Development of Life Cycle Cost Model and Analyses for
Railway Switches and Crossings

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LULEÅ
UNIVERSITY
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DOCTORAL THESIS

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Railway Switches and Crossings

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Preface

First of all I would like to express my deep gratitude to my supervisor Professor Uday Kumar and my co-supervisor Dr Aditya Parida for their support and guidance.

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Appended papers

Nissen A. (2009). Classification and Cost Analysis of Switches and Crossings for Swedish Railway – A case study, *Journal of Quality in Maintenance Engineering*, 2009 **15** (2), pp 202-220

Nissen, A. and Kumar U. RAM-analysis of Switches and Crossings for Swedish Railway – A case study, received for publication 2009-10-30 by *International Journal Performability Engineering*, ISSN 0973-1318

Nissen A. (2009). LCC for Switches and Crossings at the Swedish Railway – A case study, *International Journal of Condition Monitoring and Diagnostic Engineering Management*. 2009 **12** (2), pp 10-19

Nissen, A. Parida, A. and Kumar, U. Condition monitoring of Railway Switches and Crossing using data from Track Recording Cars, submitted 2009-10-31 to *International Journal of Condition Monitoring and Diagnostic Engineering Management*, ISSN 1363-7681

List of related publications not appended

Nissen, A., Larsson, D., Espling, U. (2007). Moving from safety limits towards maintenance limits. I: *High tech in heavy haul*: Proceedings. International Heavy Haul Conference. Kiruna: Luleå tekniska universitet, 2007. s. 349-358

Espling, U., Nissen, A., Larsson, D. (2007). *Strategi och metodutveckling av underhållsgränser för fordon och bana: optimering av fordons- och banunderhåll sett ur ett ekonomiskt perspektiv (Strategy and development of methods to seek for maintenance thresholds: Optimising of vehicle and track maintenance from an economic persepctive)*. Luleå tekniska universitet, 2007. Research report 2007:7, Luleå University of Technology

Larsson, D., Espling, U., Nissen, A. (2007). Vehicle classification based on wayside monitor data: a case study. I: *High tech in heavy haul*: Proceedings. International Heavy Haul Conference. Luleå tekniska universitet, 2007. pp 471-477

Nissen, A., Larsson, D., Nyberg, J. (2006). Measuring the use of deviating train track**.** I: *Condition Monitoring and Diagnostic Engineering Management*: *COMADEM 2006*: proceedings of the 19th International Congress. Luleå tekniska universitet, 2006. pp 677-687

Nissen, Arne (2005). *Analys av statistik om spårväxlars underhållsbehov* (*Maintenance Reliability Analysis of Railway turnouts*)**.** Luleå tekniska universitet, 2005. 52 s. Licentiate thesis 2005:86

Nissen, Arne (2004). An Analysis of Inspection and Failure-Reports of Rail Points: A Case Study from Sweden, *7th International Conference, Railway Engineering 2004*, Engineering Technics Press, Edinburgh, ISBN 0-947644-54-7

Nissen, Arne (2003). Failure Statistics and Maintenance Activities for Railway Turnouts in Sweden, *6th International Conference, Railway Engineering 2003*, Engineering Technics Press, Edinburgh, ISBN 0-947644-50-4

Nissen, Arne (2002). *Spårväxlar: felutfall och underhållsinsatser*. (*Turnouts: Failures and maintenance actions*). Luleå tekniska universitet, 2002. Technical report 2002:19

ABSTRACT

Infrastructure managers need to have a safe and available infrastructure, so that train operators can deliver a transport service at an affordable price. In the future, as traffic volume increases, higher utilisation of the existing capacity, less time for maintenance and fewer unplanned interruptions will be critical for meeting the ever increasing need of transport capacity. Improved performance and added capacity on the existing track can be achieved by optimising the operation and maintenance of infrastructure systems. In general, RAMS (Reliability, Availability, Maintainability and Safety) and LCC (Life cycle cost) analyses are used as tools to optimize the performance of infrastructure and make it economically viable. RAMS analysis is used to establish the need of maintenance by analysing corrective and preventive maintenance data. LCC is a method of highlighting the cost for investment, operation, maintenance and unplanned interruptions throughout an asset's life cycle.

Switches and crossings (S&Cs) are one of the major subsystems in the superstructure of the railway. The major function of an S&C is to allow trains to shift from one track to another track in a safe way. To enable this, an S&C consists of movable and fixed mechanical parts, as well as signalling and electrical systems. Each of these systems has a need for maintenance and is susceptible to failures which ultimately lead to train disturbances. The investment costs for new S&Cs are high and the technical lifespan is often very long (up to 40 years). Therefore, the maintenance cost is considerable. If the S&C is causing many train interruptions, the cost for train delays is also an important factor for consideration.

During the course of this research study, reliability and maintainability characteristics of switches and crossings are analysed using real data from Banverket. In addition, an LCC model is developed using information from Banverket. By applying this model, correct maintenance and investment decisions can be made. Some parts of the Research work have been performed within the European Framework of FP 6 IP Project INNOTRACK with a goal of reducing the LCC of infrastructure by 30%.

This research study confirms that the infrastructure managers have enough data to apply the LCC models for the S&Cs. The model developed can be used to evaluate new S&C designs and to take decisions regarding alternatives for S&C specification to be used under different traffic situations. Also the issue of decisions regarding renewal versus extended life through maintenance is highlighted by use of the LCC model.

Keywords:

Railway Infrastructure, Switches and Crossings, Maintenance Decision, Life Cycle Cost, RAMS

Glossary and abbreviations

BIS – Asset register

Bessy – System for preventive maintenance recording inspection remarks

CBS – Cost Breakdown Structure

CM – Corrective Maintenance

CYCM – Yearly Cost of Corrective Maintenance

CYIN – Yearly Cost of Inspections

CYPM – Yearly Cost of Preventive Maintenance

IM – Infrastructure Manager

IRR – Internal Rate of Return

LCC – Life Cycle Cost

LCT – Cost of the Termination phase

LOC – Life Operational Cost

LUC – Life Unavailability Cost

MDT – Mean Down Time

MTBM – Mean Time Between Maintenance

MTTR – Mean Time To Restoration (Repair)

0felia – System for corrective maintenance recording failures

PBS – Product Breakdown Structure

PM – Preventive Maintenance

PPM – Cost of Periodical Preventive Maintenance (Maintenance occurring with longer intervals than 1 year)

RAMS – Reliability, Availability, Maintainability and Safety

S&C – Switches and Crossings

TLT – Technical Life Time (of the system)

WBS – Work Breakdown Structure

Mathematical notations

β_{CM} – Form factor for the corrective maintenance

β_{PM} – Form factor for the preventive maintenance

T_0 – Total load of traffic at which the maintenance data is estimated in time

T'_0 – Traffic load per year

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1 Introduction

In this chapter the background to the problem and the research questions are presented. Chapter 2 gives an overview of the research work concerning degradation of switches and crossings and life cycle costs for railways. Chapter 3 describes the system studied, and basic information about the method used in the study. Chapter 4 covers the research methodology. Chapter 5 describes the databases that have been used, and Chapter 6 presents the Life Cycle Cost Model that has been developed. Chapter 7 gives a summary of the appended papers. Chapter 8 discusses the findings and presents the conclusions. The author's contribution is presented in chapter 9, which also indicates the scope for future work.

1.1 *Background*

An Infrastructure Manager (IM) has to keep different kinds of tasks in mind that must be handled in a holistic way. The railway network contains, to a great extent, components that have a very long technical lifetime (40 – 120 years), each decision therefore must consider the usage of the asset in question for at least 40 years into the future. Banverket's (the Swedish Rail Administration) long term planning is normally for about 10 years into the future, even if there is awareness that usage time is longer. The IM is in control of what type of asset is built; barely on the quality of installation; hardly the condition of the asset during operation and far less the condition tomorrow while maintenance is controlled by entrepreneurs. It is very challenging for an IM to have an overview of all the tasks to be considered so as to ensure the specified level of reliability, availability and capacity on the track.

