However, the contractor is frequently incapable of identifying the failure (i.e. no-fault-found events occur) due to the inaccuracy of the kilometre positioning system used to localize the failure.

Figure 5 (a photograph taken at a train workshop) shows a sample of some thirty used pantographs, all of which show signs of degradation outside the tolerances of the carbon slipper (the new shiny pantograph being used as a reference). These pantographs all showed clear signs of burn damage caused by sparks or luminous arcs. The pantographs all indicate that the present maintenance practice is unable to keep the contact wire within acceptable horizontal and vertical distances. However, it should be noted that the contact wire will (according to Banverket experts) inevitably come into contact with the pantograph's aluminium profile when the trains come into, or go out from sidings.

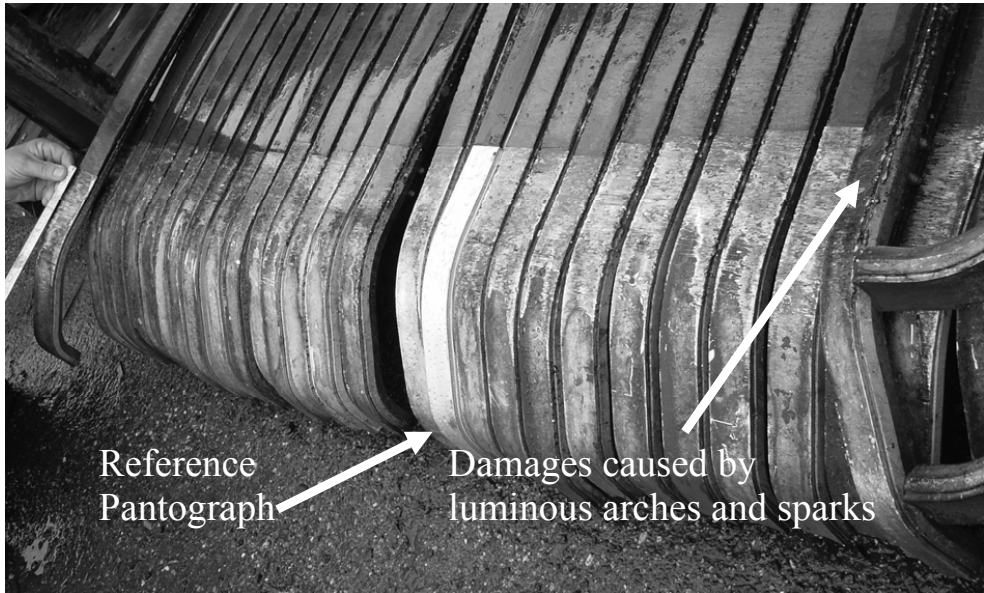


Figure 5. *Sample of some thirty pantographs showing signs of burn damage and degradation outside of the carbon slipper's work area.*

To achieve better control of the horizontal and vertical position of the contact wire, there is a need for more reliable and more frequent non-contact measurements of the vertical and horizontal position of the contact wire. This should preferably be performed with regular traffic and with the Global Positioning System (GPS).

Incorrect behaviour of the contact wire can be identified by the train driver, either as observations of contact wire motions, identification of sparks and luminous arcs or as indications of bad power conduction from the train's line voltage meter. In some cases, the train driver reports identified and localized failures for the train traffic control centre. One way of identifying the positions of insufficient power conduction (where there are sparks and luminous arcs) is to merge GPS data with line voltage meter logs. With such information, the infrastructure maintenance contractor will be able to identify and localize failures that cause insufficient power conduction more accurately (low wire tension, hoarfrost, etc.).

Stereophonic measurements can be used to assess the distance between the rail and other infrastructure items; e.g. to assess whether the vertical position of the contact wire is too high or too low. However, these measurements are only used to assess whether cargo larger than

the prescribed maximum sizes can be hauled without causing damage to the infrastructure. These measurements are used very occasionally.

Increased lift pressure monitoring is used to detect elements that can cause damage within the pantograph's motion path. This is not an automated method, since it involves lifting the contact wire to perform listening and visual inspections, filming and stopping to take pictures. There are only two measurement carriages in the whole of Sweden. The resources for these measurements are limited and, therefore, large proportions of the network are not monitored by this method. The interviewed traffic operators highlighted the importance of conducting these measurements in both directions, e.g. north and south, since their experience has shown that some failures only appear in one direction. It is important that the resources for this monitoring should be increased to gain acceptable control of the failure mode.

Weather forecasts can be used to predict hoarfrost. Micro-climate forecasts (local weather forecasts) can be one way of predicting the presence of hoarfrost even more accurately. However, their usefulness for the maintenance contractor can be questioned, since the trains will still be running. Of course, the forecasts can alert the contractor to necessary corrective maintenance activities, but the information is at present not of much use for preventive purposes. However, there are preventive methods that could be employed to remove the hoarfrost or prevent it, methods which involve defrosting the contact wire (short-circuiting the wire and melting the frost) or treating the contact wire with glycerine. These methods are not applied today. The information could perhaps be of greater use to the traffic operators, who could (as they do during winter) shorten their carbon slipper inspection intervals. Micro-climate forecasts could perhaps be useful in a longer-term perspective. If the other failure modes are under control, the true effects of hoarfrost can be assessed, and, therefore, the information can be used as input data for the redesign of infrastructure and rolling stock components.

Tension weight rollers are lubricated at periodic intervals. The applied methods for inspecting the contact wire tension are STRIX measurements (STRIX being able to detect slack indicated as wire in a low position), increased uplift monitoring and the manual lifting of counterweights to assure that the rollers are not jammed. Further resources are required to gain better control of this failure mode.

The thickness of the contact wire is occasionally inspected manually (visual inspection) by use of a cart running under the contact wire. However, this method is not especially accurate and very time-consuming. To gain control of this failure mode in an adequate way, it is essential to apply a non-contact condition monitoring method that at acceptable speed can localize the failures using GPS.

#### *4.2.1 Pantograph failure modes, effects and causes*

The identified pantograph failure causes and failure modes, the local effects, the end item effects and how they are inter-related are illustrated by the causal map in Figure 6. The descriptions of the Failure Modes (FM), Failure Effects (FE) and possible Failure Causes (FC) are subsequently presented.



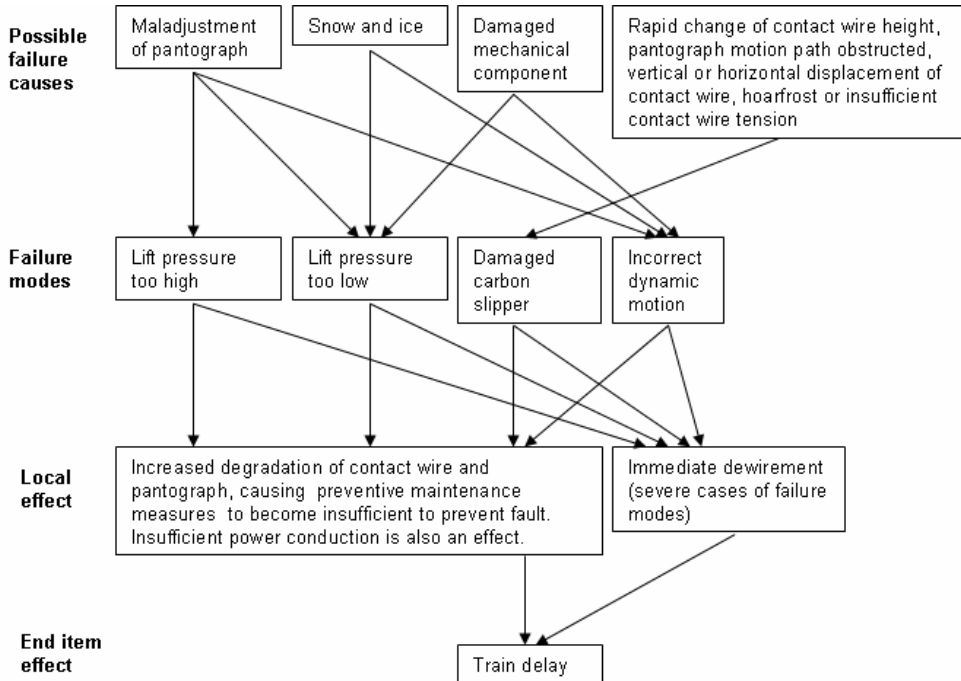


Figure 6. Causal map of identified pantograph failure causes and failure modes, the local effects, the end item effects and how they are inter-related.