Even though it is very difficult to predict the volume of traffic on railway network, the IM has to negotiate and allocate capacity slots to train operators. The current trend of increased traffic volume leading to higher utilization of the existing railway network has led to more severe degradation of railway track, which in turn requires more maintenance action on tracks.

The European Commission has set objectives for railway operation with reference to the year 2000, in terms of European Commission 2001 (ERRAC, 2007):

- Doubling the passenger traffic and tripling freight traffic by 2020
- Reducing travel time by 25-50%
- Reducing the life cycle cost of infrastructure by 30%
- Reducing noise levels to 69 dB for freight and 83 dB for high speed trains
- Increasing safety and reducing fatalities by 75%

These objectives have put additional demands on the railway infrastructure, which has led to the operational and maintenance requirements (ERRAC, 2007):

- increase of speed and acceleration
- increase of axle loads and traction power
- more rigid vehicles with greater stiffness.

Banverket has an overall goal of providing a system of transport for citizens and the business sector all over the country that is both economically effective and sustainable in the long term.

This overall goal is divided into two types of demands (Banverket, 2009a):

1. Functional demand: The railway shall be an accessible transport system for all people, assuring good quality and needs for regional development

2. Additional demand: The railway shall fulfil requirements on safety, environmental and health issues

Part of sub goal 1 can be measured by punctuality and as train delay time. A newly stated goal within Banverket is to reach at least 96% in punctuality and less than 50 hours delay time per million train km for the highly used railway network in the year 2021 (Banverket 2009b). An analysis of delay time shows that the share of S&C related failures leading to delay come to approximately 14% (Granström and Söderholm 2005). That means roughly 15 minutes delay time per S&C/year, assuming one S&C in main track per 2 km and 50 trains per day. This type of goal needs a strategy and a way of working that is new for Banverket. Banverket has been part of INNOTRACK, European Framework Project 6 and the UIC working group for S&Cs. Both these projects state, the use of RAMS and LCC analysis is a way to achieve goals that assure the performance of the network and its capacity,

The owners of railway infrastructure assets need to find solutions that improve the reliability, availability, maintainability and safety (RAMS) of the railway systems. The European Union demands an improved interoperability, which increases the demand of modifying and inventing subsystems that can meet these needs. Infrastructure managers need to have a safe and available infrastructure, so the train operators can deliver a transport product at an affordable price. Higher utilisation and less time for maintenance with fewer unplanned interruptions are therefore requirements. High operative and maintenance costs are barriers for improving the financial performance of railway operations (ERRAC, 2007). Therefore finding solutions for improving efficiency through optimising the infrastructure and rolling stock cost of investment and maintenance are becoming important (ERRAC, 2007).

As a mechanical system, the railway is not so complicated, steel wheels are guided by rails to roll from point A to point B or C. What makes the railway system complex is that it is divided into the hands of many parties. Infrastructure and rolling stock (for passenger and freight) have different owners and the maintenance is in some countries (for instance Sweden, United Kingdom and The Netherlands) is outsourced. The goals for all these companies are not the same and there is a lack of holistic understanding (Espling 2007).

The infrastructure system can be divided into different technical subsystems, i.e. substructure, track, electrical system, signalling system, and telecom system (Espling 2007). The rolling stock can also be seen as a different technical subsystem, but added to this is the logistics of transporting the passenger and goods. Both the infrastructure owner and the rolling stock operator need to have a common traffic operating control. The varying functional needs of all these systems put challenging demands on the railway management (Lichtberger, 2005).

The railway infrastructure of Sweden has in total 17 000 km of railway, 11 800 km used for daily traffic (Banverket 2008) and about 12 000 switches and crossings (S&Cs) (BIS, Asset management system 2009). Banverket administers nearly 11 000 of the S&Cs, and the rest are owned by local municipalities or industries. Cost for railway infrastructure can be seen in **Table 1**, and Banverket divides it into administration, operation and maintenance, traffic operation, reinvestment and capital costs (Banverket 2006). Banverket's cost for maintenance and operation, together with reinvestment of the Swedish railway, was 447 million Euros during 2006. The S&C costs stand for at least 13% of the maintenance costs, and as one of

several subsystems, causes most train delays on the Swedish railway (Nissen 2005). The high cost is caused by the degradation of the assets and the need of inspection to maintain a high safety level and avoid undesired risk of incidents and accidents as well as high dependability. The individual cost of an S&C is difficult to calculate. The problem of establishing this cost is due to lack of information, while the account system has no direct information about individual S&C and in the maintenance system not all actions are declared.

The life length of S&Cs in Swedish main track are, in general, about 40 years, and therefore in the reinvestment plan, it should be necessary to calculate for more than 200 new S&Cs per year. A cost benefit analysis based on life cycle costing could be a good tool for finding which S&Cs are required to be replaced. Another use of life cycle costing is in the design stage or when choices between types of S&Cs must be made.

Table 1: *Result for the cost including investment of the railway net of Banverket during 2006(Banverket 2006)*

Cost for the railway net	M€	
Administration	77	4%
Operation and maintenance	282	16%
Traffic operation	68	4%
Reinvestments	165	9%
New national investments	729	42%
Other new investments	17	1%
Contribution to other infrastructure managers	40	2%
Capital cost	59	3%
External consultancy	304	17%
Total	**1 742**	

An S&C is a subsystem in the railway system that allows traffic to change track. That is, it has two primary functional demands:

- Carry the load of the train in a safe way
- Allow traffic in either main or deviating track

An S&C consists of three major parts, switch panel, crossing panel and closure panel, see **Figure 1**. The switch panel has the movable part consisting of switch blade, bars, switch device and control device. The closure panel connects the switchblade with the crossing. The crossing panel has a crossing nose, wing rails and check rails, all of which should be able to withstand the high forces that occur when the wheel is transferring from one rail to the next at

the crossing nose. Behind the crossing panel the sleepers are longer than normal, which are combined with normal stock rail.
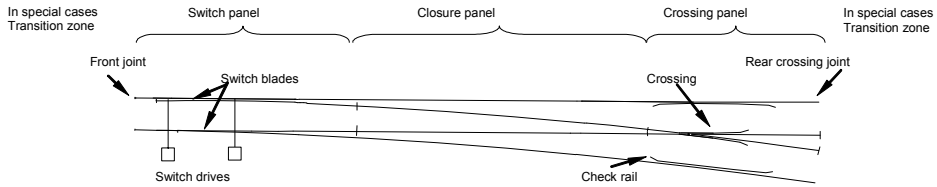

Figure 1: *Illustration of an S&C divided into 3 panels*

The research has gone from studying how the S&C performs from a maintenance perspective to seeing how the cost can be managed and still give a high dependability during the whole technical life time of the S&C. The activities of this thesis concentrate on finding a way to compare improvements made for S&Cs by using life cycle costing. It will be critical for the infrastructure management to have an overview of all of the cost drivers related to the operation and maintenance of the S&C. This facilitates correct decision making regarding replacement and investment for S&Cs.

Purpose

The purpose of this thesis work is to explore the possibility of using an LCC model for S&Cs as a decision tool for an infrastructure manager.

Objective

The objective of this thesis work is to build an LCC model for Banverket that can be used as a tool for decision making concerning S&Cs.

1.2 Research questions

From a scientific point of view, the researcher should find answers to the basic questions that are asked early in the research process. For a research project that lasts for several years these questions are not always easy to formulate in the beginning, and will act as a guideline during the first exploratory phase. The questions in this project were finally formulated in the beginning of 2008 and the journal article and the work conducted since then have been trying to find answers.

Research question 1   *Maintenance Actions*

- A)   How to identify/define maintenance actions for S&C?
- B)   How to identify the frequency of maintenance actions (reliability) for S&C?

Research question 2   *Maintenance Cost*

- A)   How is the cost related to the most important maintenance actions?
- B)   How is the cost estimated for chosen maintenance actions?

Research question 3   *LCC model*

    A)   Which are essential elements in an LCC model for S&Cs?

    B)   How is residual life value estimation and maintenance for prolonged usage after technical life reached?

    C)   Can the LCC model provide decision making support during upgradating and modifications of S&C (See question 5)?

Research question 4   *Asset health condition assessment*

    A)   How can asset health data be used to identify a specific S&C for replacement decision making?

Research question 5   *Designed aspect*

    A)   If a group of S&Cs should be modernised, what type of S&C should be used is given traffic data, how deviating track is used considering from the LCC value and traffic volume?

    B)   What data and information are needed as input to the LCC model during investment   projects in selection of S&C type for a defined task?

1.3 Scope and limitations

The scope of this research work is confined to S&Cs deployed on the Swedish rail network and environment. The data may differ considerably from what other railways have. Cost for operation has not been included in the model, and these costs are considerable in the northern part of Sweden, especially for snow clearance and heating.

Risk assessment has not been part of the study, even though the author is aware that this should be either incorporated in the model or done as a parallel activity. Several areas of hazards exist when introducing new components into a system that has been in place for a long time. One example in Sweden is that trains have been running over a closed movable crossing nose although it is not trailable (possible to pass backwards without opening the switch blade in advance), which leads to derailment and high consequential costs. Accidents may also be caused as a consequence of maintenance work (Holmgren, 2006) and this should also be considered in the design stage, but has not been incorporated in this study**.**

2 Research in the area of LCC of S&C

2.1 Degradation, failure and maintenance cost of S&Cs

In Sweden several researchers have been studying S&Cs from different point of views. A study performed by Ragnar Hedström (2001) initated the research on switches and crossings in Sweden at university level. Research on dynamic train/turnout interaction has been the focus for Chalmers and has been conducted by Göran Johansson (2006) and Elias Kassa (2006).

In Sweden, several reports have been created on the subject of superstructure degradation. KTH is doing research on vehicle/rail interaction. At Luleå University of Technology research on different aspects of superstructure degradation and maintenance have been conducted. Parts of these studies have been in cooperation with Gopi Chattopadhyay (Chattopadhyay 2009, Reddy 2007) at Queensland University in Australia .

In Europe, studies have been performed in several countries. Some of these reports are not available for the researcher as they are internal for the infrastructure managers or companies involved in manufacturing or maintenance of switches and crossings. Universities in Graz, Delft and Birmingham have contributed in the area of degradation of S&Cs. Other reports that may be of interest are the ORE (Office for Research and Experiments of the International Union of Railways, Utrecht, The Netherlands) D161-Report 3 (1988) and the EcoSwitch-study initiated by ERRI (2002) (European Rail Research Institute, The Netherlands).

Each contribution is shortly presented here:

- Hedström (2001) came to the conclusion that replacement of S&Cs is mostly based on general judgement and that the two main reasons were either the need of rebuilding station areas (to increase capacity for instance) or technical reasons (too much wear, bad sleepers, not possible to maintain within tolerance). He could not find any objective measures for these types of decisions.

- Johansson (2006) established a model for large ratcheting strains which can be used for the plastic deformation of the switch blade and crossing. During his work the data for material used in crossings was not available, but INNOTRACK has provided this type of data and a first calculation for R350HT material has been made (Nicklish 2009).

- Kassa (2008) has used the programs Gensys and Diff3D to build a model for calculating the train/vehicle interaction for a UIC60-760-1:15 S&C running with a train with 25 tonnes axle load. Both by simulation and practical measurements, vertical and lateral forces were examined. The highest vertical and lateral forces were encountered for the diverging route (speeds up to 80 km/h). The lateral force having its maximum (up to 85 kN) in the switch panel (7 – 9 m into the panel) and the vertical force having its maximum (up to 260 kN, 208% of static load, 125 kN) at the crossing. More work in this area has been conducted by the INNOTRACK project.

- Stichel (2005) and Öberg (2006) have gone through the theory of rail and superstructure degradation.

- Jönsson (2006) has been working with a simulation model for freight wagons and concludes that the track maintenance cost is mostly influenced by track geometry degradation, wear of rails, rolling contact fatigue and component fatigue due to the load from the traffic.

- Larsson (2004) has developed a relative cost model for railway track degradation in the situation where there are changes in traffic.

- Zwanenburg (2006, 2008) has been working to establish a model for degradation processes of S&Cs and their components. In his findings he presents statistics of technical life time as well as the influence of switch angle and soil conditions. He states that 600 MGT is a possible life time for a UIC60 S&C and that SBB (The Swiss Railway) normally replaces the S&Cs before this total load.

- Bonaventura (2008) presents a tool for managing S&C inspections. He proposes that by using numerical priority ratings more efficient maintenance will be achieved.

- Li (2008) has been studying the root cause of squats. Squats is a rail defect that is caused by stiffness changes which occur at fishplate joints and S&Cs. A multibody-finite element model of vehicle/track vertical interaction has been used to simulate the dynamics in order to identify factors that can lead to the development of squats.

- Ling (2006) has created a model for cost estimating railway renewal projects at the early stage of a project life cycle and used it in a case study for switches and crossings.

- García Márquez (2003) has been using condition monitoring and developed algorithms to detect gradual failures in railway S&C to decrease the failure rate.

- Roberts (INNOTRACK 2008, appendix A and B) has been working with FMEA (Failure Mode and Effect Analysis) to establish which conditions that can be measured for S&Cs to prevent failures. His work has been focussing on DC-point motors.

- Chattopadhyay (2009) has been studying rail degradation, and has identified the important factors as:
    - type of track
    - curvature,
    - traffic type (including characteristics of bogies) and load (MGT),
    - environmental conditions.

- UIC/ORE initiated a number of committees to increase the understanding of railway degradation; one of the committee's (ORE D161,1988) findings was that the degradation rate of rail is a function of axle weight, vehicle speed and total load in MGT since last restoration.

- EcoSwitch (2002) is proposing a maintenance management system to lower the life cycle cost for maintaining S&Cs. The EcoSwitch report also proposes development of a deterioration model which can reduce the need for inspections and enhance the planning of maintenance.

2.2 The use of LCC in railway and S&C in particular

Not very much has been written and published in scientific journals during the time of the research on LCC of S&Cs. Zwanenburg (2008) is one of few researchers in Europe that has been working in this area since the EcoSwitch project. García Márquez (2008) has written about LCC for condition monitoring of point machines. Association of American Railroads has written a report on the subject, but it is old and has not been available (AAR, 1993). Sintef in Norway made a report in 1998 (Hokstad, 1998).

To broaden the perspective literature concerning railway LCC has also been looked for. The University of Graz (Austria), the Norwegian University of Science and Technology (Trondheim), and Technische Universiteit Delft (The Netherlands) have all been involved in different railway projects using LCC. Naturally, much has been written on cost estimation of railway infrastructure, and in the area of life cycle perspective the following has been found of interest:

- The "High Level Group on infrastructure charging" asked a work group to find methods to establish a cost model to depending on traffic load (Link 1999). Bottom-up and top-down approaches is discussed as well as experimental based estimations. It is also stated that cost function based on engineering knowledge do exist. It is concluded that there is not sufficient data to develop a full cost model so a marginal cost model is proposed. Such a cost model has a fixed part and a variable part (linear function of traffic volume).