FM (Lift pressure too high): The pantograph exerts a certain pressure towards the contact wire to assure proper power conduction, and the pressure is in many cases increased at higher train speeds. FE: If the lift pressure is too high, the pantograph's motion path can become obstructed (due to high operation). Besides increased degradation of the carbon slipper (due to high contact pressure), this can cause the pantograph to smash into infrastructure objects, thus causing dewirement. FC: One cause of too high an uplift pressure can be maladjustment of the pantograph.

FM (Lift pressure too low). FE: If the lift pressure is too low, this can cause sparks and luminous arcs between the contact wire and the pantograph. In addition to increased degradation of the system, this also causes bad power conduction. Severe cases can cause dewirement. FC: Too low a lift pressure may be caused by maladjustment of the pantograph, or snow and ice becoming attached to the pantograph and preventing it from operating properly.

FM (Damaged carbon slipper): The carbon slipper is attached to the pantograph's aluminium profile. The function of the carbon slipper is to receive electric energy from the contact wire and at the same time allow for minimum degradation of the contact wire. FE: If the carbon slipper is damaged and pieces of carbon are removed, the aluminium profile will come into contact with the contact wire, causing increased degradation. Severe cases cause dewirement. FC: Possible causes of damaged carbon slippers are that the pantograph lift pressure may be too high or too low or that there may be incorrect dynamic motion of the pantograph. The following infrastructure failure modes can also cause damage: rapid change of the contact wire height; the pantograph's motion path being obstructed; vertical or horizontal

displacement of the contact wire; and hoarfrost or insufficient contact wire tension. Another identified cause of carbon slipper failure is poor carbon quality [22].

FM (Incorrect dynamic motion): FE: If the dynamic motion of the pantograph is incorrect, this can cause increased wear on both the contact wire and the pantograph owing to the dynamic impacts and the luminous arcs that may appear. It may also be difficult to keep the pantograph’s motion path free from obstacles (due to intensive operation). FC: The causes of incorrect dynamic motion can be maladjustment of the pantograph, ice or defective mechanical pantograph components or insufficient contact wire tension.

The only identified compensating provision against the pantograph-related failure modes presented above is the Automatic Drop Device (ADD), which is fitted on some locomotives. The ADD’s primary function is to drop the pantograph when the carbon slipper gets damaged. There are also ADDs that drop the pantograph when too rapid vertical accelerations are applied to them.

4.2.2 Applied methods for pantograph failure mode identification

The applied methods for the detection of pantograph failure and the information needed to gain control of the failure modes are presented in the causal map in Figure 7. The additional information required to gain better control of the respective failure modes, compared to the present-day situation, is represented by the information gap.

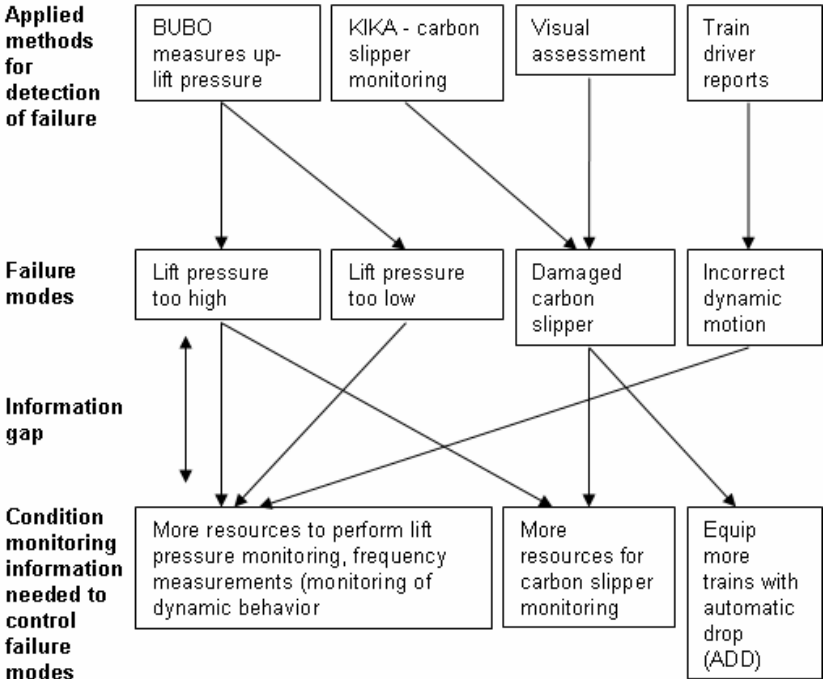


Figure 7. Applied condition monitoring methods for detecting pantograph failure modes and the information needed to gain control of failure modes

Too high a lift pressure can be monitored by the BUBO system, which measures the height of the uplift on the contact wire. The pressure measured is based on the contact wire tension and

the measured uplift. However, the measurement data from the current installation is questionable, since there has not been any calibration of the contact wire tension since the installation. BUBO can also monitor whether the uplift pressure is too low, but this function is not used at present. Hopefully, further developed uplift monitoring units will also be able to detect incorrect dynamic motions of the pantograph (frequency measurements). At present there is only one BUBO unit installed on Banverket's infrastructure. To gain control of this failure mode, there is a need for many more uplift monitoring units (calibrated units). Further, there is also a need to correlate the measurement data with vehicle identification information, preferably obtained by use of Radio Frequency Identification (RFID) tags mounted on the rolling stock. Vehicle identification data can enable more reliable decision support (maintenance decisions based on more than one measurement and the possibility of trend detection).

The KIKA system is based on the same technology as that used in police speed cameras. KIKA uses radar to spot the presence of a pantograph, takes a picture of the pantograph and performs an image analysis to determine the presence of pantograph failure. If a pantograph failure (e.g. a damaged carbon slipper or damaged aluminium profile) is spotted, an alarm sounds at the train traffic control centre, the train driver is contacted and hopefully the pantograph is dropped. A few KIKA detectors are installed in Sweden, but their reliability differs. One problem is to get the camera to take a picture at the right moment as the pantograph passes. One way to make the function more reliable is to apply some form of radar-reflecting material on the pantographs and thus enable a more accurate positioning of the pantograph. The operators state that they are willing to attach such material if they can obtain access to the photos taken by KIKA (which, if connected to vehicle identification data, can be used for degradation assessment). As for uplift monitoring, there is a need for far more carbon slipper monitoring units and for better correlation to vehicle identification.

#### 4.3.1 Prioritization and detectability of identified failure modes

In total, the FMEA resulted in the identification of seven infrastructure failure modes that must be controlled to enable the proper transfer of electric energy to the locomotives (see Table 2). The study also identified four pantograph failure modes that must be controlled to receive electric energy from the infrastructure properly. The failure modes and the experts' judgements of the failure modes' priority and their detectability by using currently applied condition monitoring methods are presented in Table 2.

Priority	Contact wire failure modes	Detectability
1	Pantograph motion path obstructed	2
2	Horizontal displacement from working point	5
3	Rapid change of contact wire height	2
4	Hoarfrost	3
5	Too thin contact wire	8
6	Vertical displacement from working point	3
7	Contact wire tension is either too high or too low	6
Priority	Pantograph failure modes	Detectability
1	Lift pressure too high	4
2	Damaged carbon slipper	3
3	Lift pressure too low	4
4	Incorrect dynamic motion	9

Table 2. The identified contact wire failure modes and pantograph failure modes, their estimated priority ranking and estimated detectability.

The priority ranking (1 = top priority) and the detectability judgements (1-10, where 1 is almost certain detection and 10 is almost impossible detection) in Table 2 can be used as indicators of which failure modes should receive attention first and for which failure modes applied condition monitoring practices are inadequate. Note that the detectability figure only represents the ability of the condition monitoring methods to detect the failure mode (while performing condition monitoring), not the overall detectability. For example, the increased uplift pressure monitoring method (see Figure 4) provides quite a good possibility of detecting the failure mode ‘pantograph motion path obstructed’ (see Table 2). Hence, efforts to gain better control of this failure mode could be focused on increasing the frequency of this monitoring method. However, considering the failure mode ‘horizontal displacement from working point’, the applied monitoring methods seem inadequate. Hence, efforts to gain better control of this failure mode should initially be focused on finding and applying more appropriate monitoring methods.

## **4.2 Stakeholder perspective**

Section 4.1 provided a perception of what kind of information is needed to gain control of the failure modes. This section adds the stakeholders’ perspective to illustrate why the information is needed.

Independently of whether the initial failure mode is related to infrastructure or rolling stock, it is apparent that any one of the failure modes can inflict a loss of system function, causing delays and increased costs (in terms of increased maintenance efforts, increased degradation of bound capital and train delays). The failure mode of one subsystem can inflict damage primarily to another subsystem and secondarily to itself. The root causes of problems are not always easy to assess. A dewirement could be the result of a damaged carbon slipper. The damage to the carbon slipper could be due to regular wear and tear and insufficient carbon slipper maintenance. It could also be caused by an obstructed pantograph motion path, inadequate contact wire alignment, hoarfrost or too high a lift pressure of the pantograph, etc. (see causal maps in Figures 3 and 6). This line of reasoning illustrates the fact that the issue of controlling the degradation behaviour in the interface cannot be solved only by trying to prevent one of the identified failure modes. It is also important to be aware of the fact that applying a solution to gain control of one failure mode is not sufficient to gain control of the failure interaction effects within the system. Hence, a variety of different condition-monitoring methods (manual or technological) must be applied in order to gain acceptable control of the critical failure modes that affect system degradation.

During the interviews it was made clear that there is no effective quality assessment being made of the maintenance work performed on the infrastructure. STRIX makes its runs and a failure report is sent to the maintenance contractor. However, once the maintenance work has been performed, there is no assessment or additional run made to verify the quality of the work performed. The same kind of problem can be identified with track tamping. To obtain a quality assessment of the work performed, more frequent measurements are needed.

In order to improve punctuality on the railways, one must acknowledge the symbiosis between the stakeholders. The functioning of the railway system depends on both the operators and the contractors taking their responsibility to deliver correct technical subsystem functions. Further, the operators and contractors depend on Banverket controlling all the actors and penalising those who prevent other actors from delivering correct technical subsystem functions. Take, for example, an infrastructure maintenance contractor who does

not perform adequate maintenance to prevent the presence of failure modes. This contractor can cause increased degradation and damage to all the operators' rolling stock (operational on the contractor's infrastructure). The affected operators will then run with damaged rolling stock on other contractors' track sections. Thus, the imposed degradation on the rolling stock can cause the infrastructure systems of other contractors to fail. This in turn can lead to increased maintenance efforts and costs.

Due to these failure interactions, Banverket needs information to monitor whether all the actors are performing as they should. This line of reasoning can be used to justify, for example, the necessity of equipping all the rolling stock with RFID tags to link deviating performance characteristics with the responsible parties.

It is important to consider the type of information that Banverket needs to assess the operators' and contractors' progress in ensuring proper railway system functions. Many interviewees felt that the bad actors (those who cause faults) must be penalised, since this seems to be the only way to make them perform better. However, due to the complexity of identifying what the initial failure was, and who caused it, the author suggests using condition monitoring technologies to identify and penalise the bad actors (operators or contractors) when failure occurs, rather than responding to faults. Or preferably, reward those who perform a better job than others, and in such a way make it beneficial for contractors and operators to excel in their maintenance practices.

It is interesting to reflect on the different roles of the stakeholders and their need for information on different levels. Banverket, the operators and the maintenance contractors depend on the identified subsystem functions being under control to keep track of the degradation of the system, enabling the system to provide adequate service.

- Banverket primarily needs the information necessary to assess whether the operators and contractors are performing adequately to prevent the occurrence of failure modes. This information is rather primitive, stating either that they are acting properly, or that they are not.
- The operators and contractors need the information necessary to assess the degradation of their respective systems, in order to assess when and where maintenance is to be performed to prevent failure modes.
- Banverket secondarily needs the information necessary to obtain adequate decision support for future modifications and reconstructions of the infrastructure system. It is essential that the input data should be within acceptable statistical control. This means that the statistics should be based on what caused the failure rather than what caused the final fault. In relation to this, the condition monitoring methods discussed can provide valuable input data for identifying the failures which, when correlated to rectification reports (cause of failure), can be used to identify weak links in the system (provided that the other failure modes are under control).
- Banverket also needs the information necessary to generate decision support for their process of constructing regulations or constructing contracts with economic incentives. With such information, Banverket can assess how it can obtain value for money (how much functionality it can obtain per invested monetary unit). This information is valuable for adjusting rewards or penalties. If certain types of rolling stock systematically behave in undesirable ways, regulations for prohibiting them can be introduced.

The above discussion illustrates different applications of condition monitoring information. It is interesting to observe that, in all four cases, it is the same condition information that serves as input. The only difference is in the detail level. Even though the information may serve other application areas, this indicates the importance of having Banverket as the primary owner of the information and the monitoring systems, since the agency has a long-term commitment to assuring the functioning of the system. However, sharing information is equally important; i.e. it is equally important that the maintenance contractors and operators should be provided with the information so that they can provide the required subsystem functions.

## **5 DISCUSSION**

It is difficult to generate delay statistics that represent the true causes of faults instead of the symptoms that are identified as the causes of faults. Therefore, to enable effective improvement efforts (e.g. redesign or acquisition of better material) based on statistics, there is a need for better correlation to the cause of the failure rather than the cause of the fault. Not knowing what the initial failure was that caused a fault is what causes difficulty when trying to estimate the improvement potential of applying condition monitoring solutions. What can be estimated from this study, however, is the improvement potential if all the identified failure modes are under control. If we regard the figures presented in Figure 2, and assemble all the causes, which correspond to the identified failure modes (pantograph failure, fatigue of material, unexpected mechanical stress, train vehicle, etc.), an estimated improvement of somewhere around 60% can be achieved.

Luminous arcs and sparks cause electromagnetic disturbances. A possible synergy effect of gaining control of the identified failure modes is that the electrical environment surrounding the railway might benefit from improved power conduction. Hence, no-fault-found effects induced by electrical disturbance on adjacent wayside systems are likely to decrease as a result.

This is a first attempt to obtain a holistic perspective on the engineering interaction between Banverket's infrastructure and the operators' rolling stock. This study may therefore not have covered all the aspects of the problem formulation. One aspect that has not been considered is the malfunctioning of the locomotive's suspension, which may cause the train to tilt and thus position the pantograph incorrectly in relation to the contact wire. However, if all the other failure modes are under control, degradation of the pantograph's aluminium profile can indicate a problem (as long as it is not so severe as to cause a dewirement).

## **6 CONCLUDING REMARKS**

It is apparent from this study that the current condition monitoring practices are not able to satisfy the need for information to control the failure modes within the system. Some of the applied condition monitoring methods are able to provide adequate information, but they are far from able to satisfy the need fully.

A system perspective is essential for determining what information is required to enable control of the failure modes within the system. The stakeholder perspective is essential for determining what to do with the information. From the study, we can see that the same kind of information can help the stakeholders to cope with their different responsibilities in different ways. Therefore, the stakeholder perspective adds an important dimension to the condition

monitoring acquisition process; i.e. the process of acquiring technologies to serve the system and provide stakeholders with information that can form the basis of the decision support needed to perform effective and efficient maintenance management, and thus improve punctuality through more effective and efficient condition-based maintenance.

The methodology used was perceived by the participants to be structured and informative, as it helps to highlight the stakeholders' interrelationships, responsibilities, and mutual dependence, as well as the engineering aspect of their respective subsystems' interaction. The methodology used seems applicable to systems dependent on the interactions between stakeholders and their respective subsystems, and can therefore be recommended for further use.

## ACKNOWLEDGEMENTS

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## Paper 5



# **Scientific maintenance management for improved railway punctuality**

**Rikard Granström**

## **Purpose**

The purpose of this paper is to describe how condition monitoring technologies can support systematic punctuality improvements by more effective and efficient maintenance management.

## **Approach**

The principal-agent problem is used to connect objectives, performance measures and incentives with railway maintenance requirements, with a focus on the role of condition monitoring. An implementation and utilization approach for condition monitoring to manage stakeholder actions and thereby the fulfilment of overall railway objectives is also outlined. This approach is influenced by theories of Scientific Management and a generic maintenance process. Empirical material is collected from the Swedish railway through archival analysis, interviews and document studies.