- Andersson (2007) has been studying the renewal and marginal cost for Swedish railway.

- Veit (2007) has been formulating a theory for tamping. This theory has been used by the UIC group for "Durabilitry of track geometry maintenance" has written an guideline including S&C tamping (UIC 2008).

- Zhao (2006) has been working with stochastic estimation of hazard rate of alumino-thermic weld failures to find an optimal economical rail life. He uses a Non Homogenous Poisson Process (NHPP) to predict the number of failures over time.

- Reddy (2007) studied the rail grinding cost and made an LCC model for this.

- Zoeteman (2004) has discussed the LCC based maintenance decision support for infrastructure

- Patra (2009) developed a LCC model for rail track based on the following maintenance actions:
    - Track inspection
    - Rail: grinding, lubrication, replacement, renewal
    - Ballast: Tamping, cleaning, renewal
    - Sleeper: renewal
    - Fasteners: renewal
    - In the model he uses distribution function to model the uncertainty of the input data and Monte Carlo simulation to estimate the LCC value.

Besides the work of Larsson-Kråik (Reddy 2007) and Patra, not many studies (known to the author) have been undertaken showing the use of LCC within Banverket. In Europe it is known to the author that Prorail, ÖBB, DB, Network Rail and Jernbaneverket have

incorporated, to some extent, the use of LCC when making decisions for investment and renewal projects.

3 Definition and basic concepts

In this chapter, the subsystems of an S&C and the maintenance actions needed are described. This chapter also briefly describes the RAMS and LCC methods.

3.1 S&C - definition

S&Cs are very important subsystems in the railway which allow the trains to shift from one track to another. By enabling trains to meet, and allowing slower trains to be overtaken, S&Cs contribute to achieving a high capacity both on single track as well as double track lines.

Functions and demands of an S&C
- Carry load
- Be part of the track signalling circuit
- Act as flange protection
- Move the switch blade to enable one of two or more alternative ways
- To enable train to move from sidings and re-enter main track (or visa versa)
- Give information back to the interlocking system that the switchblade is in the correct position
- To withstand adverse weather conditions (snowfall, heavy wind or cold weather)
- To keep the forces transmitted to the ballast at an acceptable level
- To keep the reactive forces transmitted back to the train at an acceptable level
- Good maintainability

3.1.1 Subsystem of an S&C

An S&C consists of many parts, which can be grouped in number of subsystems

- Base plates
- Slide plates and switch rollers
- Fastenings
- Stock rails
- Switch blade
- Joints (welded and insulated)
- Locking device
- Switch blade
- Crossing
- Check rails

- Heating (de-icing system)
- Sleeper
- Ballast
- Switch motor
- Stretcher bars, motor bars, control bars
- Signalling system (Switch Blade Position Detector and Switch Drive Position Detector)

3.1.2 Type of S&C

Table 2 show the most important S&Cs used in Sweden. Even though S&Cs in Europe have great similarities, there are few turnouts that are exactly the same in different countries. Some parameters are starting to be more standardised, even if the manufacturing design is not exactly the same. The most important parameters of a standard single S&C in main line are:

- Geometry (Radius and angle at the crossing nose)
- Rail type

- Sleeper type
- Sleeper, rail and crossing Material

Table 2 Most important S&C in the Swedish rail network (BIS, 2009)

S&C type	Main track with speed > 40 km/h	Non main track or <=40 km/h	Total	Rail weight [kg/m] (Profile)	Length Switch blade [m]	Total length [m]	Radius [m]	Angle of frog nose
DKV-SJ50-7,641/ 9,375-1:9	244	129	373	50(E3)	7,6 and 9,4	69,9		1:9
EV-SJ41-5,9-1:9	33	206	239	41	5,9	46,5	210/ 243	1:9
EV-SJ43-5,9-1:9	219	690	909	43	5,9	46,5	210/ 243	1:9
EV-SJ43-11-1:9	159	202	361	43	11	46,5	300	1:9
EV-SJ50-5,9-1:9	197	450	647	43	5,9	46,5	210/ 243	1:9
EV-SJ50-11-1:9	1716	1255	2971	50(E3)	11	46,5	190/225	1:9
EV-SJ50-12-1:15	473	30	503	50(E3)	12	70,8	600	1:15
EV-BV50-225/190-1:9	238	120	358	50(E3)	11	46,5	190/225	1:9
EV-UIC60-300-1:9	628	14	642	60(E1)	13	49,8	300	1:9
EV-UIC60-760-1:15	747	2	749	60(E1)	21,5	83,1	760	1:15
EV-UIC60-1200-1:18,5	261	0	261	60(E1)	23,3	97,2	1200	1:18.5
Others	1507	1279	2786					
Total	6422	4377	10799					

The radius of the switch blade is the base to calculate the maximum allowed speed of the S&C. The rail type and sleeper type is, to large extent, influential on the possible technical life time (TLT) of an S&C. In Sweden, no direct limit is stated, but in Finland figures of 300 MGT for S54 profile and wooden sleeper and 450 MGT for S&C with UIC-60E1 profile and concrete sleeper has been presented (Nummelin 2004). Zwanenburg (2008) presents a possible TLT around 400 MGT for all type of S&Cs and believes that 600 MGT should be possible with 60 kg rail.

Steel material of the stock rail, switch blade and crossing is important for the life time of these components. In Sweden R350HT[1] material is used in stock rail and switch blades and

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[1] **Head hardened carbon steel with hardness ≥ 360 HB and ultimate tensile strength of 1300 MPa**

explosion hardened manganese in crossings in newer S&Cs used in main track. This is an area where further improvement is expected.

In Sweden, the most common S&C is the SJ50-11-1:9 and similar turnouts are found in many other countries. Today Sweden prefers to install new turnouts of the dimension UIC60-760-1:15, but in other countries UIC60-600-1:12 are the most preferred S&C (Norway, Germany).

3.1.3 *Maintenance action for S&C*

There are different maintenance actions for an S&C. On a short term basis the lubrication of slide chairs can be done every month. In the longer term, surface welding, tamping and grinding are needed, and are normally done after a period of 1 - 5 years. A very long time between maintenance is required for the replacing of switch blades, crossing and renovating of point machines. These are done on a time scale of 5 - 20 years. Most of the maintenance decisions are taken based on an inspection report. A regular inspection interval might be 1 – 3 months. In some countries a simplified visual inspection is done every week on the most important S&Cs.

The planning and organisation of the maintenance is affected by factors such as availability of track, geographical location and climatic conditions (Espling 2007).

3.1.4 *Inspections of S&Cs*

Maintenance for S&Cs is normally based on inspection reports. The inspections can be divided into four types

- Simple visual inspections
- Detailed visual inspection
- Measured inspections
- Non destructive testing

Simple visual inspection can be performed with 1 – 4 weeks interval, just to have an overview and confirm that there are no safety problems.

Detailed visual inspection and measured inspection are normally performed at the same time and can be performed with an interval of 2 - 6 months. Safety issues are noted, and also issues of replacement or repair in the longer term are proposed by the inspector. For this type of inspection a protocol is filled in and stored.

Non-destructive testing is done using ultrasonic equipment to check for internal cracks in the rails and crossing materials. The track recording car measuring level, alignment, twist and gauge can also be treated as a non destructive testing although it is normally referred to condition monitoring.

Actions that are taken as a consequence of the inspection reports or a failure are

- Adjustments
- Lubrication
- Cleaning/Rinsing
- Functional control
- Repair
- Replacement

- Grinding
- Tamping
- Compressing the ballast under certain "dancing sleepers"
- Restoration (replacement of all worn parts at the same time)
- Most of these actions are not time consuming and can, if the work is performed as planned, be done without interfering with the traffic.

3.2 RAMS

RAMS is a methodology to ensure that products fulfil requirements of dependability and safety. Railway companies have to follow the standard EN 50126:1999, "Railway application – The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)". According to the standard, the measurement of dependability, availability and performance is based on the measurement of reliability, maintainability and actions for operation and maintenance (maintenance support), see **Figure 2**. Availability is generally the most appropriate measure for the performance of repairable items (Modarres, 2006). Reliability and maintainability are decided and dimensioned during the design and development phase of the system life cycle, as they are characteristics of the technical system.

There are no universal agreements on the definition of the term availability and how it should be measured. Availability can be measured in several different ways and a common definition is the ratio between the time during which the equipment is available for use and the total planned time for operation: Availability = Up-time / Total planned time. A more abstract availability measure can be defined as: The probability that a system will be in a functioning state on demand. When defining availability it should also be decided whether the waiting time or the preventive maintenance times are included in or excluded from the calculation. This has lead to several measures. One of these measures is the operational availability that is calculated by equation (1), this could be used by the management for assessment purposes for an existing asset in a realistic operational environment (Kumar and Akersten, 2008).
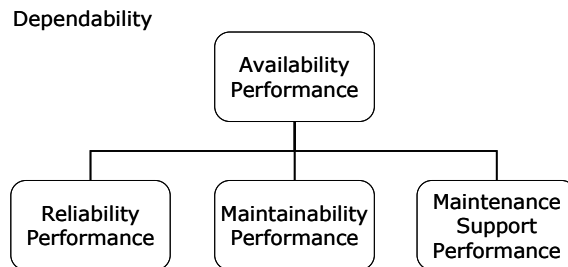
Dependability

Figure 2, Dependability divided into three factors: reliability, maintainability and maintenance support (EN 50126:1999)

$$A_o = \frac{Mean\,Time\,Between\,Maintenance}{Mean\,Time\,Between\,Maintenance + Mean\,Down\,Time} = \frac{MTBM}{MTBM + MDT} \quad (1)$$

3.3 Life Cycle Cost analysis

Within the European Project INNOTRACK, six deliverables have been published on the subject railway LCC until October 2009. The conclusions from these deliverables give a

picture that work with RAMS and LCC has been undertaken by several Infrastructure Managers for many years, but that the Railway Industry as a whole is just beginning to establish this as a normal routine A major problem is that data quality is not sufficient and effective systems for collecting data are lacking (INNOTRACK 2009).

Life cycle costing has been used since the late 1960s and has its roots in the American defence industry (Kawauchi and Rausand, 1999) as a tool for decision making by assessing the total cost of acquisition, ownership and disposal of a product (IEC 60300-3-3).

A product's life cycle consists of six major phases according to IEC 60300-3-3:

- Concept and definition
- Design and development
- Manufacturing
- Installation
- Operation and maintenance
- Disposal

An LCC model is basically the sum of several mathematical expressions used to estimate the cost of different elements (see **Figure 3**),which together cover the total life cycle cost of a product.

An LCC model usually includes:

- Ground rules and Assumptions
- Cost breakdown structure (CBS)
- Product/Work breakdown structure (PBS/WBS)
- Selection of cost categories
- Selection of cost elements
- Estimation of costs
- Presentation of results

LCC is an appropriate method to identify cost drivers, allow the comparison of different systems and deliver the necessary information for technical and economic decisions to be made.

Both the CBS and PBS are hierarchical tree structures necessary for describing an LCC model. If necessary, a work breakdown structure (WBS) is used to describe which activities the product needs to be produced or used.

In the longer term, as is the reality for railways, costs will vary due to technology improvements, therefore detailed cost estimation might be difficult to obtain. To balance this, experts are interviewed to improve, calibrate and validate the cost estimation relationships. To be able to compare different calculations and handle cost distributed in time net present value, annuity method, internal rate of return (IRR) and break-even calculations can be used.
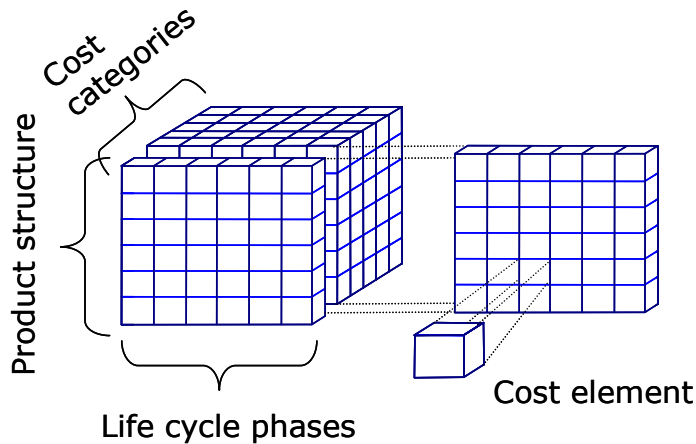
Figure 3, Cost element concept. (IEC 60300-3-3, 2005)

Different cost calculation methods can be used to estimate cost elements. According to IEC the most common methods are (IEC, 2005):

- Analogous cost method; A method that draws conclusions based on historical data from components of similar products
- Parametric cost methods; For this method mathematical cost equations are developed between parameters and variables and general characteristics of the product or process are defined. This method is especially important when actual or historical detailed product component data is limited to few parameters
- Engineering cost method; The method involves the direct estimation of a particular cost element by examining the product component-by-component and uses standard established cost factors to develop the cost of each element. This method is used when there is detailed and accurate capital and operational cost data

The INNOTRACK document also mentions that data from accounting systems can be used. This is based on the concept of Activity-Based-Costing and should lead to an improvement in the initial estimations (Zoeteman, 2004).

3.3.1 *Data from LCC analysis for S&C*

Very few researchers have presented LCC models with LCC values for S&Cs. In Finland and by the UIC project Infracost (Numelin 2004) the following has been anticipated for an S&C.

- Maintenance cost for an S&C equals the cost of maintaining 400 m rail track
- Technical Life Time 31 year (Average age 15.5 year in 2001)
- Replacement cost 200 000 - 300 000 € (R>=760 m)

In Austria, a research project has made an LCC model, but the report is not published.

Zwanenburg (2008) presents technical life time of S&Cs in the order of 400 MGT for the Swiss railway net.

4 Research methodology and approach

This chapter provides a short description of the research approach and the research methods.

A researcher should be able to present her/his way of investigating and verifying the research question leading to the results, whether it provides the desired answer or not. The researcher should be able to define her/his way of making the journey from question to result, thereby making it possible for other researchers to follow the steps taken. Other researchers may have different opinions, but by defining the choice of route and declaring the conclusions the first researcher makes it possible for followers to broaden out the research results. It is, therefore, essential for every researcher to be able to define the research process and their chosen methodology in a way that can be easily followed by other researchers (Backman, 1998, Gummesson, 2000).

The purpose of this research is to improve the reliability of railway infrastructure and in the long run decrease maintenance costs. The subsystem S&C has been in focus but the methodology can be used for other type of subsystem as well.

Banverket has large costs for maintaining S&Cs in their railway network. It has been considered that by renewing old S&Cs to modern ones there should be less failures and lower maintenance costs. It was encountered that the renewing programme of S&Cs was not solving the problem of high number of failures in 2002 projects to find explain the situation was started. Banverket has started technical projects to improve technical reliability and also initiated research projects to establish reasons for taking replacement decisions and finding causes for maintenance.

The latter research was the start of this dissertation. During the research work a cost perspective has been incorporated and five research questions have been asked.

4.1 Research Methodology

The research methodology in this project can be described as an exploratory process. The stated problem of the low reliability of S&Cs has been studied using what is actually recorded in the maintenance systems. Thereafter scientific way of describing this is to make a model based on failure statistic theory. In this work it has been encountered that not all failures can be described by the theoretical model. The work has then been concentrating on finding ways to explain deviations. Most of this work has been a combination between using statistics and interviewing people working with maintenance within, and sometimes outside, Banverket. In the end it has been decided that what is recorded should be treated as the "truth" about the maintenance activities. This implies that Banverket needs to work on the quality of the data to improve the usefulness of this type of information.