## **Findings**

There are a number of obstacles to the performance of railway maintenance, e.g. different stakeholders with heterogeneous interests and responsibilities, as well as a lack of appropriate decision information. A Scientific Maintenance Management approach can be supported by accurate and objective decision information derived from condition monitoring technologies. This approach supports an alignment of the objectives of separate stakeholders with the maintenance requirements of the technical systems. These system requirements must be fulfilled to enable effective and efficient maintenance management, and thereby improved railway punctuality.

## **Research implications**

The presented management approach supports further research related to improved railway punctuality by more effective and efficient maintenance.

## **Originality/value**

The author has not found any other published study that describes the combination of condition monitoring technologies with Scientific Management to support the improvement of railway punctuality.

## **Practical implications**

The study describes how the railway sector can adapt an approach to the scientific management of maintenance for improved punctuality. The approach is also valuable for other sectors where multiple organizations are dependent on each other to succeed in their individual tasks, since the competitiveness and the price of the end product (goods, service or any combination thereof) are determined by the success of their combined efforts. The most relevant industries are those that are dependent on capital-intensive and complex technical systems with long life lengths, e.g. aviation, power generation and distribution, pulp and paper, steel and mining.

## **Keywords**

Punctuality, maintenance, scientific management, stakeholders, railway, condition monitoring

## **Paper type**

Conceptual paper

## **The Swedish Railway context**

There is a social need and a political will to transfer a significant part of the Swedish domestic transportation service from roads to rail (European Commission, 2001). The railway traffic in Sweden is increasing (Banverket, 2006), which is having a direct impact on maintenance and the punctuality of the transportation system. As tracks are becoming crowded (due to increased capacity utilization), the impact from infrastructure and rolling stock failures on train delays and knock-on train delays (trains that are delayed due to other delayed trains) is becoming more severe (due to reduced slack in the timetable). The increased capacity utilization of the infrastructure is also causing it to deteriorate at a greater pace, which is increasing the demand for maintenance and reinvestment. At the same time, as the need for maintenance is increasing there is less time for executing it (due to the increased traffic). This is resulting in new requirements for predictions regarding degradation and maintenance need assessment of the infrastructure and rolling stock assets, in order to avoid corrective maintenance and allow timely performed preventive maintenance. In addition, the infrastructure maintenance budget is not increasing much (Banverket, 2004, 2005, 2006). Hence, more or better maintenance has to be executed with almost the same amount of money, in order to retain and restore the function of the infrastructure. Different research studies have shown that seventy to ninety percent of complex equipment fails prematurely after maintenance work has been performed on it, see e.g. Broberg (1973), Nowlan & Heap (1978), Moubray (1997), Allen (2001), and Reason & Hobbs (2003). In other words, excessive maintenance execution is to be avoided. Therefore, condition-based maintenance is in many cases favourable compared to predetermined maintenance (which entails the risk of excessive maintenance execution). Hence, in order to improve punctuality, there is a need for more effective (doing the right things) and more efficient (doing the things right) condition-based maintenance, where the elimination of waste (activities which do not create any value) comes to play a central role. In correlation with this, Banverket (the Swedish Rail Administration) has initiated studies to explore how the punctuality of the railway system can be improved by applications of condition monitoring technologies (LTU, 2005).

The Swedish railway sector is partly deregulated, which means that private entities (infrastructure maintenance contractors) are allowed to compete for contracts to perform infrastructure maintenance on the rail network. This also applies to rolling stock operation, where private entities (rolling stock operators) are allowed to run trains on the rail network. In Sweden, 80 percent of the railway network is owned by the Swedish Government (Banverket, 2006). The Government controls the infrastructure and most of the Swedish railway sector through Banverket. Banverket's main objectives are, in accordance with the Government's transport policy objectives, to ensure cost-effectiveness, reliability of service and sustainability, e.g. in terms of environmental impact and longevity of transportation provision for the public and for industry. Governmental demands state that Banverket has a sector responsibility, which means that it has an overall responsibility for the whole railway (Banverket, 2006). This implies that Banverket should monitor and actively pursue development throughout the railway sector. Hence, the responsibility for improving punctuality, among other things, lies with Banverket (Ericsson et al., 2002). The basic purpose of exposing railway stakeholders to competition is to obtain more railway functionality per monetary unit (Espling, 2007). The belief is that this will spur

methodological and technological development and lead by gradual stages to a maximization of the prosperity of society (Laffont, 1994). A maximization of prosperity for society comes from achieving the required system functions at the lowest cost (Banverket, 2006). This means controlling maintenance to assure that the proper function is obtained at the same time as the degradation of the bound capital (money invested in rolling stock and infrastructure) is optimized to generate the lowest system cost. Thus, the elimination of waste ensues, in the form of elimination of activities that do not correspond to the lowest cost functionality and in the form of elimination of waste of natural resources.

Banverket can stimulate contractors and operators to achieve methodological and technological objectives through regulations and contracts, which may have economic incentives (Ericsson et al., 2002). This can be seen as a principal-agent problem where the principal (Banverket) compensates the agents (contractors) for performing acts that are useful to the principal and costly to the agent, and where there are some elements of the performance that are costly to monitor (Vickerman, 2004; Wikipedia, 2007a). The agents maintaining the infrastructure will have better knowledge than the principal of the infrastructure's long-term ability to deliver a certain level of service quality. Agents can act opportunistically, due to the information asymmetry between the principal and the agent. Hence, since the life length of railway systems typically is five to 10 times longer than the duration of contracts, there may be an incentive for the agent to allow the system to degrade more rapidly (i.e. not to perform maintenance), if there is no penalty tied to the system's actual condition at the end of the contract (Vickerman, 2004). In terms of game theory, the principal has to change the rules of the game in order to align the agent's interests with the principal's interests (Fudenberg and Tirole, 1991; Stanford, 2007).

Different attempts to achieve this alignment can be seen in the evolution of contracting within the Swedish railway. The most common categories thereof are prescriptive or performance contracting. Prescriptive contracting basically involves the principal determining on a very detailed level the amount of maintenance that has to be performed, and the lowest bidding agent being compensated accordingly for executing the prescribed maintenance. These contracts have been known to be a source of adverse behaviour among agents (Espling and Olsson, 2004); for example shortcomings in enquiry documents or unforeseen events can be used by the agent as an opportunity to add charges. For the principal this introduces the risk of budget overruns (Sako, 1992; Olsson and Espling, 2004). In response to this, performance contracting has been applied to shift the focus from highly detailed contracting to contracting based on a few, but vital performance measures. Within performance contracts, the agents are compensated based on their ability to deliver results in accordance with the stated performance criteria. Three examples of these criteria are: the highest permitted level of train delays per year, the highest permitted level of functional failure, and the lowest permitted level of comfort indexes for the train passengers. However, one risk with performance contracting at a fixed price is that system performance improvements may not be realized (Espling, 2007). Hence, it has become more common to construct performance contracts with economic incentives attached, where the agents are compensated according to a fixed price combined with an economic incentive for delivering better results (according to performance criteria). If the agents fail to achieve the stated criteria, an economic penalty can be imposed on them. In this way the agent's objective of generating revenue is aligned with the principal's objective of achieving increased performance and continuous improvement. Due to the profitability of achieving mutual objectives, it has become vital for the stakeholders to communicate (overcome information asymmetry) and cooperate. This form of cooperation is

commonly known as partnering within Banverket, and has proven to generate a win-win situation among the stakeholders (Espling and Olsson, 2004; Espling, 2007).

However, overcoming information asymmetries between single agents and the principal will in some cases not be sufficient to overcome the problem of improving punctuality and optimizing the degradation of bound capital. The reason for this is the physical interrelations between the infrastructure and the rolling stock. The Swedish infrastructure items that cause most train delays due to the absence of required functions are the contact wire (providing electrical power for the rolling stock) and the track (Banverket, 2004, 2005, 2006). The track is also the infrastructure item that generates the highest lifecycle costs (Larsson, 2004). In both these cases the required maintenance of one contractor is affected by the interactions between the rolling stock and the infrastructure, which in turn is heavily dependent on the maintenance conducted by traffic operators and other contractors (Granström, 2008). Some 40 percent of the contact wire faults are due to failures of the rolling stock (Granström, 2008). However, using present result-oriented performance measures (measuring the effect of maintenance, e.g. train delays and functional failures), it can be almost impossible to assess the root causes of faults and to identify the agent responsible (Näslund, 2007). This is a known source of disagreement between the infrastructure manager, operators and contractors. Consequently, performance measures should take into consideration the symbiosis between the stakeholders. An infrastructure maintenance contractor who does not perform adequate maintenance to prevent the presence of failure modes (which can inflict damage on rolling stock) can induce increased degradation of and damage to all the operators' rolling stock (operational on the contractor's infrastructure). The affected operators will then run damaged rolling stock on the other contractors' track sections. Thus, the degradation imposed on the rolling stock can cause the infrastructure items of the other contractors to fail. Hence, performance measures (lagging indicators) such as the level of train delays and the number of functional failures will not provide a representative measure of a contractor's maintenance performance. Nor will performance measures provide evidence that the contractors and operators are provided with an operational environment that allows the degradation of their respective subsystems to take place in such ways that effective and efficient preventive maintenance measures can be taken. Using lagging performance measures for the railway could be likened to "managing a company by means of monthly reports" in the following analogy: "*managing a company by means of monthly reports is like trying to drive a car by watching the yellow line in the rear-view mirror*" (Timberlake, 1999; Wikipedia, 2007b). Due to the failure interactions between technical items (the failure in one item can have widespread knock-on effects), new information asymmetries arise between the stakeholders. Hence, to manage the situation, the principal needs leading indicators that can assess each agent's performance in terms of providing an operational environment that allows the degradation of items to take place in such ways that effective and efficient preventive maintenance measures can be taken. These indicators can be used to create incentives which align the agent's objective of generating revenue with the principal's objective of providing an operational environment that enables controllable degradation.

Utilizing condition monitoring technologies (sensors and data acquisition tools) to assess the health of the physical interaction parameters of the rolling stock and infrastructure is one way to overcome information asymmetries. Therefore, the information retrieved from monitoring the physical health of items is a leading indicator of the system's and the agent's ability to provide adequate services. In addition, the same health information can be used by agents as a tool to forecast and plan preventive maintenance measures (Granström, 2008). However, without a structured strategy for how to apply and utilize performance measures (derived from

condition monitoring technologies, for example), there is a risk that potential benefits of the technological solutions will be lost (Granström, 2005). Hence, condition information may not be utilized or maintenance efforts may be ill directed due to, for example, erroneous maintenance task thresholds, failure modes not considered, measuring the wrong parameters or the inability to transform information into adequate maintenance tasks (Granström, 2005). In summary, without a focused strategy for how to apply and utilize health performance information, merely acquiring condition monitoring technologies to assess the technical health of items will be unlikely to fulfil Banverket's objective of contributing to a maximization of prosperity for society (environmental impact, cost-effectiveness and reliability of service).

### **Scientific Management and the railway**

Until the beginning of the 20<sup>th</sup> century, there was no developed systematic body of knowledge concerning the management of industrial organizations (Kelly, 1989). In Kelly's review of contemporary management methodologies, Scientific Management (1911) was the very first. Scientific Management is portrayed in many different ways in the literature: some studies claim that it is a ruthless approach for exploiting work forces (commonly known as Taylorism), while other studies show how many management fundamentals identified almost a century ago still are valid, e.g. within Total Quality Management (TQM), Total Productive Maintenance (TPM), lean production, general management, public administration, office management, marketing and psychology (Fry, 1976; Locke, 1982; Hodgett and Greenwood, 1995; Sandkull and Johansson, 1996; Payne et al. 2006; Tribus, 2007). Even though it is portrayed differently within the literature, Scientific Management has substantially proven its value throughout industrial history, see e.g. Taylor (1911), Hodgetts & Greenwood (1995) and Sandkull & Johansson (1996).

The performance measures widely used today were developed during the Scientific Management movement pioneered by Frederick Winslow Taylor about a century ago (Tsang and Jardine, 1999). Two maintenance management methodologies that rely on performance measures for continuous improvement and that have proven valuable for modern society are: RCM (Reliability-Centered Maintenance) and TPM (Total Productive Maintenance), see e.g. Nowlan & Heap (1978), Nakajima (1986), Moubray (1997) and Campbell & Jardine (2001). RCM focuses on the design of effective and applicable maintenance to ensure a system's inherent reliability and safety at the lowest cost, which is based on the failure consequences on the system level that arise from insufficient component functions during normal operation (Moubray, 1997). In TPM, maintenance is viewed from the perspective of its impact on production, measured by the effect on the equipment availability, production rate and output quality (Nakajima, 1986). Hence, both RCM and TPM view maintenance in a broader context and consider the link between failures of component functions and their impact on the business performance. Campbell & Jardine (2001) state that physical asset management may be seen as the highest level of maintenance management, and propose a combination of RCM and TPM that, together with continuous improvement, aims at maintenance excellence. However, Murthy et al. (2002) describe deficiencies of both RCM and TPM in comparison with their proposed Strategic Maintenance Management (SMM) approach. Murthy et al. (2002) state that RCM and TPM assume a nominal operating condition and that the maintenance strategy is designed for this condition. Hence, neither RCM nor TPM models the load on the equipment and its effect on the degradation process. In relation to the previously described interactions of failures within a railway context (i.e. between the rolling stock and the infrastructure), short-term profit seeking by operators or contractors through cutting the

maintenance costs (for their rolling stock or infrastructure items) can cause increased degradation, decreased system availability and increased maintenance costs in the long run. Consequently, the operating load and the maintenance strategies have to be optimized jointly from the overall business perspective, since the load degrades the equipment and the maintenance actions control this degradation (Murthy et al., 2002). Another limitation of RCM and TPM is that neither deals with issues such as the outsourcing of maintenance and its associated risks (Murthy et al., 2002). In a similar way to the SMM approach proposed by Murthy et al. (2002), Scientific Management is used in this paper as an approach to managing maintenance from a long-term strategic perspective and to integrating the different technical and commercial issues of the railway system in an effective manner. As will be shown, Scientific Management covers (in a crude sense) the key features of the SMM approach, which are: understanding the science (of degradation), proper data collection and analysis, evaluation for selecting the optimal (maintenance) strategies and continuous improvement. The choice of Scientific Management as the fundamental theoretical framework of this paper is based on the fact that it has been proven valuable over the past century. Another reason is the many observed similarities between the problems facing contemporary railway management and the problems facing Taylor at the time of the development of Scientific Management. Even though the present author is not trying to advocate that Scientific Management is the ultimate approach for managing railway maintenance, a management methodology which is much debated and almost 100 years old is applied here in a modern context to inspire a search for historical knowledge to solve contemporary problems.

Similarly to Banverket in their current objectives, Taylor felt a deep concern regarding national efficiency and as a solution to this concern he proposed the reduction of waste. This waste is related to natural resources and human labour. The waste of natural resources causes environmental problems, such as deforestation and pollution. The waste of human labour is related to the inefficient activities of men, which leave nothing visible or tangible behind (Taylor, 1911).

The very essence of Scientific Management is the achievement of a complete mental revolution within organizations (Taylor, 1911). This entails a mental revolution on the part of the employees as to their duties towards their work, towards their fellow men and towards their employers. The same applies to the total mental revolution of all those involved in the management regarding their duties towards their fellow workers in the management, towards their employees and towards all of their daily problems. As in the case of the principal-agent problem, game theory and modern railway management, this mental revolution is achieved through a management system which aligns the individual objectives of the employees with the overall objectives of the business. Looking at the failure interactions between the rolling stock and the infrastructure, Taylor stated that the primary cause of conflicts between the management and the employees is the fact that the management, without knowing what can be accomplished in terms of work, tries to secure output by pressure. This means that the infrastructure manager exerts pressure on a maintenance contractor to ensure the fulfilment of performance objectives, while simultaneously the contractor's ability to fulfil the objectives is influenced by the performance of the other contractors and the traffic operators. Therefore, Scientific Management also stresses the importance of providing the means to achieve the objectives. This means that the infrastructure manager must provide the means to ensure that abnormal interactions between the rolling stock and the infrastructure are prevented. Taylor stated that "it is useless to assign a task unless at the same time the adequate measures are taken to enforce its accomplishment". Scientific Management has as its very foundation the firm conviction that the true interest of both the employer and the employees is one and the



same; that the prosperity of the employer cannot exist for a long period of time unless it is accompanied by the prosperity of the employee, and vice versa; and that it is possible to give the employee what he wants – high wages – and the employer what he wants - a low labour cost – for his manufactures. Translated into railway terms, the common interest of the stakeholders lies within the competitiveness of the railway compared to other transportation modes (e.g. transportation by ship, truck, and bus), and the interest of individual stakeholders is to generate high revenue.