The maintenance statistics and information from account systems has been the foundation for building an LCC model. The LCC model is not verified in the sense that the input value has been tested by Banverket, but the intention is to make it useful in future work where more specific alternative is specified. Within INNOTRACK the model has been tested in three cases.

The basic hypothesis has been that using LCC modelling will help in making future decisions in choosing, for example, designs or materials for a new generation of S&Cs.

Analysis has been conducted in order to verify that suitable data is available and that the LCC model is built in a way so it can be useful.

4.2 Research approach

Mainly the research has been conducted by studying the data, statistics and information available in Banverket databases. In addition, within the framework of INNOTRACK, many participating European IMs have also shared their experiences when it comes to reliability and cost drivers for S&C operations.

4.3 Structure of the research

The thesis work started as an exploratory investigation on why even newly installed S&Cs fail. From focusing on failures the scope was broadened to all types of maintenance actions. Later in the project came the question of how to compare failures, preventive maintenance and train delays in one model. Most of the work has been concentrated on how to establish values for reliability and maintainability and some work on building a cost model to make the cost comparisons.

5 Data collection, classification and analysis

The research project has been possible by fully accessing vital parts of Banverket's (Infrastructure Management) systems. Data has been collected from Banverket's internal intranet, Banverket's Infrastructure system for assets BIS, failure system 0felia, Inspection System Bessy, track recording measuring data, and from way side monitoring systems for wheel flats and hot bearings.

5.1 Data sources

5.1.1 Asset register, BIS

The asset management database is called BIS (Baninformation systemet) and is updated on all features that concern the S&Cs. For analysis purposes, type of S&C and age are two examples of information that is needed. The name of the S&C is decided in this system and should be the same in all other databases. This is the situation today (2009), but it has been a problem in earlier years. BIS still has no information on previous installations or the age of components. Banverket is having an internal discussion concerning this subject. Basic data from BIS is shown in Appendix A. The first four columns in **Table 2** show processed data from BIS.

5.1.2 Failure reporting system, 0felia

0felia (Noll fel i anläggningen, zero failure asset) stores the information on all corrective actions. In 0felia information subsystem, type of action, cause and train delay time is found. The first step in processing of this data is to decide which S&C is to be studied. For instance is a number of track sections, types of S&Cs and that the S&Cs is in the main track chosen for a certain study. Coorelation between BIS and 0felia is therefore done by using the name and number of the individual S&C. In this system about 15% of all records have no asset number so manual work is needed to correct this. See Appendix B for basic data.

5.1.3 Inspection report system, Bessy

The maintenance system is divided into separate systems for preventive and corrective actions. Bessy (Bessiktningsystemet) stores data from inspection reports and the type of actions that have been taken after the inspection remarks. Some of the remarks need immediate action and are treated as corrective actions. Information in this system includes subsystem, type of action, priority (how soon the action should be taken). Some maintenance actions, especially restoring actions, are not stored as they are normally carried out without prior inspection. A new system will be established to cope with this issue. See Appendix C for basic data.

5.1.4 Measurements using track recording cars

The track recording car records alignment, levelling, corrugation and rail profile data. This is based purely on kilometer measurement and can only indirectly be combined with S&Cs. Information on levelling data can be of important to establish a quality index for each turnout. This is right now a started project but in an early stage. Appendix D shows the basic data.

5.1.5 Way side monitoring system

Way side monitoring system is used to collect information about the traffic. Although there is a database for traffic information (TFÖR) a way side detector counts the number of axles, which is important as the total load on a S&C is measured in MGT (million gross tonnes) rather than by the number of trains. In some cases the weight of each axle is measured in the wheel impact load detectors (WILD). In these cases the total load can also be accurately measured, otherwise it is calculated by using an average weight per axle. This information is assumed to be the same for a whole track section, but is not always the truth. See Appendix E for basic data.

5.1.6 Other sources

The track recording trains records a video over the full track length. Viewing these videos helps in understanding the position of individual S&Cs and their surroundings. Also physical visits of a number of station areas have been carried out as part of this work. During the years, a number of presentations and discussions have been held, and talking to experts has been very helpful in understanding some of the degradation mechanisms.

5.2 Data analysis

Data has been collected and sorted so that a reasonable number of S&C on the same track section have been analysed at the same time. In most of the data mining studies it has mostly been of interest to establish key figures of reliability (maintenance need) and maintainability (maintenance performance). Some guidelines that have been followed are:

- Try to use at least 20 turnouts during 3 years when comparing failure statistics
- Establish if the S&C really is used and placed in a manner that will not detoriate faster than other S&Cs
- Comparison on an individual S&C to be "normal" or not can only be done with other S&Cs that has similar condition (traffic, location in the country, maintenance contract)
- Show data from more than just one track section to understand variations within the railway network

6 LCC analyses and development of model

The proposed model is built in Excel, but can also be used in two programmes developed for LCC calculation. The advantage of using Excel is that it is easier to spread, and the disadvantage that Excel does not have the same functionality as a specialised LCC tool. Here only the Excel tool is described.

The model is describing three phases:

- Initial acquisition
- Operation and maintenance
- Phase out

6.1 Initial acquisition phase

During the initial phase acquisition and installation is done. This is put in as fixed costs that occur the first year. There might be more costs such as training and buying maintenance equipment. In the model only the cost for training in monitoring systems has been added, as that was one of the cases. No cost for preplanning and development is used for the model, as the idea is that the infrastructure manager is buying a complete system and is not developing it.

6.2 Operation and maintenance phase

In the calculation there is one sheet just for a number of global parameters, such as discount rate, number of workers per action, work hour cost and so on. A separate sheet is used for detailed information on maintenance actions.

For operation and maintenance five input parameters are used for calculating the corrective and preventive maintenance cost:

- Mean time between failure/Mean time between maintenance (MTBF/MTBM)
- Mean time to repair (MTTR)
- Mean logistic delay time (MLDT). This value is dependent on the organisation and its planning of the maintenance
- Material cost
- Equipment cost

Two parameters are added to calculate the consequence cost:

- Probability that a failure will cause a train delay
- Train delay per train stopping failure

The data can be input for each maintenance action (of 4 possible) and for each subsystem (of 8 possible). This gives 32 input rows in total. In cases where deatiled information isn't required, only one or two of the rows are used.

Separate from the detailed information on subsystem level interval and cost for grinding, tamping, inspection and operation is inputted.

6.2.1 Treating of maintenance rate and discount rate

The increasing maintenance rate has been incorporated by using a NHPP model (Non Homogenous Poisson Process). **Figure 4** shows the effect of using such a model. Normally a yearly maintenance cost is multiplied with the Net Present Value, NPV-factor (1+r)-t. By also multiplying with NHPP-factor the two curves NPV*NHPP, r=4% and NPV*NHPP, r=8% is created. The two parameter β and r change the shape of the curve and should be chosen by care. With β=1 the NPV and NPV*NHPP curves will be the same.
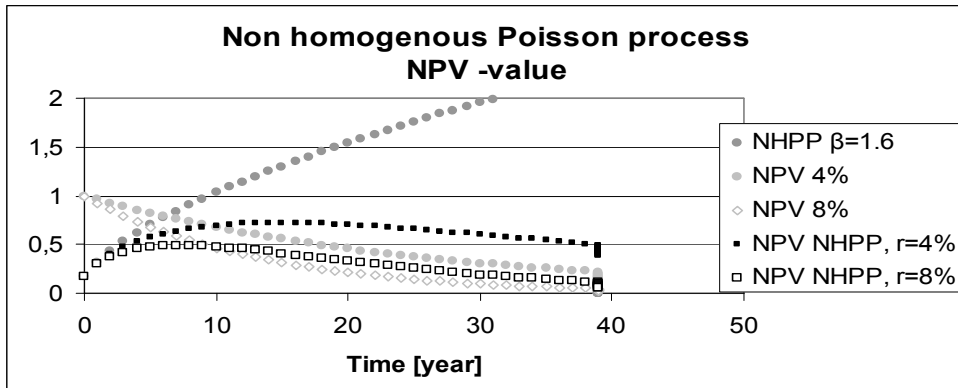
Figure 4, NPV value is affected by the discount rate. By using the NHPP model with an increasing failure rate (line PM, preventive maintenance) a value for maintenance cost per year can be calculated. With β=1.6 and 4% discount rate the annual cost for PM increases until year 15.