There is a certain similarity between Espling's (2007) description of the risk of not achieving system performance improvements within performance contracting at a fixed price, and Taylor's statement that a setback within traditional management systems is that management constantly seek to increase the productivity of labour without generating additional remuneration for the employees. Thus, more work has to be conducted without any increase in pay. The general response to this is that the employees perform as little work as they dare, while at the same time trying to persuade the employer that they are working to their limits. Consequently, Taylor stated that, in order to have any hope of obtaining the initiative (required to achieve improved productivity) of his employees, the employer must give some special incentive to his men beyond that which is normally given in the business area in question.

Taylor's core values were: the rule of reason, improved quality, lower costs, higher wages, higher output, labour-management cooperation, experimentation, clear tasks and goals, feedback, training, mutual help and support, stress reduction, and the careful selection and development of people (Weisbord, 1987). Taylor was the first person to present a systematic study of interactions among job requirements, tools, methods, and human skill, to fit people to jobs both psychologically and physically, and to let data and facts have a decisive significance rather than prejudice or opinions (Weisbord, 1987). Clear similarities between Scientific Management and partnering can be seen in the way in which successful partnering requires trust among stakeholders, the management's support, the right personalities, adequate resources, organizational culture and learning, openness in communication, teambuilding, coordination, creativity and long-term commitment (Barlow et al., 1997; Cheng et al., 2000).

Taylor claimed that the best type of management in ordinary use may be defined as management where the employees give their best initiative and in return receive some special incentive from their employers. This management is referred to as the management of initiative and incentive. The management of initiative and incentive is a form of management where the attitude of the management involves "putting the work up to the workmen, and leaving them to solve it alone", which is not unlike performance contracting with economic incentives within the railway sector. Taylor stated that the major advantage of Scientific Management compared to the management of initiative and incentive is that under Scientific Management the initiative of the workmen (their hard work, good will and ingenuity) is obtained practically with absolute regularity, whereas, even when applying the best of the other types of management, this initiative is only obtained spasmodically and somewhat irregularly. Secondly, Taylor stated that by far the greatest gain under Scientific Management comes from the new, the very great, and the extraordinary burdens and duties which are voluntarily assumed by those on the side of management. These new management duties are divided and classified into four groups, known as the principles of Scientific Management (Taylor, 1911):

1. The development of a science to replace the old rule-of-thumb work methods with scientifically investigated laws and rules. This is accomplished through scientific investigation, the benchmarking of best practice and experiments. It involves the exploration of the best way of performing work to enable the maximum output, which, besides monitoring the physical time for performing the work by the workman, also involves the study and standardization of material, tools, and machines, the manipulation of tools or machines, and the best flow of work and sequence of unit operations.
2. The careful selection and subsequent training of the work force in accordance with the developed science, whereas in the past the workmen trained themselves as best they could.
3. Bringing the science and the selected workmen together. This involves rigorous cooperation (e.g. the support and training of workmen) between the management and the men to ensure that all the work is being carried out in accordance with the principles of the developed science. Monitoring the achievement of tasks is a key to assessing the workmen's effectiveness (doing the right things) and efficiency (doing the things right) in performing the task.
4. An almost equal division of the work and responsibility between managers and workmen, which involves the managers applying the developed Scientific Management principles to plan the work and the workmen performing it.

### Scientific management of the maintenance process

The four principles of scientific management are here applied within the maintenance process to support an introduction and utilization of condition monitoring technologies and the subsequent stakeholder actions required to achieve the railway objectives. In addition, the maintenance process is used (see Figure 1) to structure the stakeholders' responsibilities for the fundamental elements within the process.

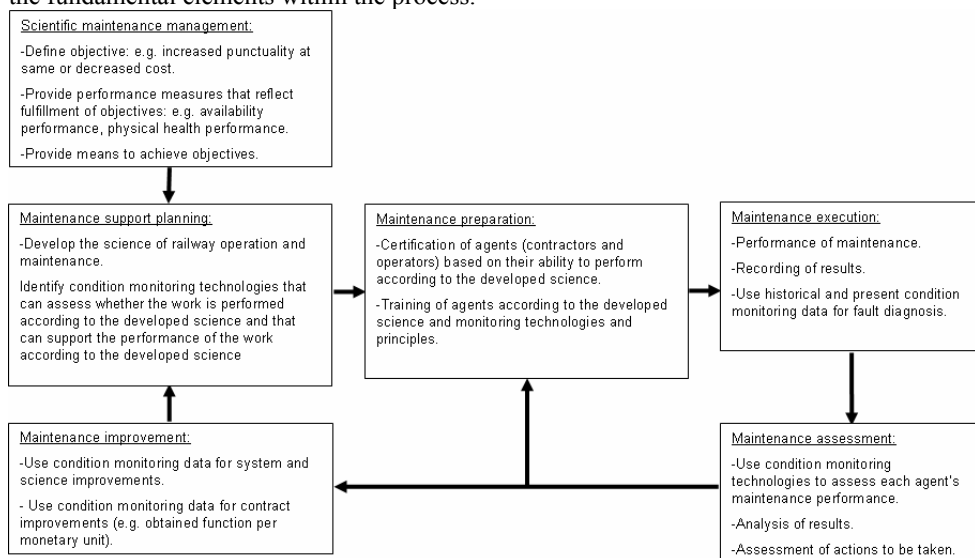


Figure 1. Maintenance process according to IEC 60300-3-14 (2004) adapted to structure an introduction of condition monitoring technologies and subsequent stakeholder actions required to achieve railway objectives.

The combination of generic maintenance activities or actions that are repeated and transform input into output may be seen as a maintenance process (Campbell and Jardine, 2001; ISO/IEC 15288, 2002; Holmgren, 2003; Liyange and Kumar, 2003; Söderholm et al., 2007). The purpose of the maintenance process is to sustain the capability of the system to provide a service (ISO/IEC 15288, 2002). The maintenance process monitors the system's capability to deliver services, records problems for analysis, takes corrective, adaptive, perfective, and preventive actions and confirms the restored capability (ISO/IEC 15288, 2002). Besides the individual actions of the process, it also gives a structure for continuous improvement, see Shewhart (1931) and Deming (1993), i.e. applying the cycle of steps, plan (maintenance support planning and maintenance preparation), do (maintenance execution), study (maintenance assessment) and act (maintenance improvement).

Here the operators and contractors are regarded as Banverket's (the infrastructure manager's) employees. However, the illustrations seek to show that the same principles can be used to control the relations between the operators, the contractors and their employees.

### **Scientific maintenance management**

In line with Taylor's objective of achieving a total mental revolution within companies, Hodgett & Greenwood (1995) expressed how the development of a science in our modern day and age requires focusing efforts on deciding the objective of the work. In the case of the railway, the objective is to provide increased punctuality at the same or decreased cost. Subsequently, Hodgett & Greenwood (1995) also stressed the importance of identifying external and internal customers; i.e. identifying whom are we responsible to, and what we have to do to meet this responsibility. In terms of punctuality and cost, the infrastructure manager, the operators and the contractors are responsible to the customer (society) and to themselves for providing an operational environment which can enable them to deliver a cost-effective and reliable service. (Naturally, the operators and contractors are also responsible for generating profit for the owners of the entities.) In terms of availability performance, the operators and contractors must assure the functions required from their respective items, and they must also ensure that they do not interfere with each other's activities (keeping to the timetable and thereby allowing each other to perform scheduled activities). In terms of abnormal interactions, the operators and contractors must also provide such technical performance (health) of their respective items that the degradation of assets can be controlled. In this connection, the infrastructure manager's responsibility is to identify the performance measures that reflect the fulfilment of stated objectives (see Figure 1). These performance measures should also be used to provide means for operators and contractors to achieve their performance objectives and as an enabler of a business climate that enforces the achievement of objectives.

### **Maintenance support planning**

The purpose of maintenance support planning is to establish the maintenance concept for items requiring maintenance, to provide the necessary maintenance resources and to ensure that the required information is collected during maintenance (IEC 60300-3-14, 2004). This phase represents the first of the scientific principles, i.e. the development of the science. Taylor referred to science as the organization and classification of knowledge. In more detail,

this involves reducing the gathered knowledge to laws, rules and formulas. Hence, the science should rest upon clearly defined laws, rules and principles. For the infrastructure manager, this entails scientific studies of the degradation and interaction of materials to assess the quality objectives of maintenance. The infrastructure manager has to decide where the maintenance task thresholds are to be established (see the illustration in Figure 2), e.g. at what tolerances track grinding and wheel refurbishment should take place to ensure the provision of the required technical function and to optimize the degradation of the joint system (indicated as capability in Figure 2).

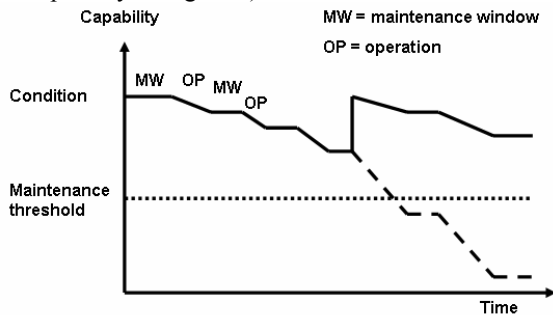


Figure 2. Relation between item condition and time, inspired by Nowlan & Heap (1978). The maintenance threshold represents the quality objective resulting from the infrastructure manager's development of the science.

It is possible to depend solely on manufacturer recommendations for maintenance tasks, but users need to confirm that they are appropriate to their specific operational use. The manufacturer is usually not able to anticipate factors such as the business-related consequences of failure, safety considerations, regulatory requirements, the use of condition monitoring technologies, the availability of resources and the unique environmental conditions (IEC 60300-3-14, 2004). The maintenance task thresholds (Figure 2) should be selected in accordance with the overall railway objectives, e.g. regarding punctuality and cost-effectiveness. Taylor stated that the development of the science should be conducted by the management and not by the workman. The reason for this was to avoid the science becoming biased due to the workman's objectives; for example to avoid the physical tolerances for wheel refurbishment being selected to optimize the cost of the traffic operators instead of that of the joint system. However, within the railway sector, the infrastructure maintenance contractors and the traffic operators are likely to possess more knowledge than the infrastructure manager about the maintenance of infrastructure and rolling stock assets. Therefore, a cooperative approach to the development of the quality aspect of the science could be advantageous. An example of a cooperative approach to the development of science concerning operation and maintenance can be found in the activities performed within the TURSAM (Applied Maintenance in Cooperation) group (JVTC, 2006). The TURSAM group is an interdisciplinary constellation of railway stakeholders who through joint efforts are developing knowledge on operation and maintenance. This is achieved through research activities and continuous ongoing experimental work on the Swedish Iron Ore Line (stretching from Luleå on the Swedish east coast, to Narvik on the Norwegian west coast). The group consists of both Swedish and Norwegian infrastructure managers, train operating companies, maintenance contractors, railway consultants, suppliers of railway materials and universities. The aim of the group is to use the cooperative environment to make the operation and maintenance of railways more effective and efficient. The activities of TURSAM can be seen as a response to the methodological and technological development that can be obtained

by solely exposing railway stakeholders to competition. Using a university partner as a provider of scientific support and as an assessor of the work performed within the group can help to avoid the developed sciences being biased towards the stakeholders. Hence, the development of scientifically based quality objectives can be facilitated through groups like TURSAM in cooperation with a neutral partner like a university.

Another important aspect is the collection of relevant empirical data for the development of the science. The ongoing development of a research station at Luleå Railway Research Centre (JVTC) is an example of how empirical data useful for the development of the science can be obtained (JVTC, 2006). The research station collects field data through a variety of sensors and transmits this data for analysis by the researchers at JVTC. Hence, the research station is used to assess the effects of rolling stock degradation on the rail, which is useful for assessing maintenance task thresholds (Nissen, 2007).

To enable control of the degradation of items within the system and to ensure that the developed science stays valid, it is essential that the material properties of the items that are introduced in the system should be controlled, e.g. the steel quality and the copper alloy quality. It is the infrastructure manager's responsibility to assure that procedures are introduced to ensure that items with the right material properties are introduced into the system. In addition, performance measures (e.g. measures derived from condition monitoring technologies) must be identified to assess whether the operators and contractors deliver the technical functions in accordance with the developed science. When the infrastructure manager can control that item functions are degrading in accordance with the developed science, then the operators and contractors can initiate maintenance preparation, in the form of operational planning of maintenance tasks and dimensioning of spare part supplies, for example. However, additional cooperation between infrastructure management, operators and contractors will probably be required to develop a science for the transformation of condition monitoring data into information that can be used for the prediction and planning of maintenance tasks.

The capacity utilization of system functions will affect the maintenance contractor's preparation and execution of maintenance efforts. The reason for this is that a high capacity utilization will reduce the time that is available for maintenance execution (indicated as maintenance windows in Figure 2). This will in turn increase the risk of reduced availability for railway operation, since necessary maintenance activities are more likely to interfere with the scheduled traffic. Combining this with the need for efficient use of manpower and machinery, it is essential that the contractors should define quantitative objectives. Hence, they should develop a science to perform maintenance tasks in the most effective and efficient way. The fulfilment of this goal can be measured as the degree of retained and restored required functions at allotted maintenance windows in accordance with the timetable. Examples of required functions are: the horizontal and vertical position of the contact wire and the condition of the pantograph carbon slipper (see Granström, 2008). The newly developed methodologies, by which tasks can be performed most effectively and efficiently, should then replace the inferior ones that were formerly in use. According to Taylor, these best methodologies should become standard and remain the standard to be taught to the teachers (functional foremen) and by them to every workman in the establishment until they are replaced by a better series of methodologies. However, this quantitative aspect of the development of the science may not be as easy to facilitate within groups like TURSAM. The reason for this is that methodologies for performing tasks are likely to be regarded as trade secrets. In summary, the contractors' competitiveness depends on how effective and efficient

they are in executing maintenance tasks according to the defined quality objectives and the provided time frames. In relation to health and safety aspects, Taylor stated that the employee never should be called upon to work with a methodology or at a pace that can be injurious to his health.

### **Maintenance preparation**

As for the second of the scientific principles, the maintenance preparation work will include the infrastructure manager's careful selection and subsequent training of contractors and operators in accordance with the developed science (the maintenance task thresholds and condition monitoring technologies), and the elimination of all those who refuse to, or are unable to, adopt the science. In other words, this process will involve some form of certification of contractors and operators to assess their capability to rise to the challenge (e.g. certification of the ability to provide an adequate quality of work and the ability to complete the task within the required time frames). The same principle can also be applicable to selecting and training workmen according to the contractors' or operators' developed sciences. According to the third principle of Scientific Management, condition monitoring information will serve as a tool to assess whether the work is being performed according to the principles of the developed sciences. To optimize accomplishment, economic incentives are provided for the employee (the contractor, the operator or their employees). Since traffic operators do not receive any funding from Banverket, the likely solution here is to use penalties as an incentive.

The planned maintenance activities are scheduled, based on a priority system, to ensure that the most urgent and important activities are carried out first and that the available resources are utilized efficiently. According to the fourth scientific principle, there should be an almost equal division of the work and responsibility between managers and workmen. This means that the managers apply the developed Scientific Management principles to plan the work and that the workmen perform it. On an organizational level in a railway context, this can be compared with a situation where the infrastructure manager performs the maintenance support planning and the operators and contractors perform the maintenance preparation and execution. In this context, condition monitoring technologies will serve as a supporting tool to assess the degradation of the respective stakeholders' subsystem. On a tactical level, the infrastructure manager can use condition information to provide maintenance contractors with plans describing what kind of maintenance is to be performed and where it is to be performed. The plans should also contain the deadline for execution of the maintenance. On an operational level, the maintenance contractor can use the provided information to plan the preparation and execution efforts in more detail. The maintenance contractors' work will become more clearly defined, since their work will be more focused on the preparation and execution of maintenance according to the time frames provided by the infrastructure manager. If contractors or operators are unable to accomplish their tasks (i.e. to provide the required functions or to follow the timetable), it is the duty of the infrastructure manager's functional foremen to help them back on track, e.g. by demonstrating how the information is to be used to achieve the objectives, and so enable them to receive an increased bonus. These acts will also help to improve the cooperation between the infrastructure manager and the maintenance contractors.