6.2.2 Treating the periodical maintenance when they occur

Not all maintenance occurs each year, for instance tamping, grinding and larger replacements have a time interval of 4-20 years. By separating these types of maintenance from annual maintenance they can be calculated the year they occur. A consequence is that tamping will have a lower cost by calculating it as a periodical cost than to calculate it as annual maintenance. **Figure 5** show the maintenance done on a periodical basis. (Details are given in Paper 3).

Figure 5 Periodical maintenance is grinding, tamping and replacement of larger subsystems.

6.3 Phase out

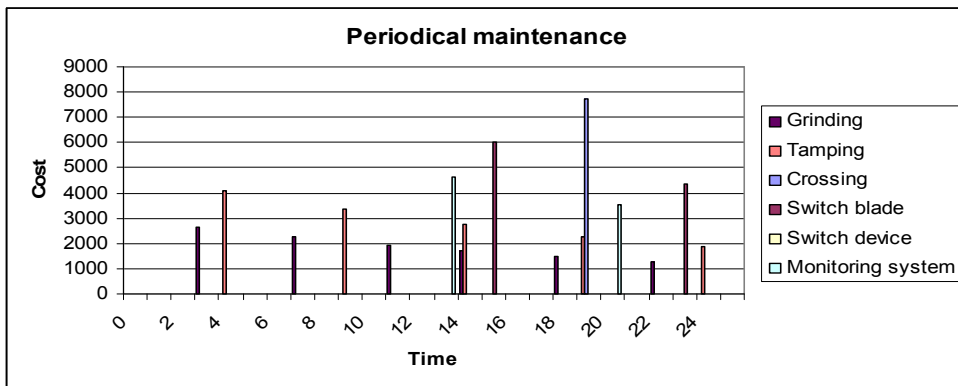The phase out can be treated both on system and component level. As an S&C in main track might be used in side track after the economical life time, residual values are calculated for both the total system and for components replaced during restoration. In case only 50% or less of the TLT is used, then the residual value of the total system dominates and to avoid double counting only the highest residual value of either system or component is used. **Figure 6** shows how the residual value makes a difference. By using the residual value in the model the annual cost does not vary very much between 10 – 50 years usage time (TLT=40 years) if the maintenance rate is constant over global time (β=1). By using increasing maintenance rate the annual LCC value will increase the longer the asset is used while the maintenance cost will increase with time. (The discount rate will also influence the calculation, in this case 4% is used). After 40 years the cost for reinvestment is seen. From **Figure 6** it should not be concluded that it is better to replace the S&C at 10 years usage instead of 40 years, while no cost for the replacement has been added.

The residual value is important to be able to compare assets with different TLTs.
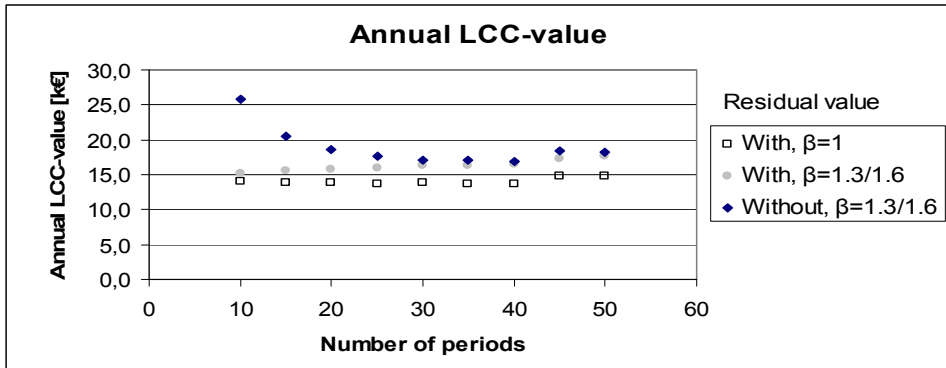
Figure 6 Annual LCC value for three different cases. Without residual value the investment cost is lost if the asset is used only less than 50% of the TLT (40 years in the case) which is shown as decrease LCC value. With residual value the annual cost is nearly constant if β=1 (no increasing failure rate with time) and increasing if there is increasing maintenance rate ($β_{CM}$=1.3 and $β_{PM}$=1.6).

No cost for termination has been added in the model so far.

6.4 Verification of LCC models

Three examples of LCC calculation have been tested within INNOTRACK. To state what a normal S&C is, it has been proposed that the maintenance need is

- 1.5 failure/year
- 0.5 train stopping failure/year
- 20 maintenance activities/year
- Tamping every 5th year (100 MGT)
- Grinding every 4th year (80 MGT)

- Replacement of crossings by 12 years
- Replacement of switch blade by 8 years

Added to this is some data of

Maintainability

- MTTR for failures 0.5 h
- MWT for corrective maintenance 1 h
- MTTR for preventive maintenance 1 h
- MWT (or MLDT) for preventive maintenance 1 h

Cost data

- Investment material cost 125 000 €
- Investment installation cost 53 000 €
- Train delay cost 80 €/minute
- Calculate with 2 persons per action
- Worker cost 50 €/h

Discount factor

- 5.0%

Traffic data

- 20 MGT/year

TLT

- 500 MGT (25 years)

The invention has been calculated by assuming cost changes in different areas, see **Table 3**.

Table 3, Changes between a standard S&C and the invention

Invention	Invest-ment	TLT	Corrective Maintenance	Train delays	Preventive Maintenance	Operation	Inspection
WP3.1 Design and material	+ 6%	+ 20%	- 30%	-30%	-30%	---	0%
WP3.2 Driving and locking device	+ 4%	0%	- 50%[1]	-50%[1]	-80%[2] -50%[3]	---	0%
WP3.3 Condition monitoring	+ 4%	+ 20%	-20%	-50%	-20%	+0.3k€/year	-37%

1) Only control device and switch device
2) Control device and switch device but not periodical preventive maintenance (large replacement)
3) Large replacement of switch device

The LCC improvement for making improvement of design and material was 14%.

The LCC improvement for changing design of the driving and locking device was 16%

The LCC improvement for using condition monitoring was 11%.

6.5 Sensitivity analyses and cost drivers

Sensitivity analyses are made to see which parameters influence the result to a great extent. Three parameters are chosen here, discount rate (**Figure 7**), traffic load (**Figure 8**) and NHPP-factor β_{PM} (**Figure 9**), more information is given in journal paper 3. Discount rate and traffic load influence the result and NHPP-factor β_{PM} does not seem to be sensitive. The latter depends on the assumption that the beta value is the same for both alternatives; if the beta value is changed between the alternatives as an effect of lower degradation rate the situation will be different.