## **Maintenance execution**

The workmen's tasks will, in accordance with the fourth of the scientific principles, become more clearly defined, since their work is the actual execution of maintenance. Therefore, the maintenance planning should provide them with detailed plans specifying which tools and spare parts should be used, the time allotted for travelling to the worksite, how the worksite should be prepared, how much time can be used, how results should be verified, how the worksite is to be cleared and how necessary information should be recorded (IEC 60300-3-14, 2004). Corrective maintenance entails the same steps as those for preventive maintenance, but also requires the additional task of fault diagnosis in order to identify the location and nature of the failure and the necessary refurbishment or replacement of components. In the event of a major fault, the cause needs to be investigated and evidence gathered prior to the repair (IEC 60300-3-14, 2004). In the case of a failure-interaction-dependent fault, it is necessary for the infrastructure manager to visit the site and together with the contractor or operator determine the cause of the fault. If it is due to erroneously performed maintenance, e.g. on the contact wire, the contractor is to be held responsible. If it is due to erroneous operation of, or a lack of maintenance on the rolling stock, the operator should be held responsible. If the fault cause is beyond the responsibility of the operators and contractors, e.g. due to an infrastructure design flaw, an expired infrastructure operational life or sabotage, the infrastructure manager should take the cost for the fault. An awareness of the condition of the system (derived from condition monitoring information) prior to the fault and an awareness of the maintenance tasks previously performed facilitate the fault diagnosis. It is important to obtain adequate feedback on both the preventive and the corrective maintenance work performed (in order to generate adequate information for maintenance improvement work). Taylor presented a methodology for assuring that proper feedback was obtained. It simply involved not paying the employee until all the necessary paperwork on his side was performed.

## **Maintenance assessment**

The organization should establish and use a standardized and repeatable methodology for collecting and analysing data and interpreting results, which may be based on corporate or industry factors (IEC 60300-3-14 2004). The results should be used to support and justify improvements (IEC 60300-3-14, 2004). It is important to have the infrastructure manager as the primary owner of information, since they have the long-term commitment to assuring the required functions of the system. Condition monitoring technologies should be used to assess each stakeholder's maintenance performance. One example of such an application is the monitoring of contact wire failure modes, such as the displacement of contact wire, wire tension and wire thickness (Granström, 2008). However, it is also important for the stakeholders to agree on the methodologies that are used for assessing performance to avoid conflicts, e.g. manifested as no-fault-found (NFF) events (Granström and Söderholm, 2006). NFF problems can be avoided if the monitoring methodology is more reliable than the system that it monitors, and if the monitoring methodology subsequently used to recognize and localize the failure is at least as reliable as the preceding monitoring methodology. The assessment of preventive and corrective maintenance tasks can be performed either each time maintenance is performed (such as after a major failure), or on a periodic basis, to review the overall performance, e.g. by the type of item for a certain time period (IEC 60300-3-14, 2004). The latter is the case when assessing the physical health performance. The former is, however, more applicable when assessing the availability performance.

## **Maintenance improvement**

The knowledge provided by the infrastructure manager's new awareness (derived from condition information and the more intimate cooperation with contractors and operators) of the behaviour of the systems and the understanding of the difficulties involved in maintaining the assets will be valuable for the redesign of the systems with regard to reliability and maintainability performance. The monitoring technologies will also help the operators and contractors to improve their maintenance support performance. One of Taylor's experiences regarding improvement work was that people have the tendency to keep good ideas to themselves. Hence, to come to terms with this he issued a plan to reward substantially those individuals who presented good ideas of how work could be improved. This would involve personnel within infrastructure management, operators or contractors being presented with a similar plan.

The infrastructure manager needs condition monitoring information to obtain adequate decision support for future modifications of the infrastructure system and the developed science (e.g. further optimization of maintenance thresholds, see Figure 2). It is essential that the data should be within acceptable statistical control. In relation to failure interactions, this means that the statistics should be based on what caused the failure rather than what caused the final fault (train delay). In relation to this, condition monitoring technologies can provide valuable input data for identifying the failures, which, when correlated to rectification reports (stating the cause of failure), can be used to identify weak links in the system (provided that the other failure modes are under control). The infrastructure manager also needs information to generate decision support when constructing regulations or economic incentives. With such information, the infrastructure management can assess how they can obtain value for money (e.g. how much functionality they can obtain per invested monetary unit). This information is valuable for adjusting rewards or penalties.

## **Concluding discussion**

As indicated in this paper, information retrieved through condition monitoring has many applications. In relation to the railway's overall objectives (cost-effectiveness, reliability of service and sustainable development) it can be used, for example, to:

- Assess the system's and its stakeholders' ability to provide the required service levels (overcome information asymmetries).
- Assess if bound capital is degrading within the prescribed tolerances.
- Generate incentives which are based on the stakeholders' ability to provide the required functions of items (aligning the interests of stakeholders).
- Support maintenance planning, e.g. through diagnostics and prognostics.
- Support dependability improvements, i.e. improvements of the technical system's reliability performance and maintainability performance and the support organizations' maintenance support performance.
- Support fault diagnosis and conflict resolution, i.e. through improved fault recognition, fault localization and cause identification.

However, unless applications of condition monitoring technologies are preceded by a thorough investigation of the financial and engineering requirements of the system, the fulfilment of the overall objectives is likely to fail. Hence, information will not be fully



utilized (e.g. to control rewards or penalties), and maintenance efforts will be ill directed due to, for example, erroneous maintenance task thresholds, failure modes not considered, measuring the wrong parameters or the inability to transform information into adequate maintenance tasks. Applying Scientific Management within a constantly changing environment (with industry constantly having to adapt to market changes) may be a challenge. However, the railway system constitutes a relatively static framework, with many railway items being constructed to last 40 years or more. Hence, the development of an operation and maintenance science can be worth the effort. Independent of whether the railway sector is organized as an in-house organization or is exposed to competition, the maintenance necessary to retain or restore the required functions of the technical system is still the same. Hence, a development of the science of operation and maintenance may be worth the effort regardless of how the maintenance responsibilities are divided between different organizations. This is also a reason why the presented process view is valuable.

It is the intention of governments to eliminate subsidies for the waste of manpower and resources by exposing railway stakeholders to competition. However, in the absence of a developed operation and maintenance science, how can one determine the extent to which waste is subsidized, in the form of excessive degradation, ineffective working methodologies and excessive corrective maintenance activities? Incentives based on the health performance of items (assessed by condition monitoring technologies) can support a reduction of waste within maintenance performance contracting. Performance contracts that state availability performance targets and physical interaction performance requirements are potential punctuality improvement drivers. As for the more cooperative partnering approach, it was previously illustrated how partnering and Scientific Management share many similarities, e.g. the role of management, the right personalities, adequate resources, organizational culture and organizational learning. However, one fundamental difference is the introduction approach. Partnering approaches are applied from a top perspective where the management environment which is created among stakeholders helps, by gradual stages, to drive development towards the production of profitable system functionality. Scientific Management, on the other hand, is initiated on a system level where the requirements of the system are explored and where the management culture applied to this task supports the production of the most profitable system functionality. In some sense, the evolution of contracting within the railway sector has, in terms of partnering, been approaching the core values of Scientific Management. However, there does not seem to be any development of the science of operation and maintenance on which one could base the objective which would specify where development should lead.

In addition to providing the perspective of how condition monitoring technologies can be applied and utilized to facilitate the improvement of punctuality by means of more effective and efficient maintenance management, this paper is written with the intent of initiating a discussion on the maintenance requirements of systems and the management regimes which are forced onto these systems. As Taylor stated, within ordinary management, or the management of initiative and incentive, the prevailing theory has been that if one could obtain the right man, the methodologies could be safely left to him. Or in a railway context, if one could obtain the right contractor or operator, the methodologies could be safely left to them. In relation to this Taylor stated that, in the past, man had been first, but in the future the system would have to be first (Taylor, 1911). The question is whether or not we have reached the stage yet where the system is first?

Even though condition-monitoring-related technologies and methodologies (e.g. RCM and SMM) for developing the science (of maintenance) have evolved substantially since the

beginning of the 20<sup>th</sup> century, the rationale of the people involved with practising the science may still be the same. (This is indicated by the similarities between the problems facing Taylor at the time for the development of Scientific Management and the problems facing contemporary railway management.) In this respect, this paper can perhaps serve as an inspiration to seek historical solutions to contemporary problems. Hence, it may be possible to combine the old principles to influence human rationale and the new methodologies for developing the science in order to manage railway maintenance scientifically to improve punctuality.

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