Emblemsvåg (2003) discusses this on infrastructure investment and concludes that it would be good to have discount rates of 0% to help the management to take decisions that improve reliability by using high quality in the investment phase. Banverket uses 4% and Deutsche Bahn in Gemany uses 8% as discount rate in their calculations.
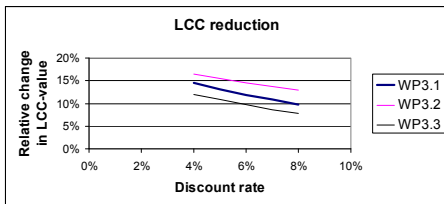
Figure 7, Sensitivity analysis with discount rate
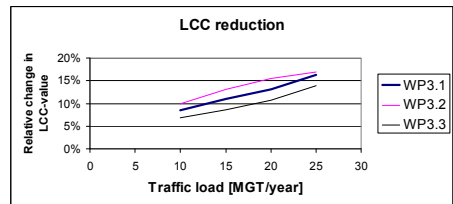
Figure 8, Sensitivity analysis with traffic load
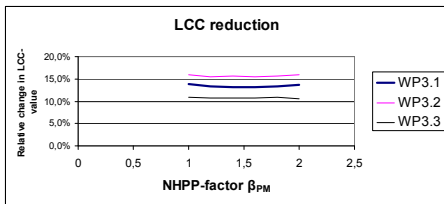
Figure 9, Sensitivity analysis with NHPP-factor for preventive maintenance
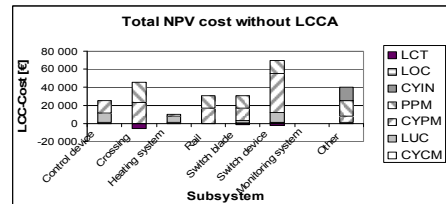
Figure 10, LCC value to analyse cost drivers. The bars split the LCC value into subsystems

A cost driver analysis is done to see which part of the system will influence the LCC cost the most. **Figure 10** shows that, of the different subsystems, the switch device, crossing, rail, switch blade and control device are the most costly. The bars also show that periodical preventive maintenance (PPM), cost for yearly preventive maintenance (CYPM), unavailability cost (LUC) and cost for yearly inspections (CYIN) are the most important.

7 Summary of the appended papers

Four journal papers have been written and are appended to this thesis. During the work, four conference papers have also been written, but are not included in the thesis. The four journal papers are:

- Classification and Cost Analysis of Switches and Crossings for Swedish Railway – A case study
- RAM-analysis of Switches and Crossings for Swedish Railway – A case study
- LCC for Switches and Crossings at the Swedish Railway – A case study
- Condition monitoring of Railway Switches and Crossing using data from Track Recording Cars

7.1 Journal Paper 1 – Costs for S&Cs

This paper is a case study based on data during the period of 2004-2006. Six track sections were selected with different kinds of traffic. Information gathered in different databases has been used in the work to identify costs for individual S&Cs. The cost for an individual S&C can be calculated in this manner. The cost varies depending on the type of S&C and amount of traffic.

Title – Classification and Cost Analysis of Switches and Crossings for Swedish Railway – A case study

Paper type – Research paper, case study

Purpose – Switches and crossings (S&Cs) are an important component of Banverket's infrastructure, and are associated with 13% of the total maintenance cost. Therefore it is important that a detailed study of different aspects of the costs of S&Cs should be undertaken to analyse individual maintenance costs. This will, in the future, give the possibility of enhancing the management of infrastructure.

Approach – A case study was undertaken to study, identify and classify the costs of S&Cs for Banverket. Data was taken from Banverket's maintenance information systems and accounting system.

Findings – A rough estimation of the cost for individual S&Cs can be identified in this way. The cost varies widely to quite an extent and a more detailed study is needed to validate the cost on this level. The average cost of a group of S&Cs varies less and is therefore more likely to reflect the true cost. The cost varies depending on the amount and type of traffic. Moreover, the type of S&C seems to reflect the cost variation, but further investigation is required to verify this conclusion.

Research limitations/implications – The accounting system does not store data for individual assets, and further research would be more fruitful if individual costs could be recorded by the entrepreneur. Larger repairs should be separated from annual maintenance tasks in a future study. Data from this study could be used to build a life cycle cost model for S&Cs.

Practical implications – Cost identification is a first step in finding a way to organise maintenance and make repair/replacement decisions in a more cost-effective way.

Originality/value – The paper shows a way of distributing costs (in the accounting system) down to individual subsystems of the infrastructure. This enables analysts to find cost drivers and plan for modification of, or reinvestment in, the asset.

This article contributes to the understanding of maintenance cost of Swedish S&C. The result shows the importance of getting a better understanding of the cost for preventive maintenance. It also indicates that the cost can vary widely between S&Cs on the same track section.

7.2 Journal Paper 2 – RAM analysis

This paper evaluates the possibility of establishing how available data can be used for reliability, availability and maintainability (RAM). More than 700 Swedish S&Cs (67% of all S&Cs in main track) were selected on three main routes (consisting of 35 track sections). RAM-data was taken from two different maintenance systems and analysed for 4 different types of S&C:s.

Title – RAM-analysis of Switches and Crossings for Swedish Railway – A case study

Paper type – Research paper, case study

Purpose – To evaluate the available RAM-data is for building an LCC model. In the study the some model concept was tested

Approach – Data was extracted from two of Banverket's maintenance systems. Comparisons between the main routes were made to establish how this type of data can vary. Underlying factors for variations can be the amount and type of traffic, climate and maintenance strategies. Analysis was carried out on separate subsystems and different types of maintenance actions.

Findings – A reliability model based on Non Homogenous Poisson Process (NHPP) has been developed and used. The data available can be used to calculate cost of maintenance for switches and crossing using an LCC model.

Research limitations/implications – The maintenance systems store data that can be used for estimating RAM-data in general. It has been possible to extract data and compare different types of S&Cs. The data quality can be questioned, especially for preventive maintenance, as there have been less recorded maintenance activities over time.

Practical implications – An LCC model can be based on the data from this paper. The proposed reliability model has been included in a Swedish LCC model.

Originality/value – The reliability model include a change of the maintenance cost over time and this makes it more economical to replace S&Cs after a certain time. A normal LCC establishes only a constant maintenance cost over time which does not imply any economical benefit to replace before the end of the technical life time.

This article contributes to show the possibility of retracting data to estimate reliability and maintainability of S&Cs in the Swedish railway network. The finding of this paper is that not all data is collected in a similar way over time, and that there is a need for expert judgement to complement the findings in the databases. A reliability model based on NHPP is proposed. A Product Breakdown Structure (PBS) for S&Cs and maintenance activities that can be categorised (similar to a Work Break Structure, WBS) are described.

7.3 Journal Paper 3 – LCC analysis for S&Cs

In this paper an LCC model is presented. The LCC value may be presented as an annuity cost, which enables a comparison between assets that have different technical lifetimes.

The cost drivers are the inspection cost and the periodical maintenance costs of subsystems, such as the costs for crossing and switch blade replacement, welding and tamping. The sensitivity analysis confirms that the most important parameter to have control of is the frequency of periodical preventive maintenance.

Title – LCC for Switches and Crossings at the Swedish Railway – A case study

Paper type – Research paper

Purpose – To achieve a lower operation and maintenance cost for S&Cs, there is a need for better understanding of the life cycle cost. LCC enable the engineer to calculate cost instead of just failure rates and the number of preventive maintenance actions. With this knowledge, it will be possible to propose changes in the design and maintenance strategy. The scope of the paper is to explore the possibility of using the LCC model as a decision tool for an infrastructure manager.

Approach – A cost model based on the acquisition phase and the operation and maintenance phase has been developed and tested. In this model, the LCC values of three types of S&Cs are compared. The model can also be used to find cost drivers, as well as to perform sensitivity analysis to find parameters that have a large influence on the result. The model has been built with the assumption that a multiple type of maintenance action is undertaken for each subsystem.

Findings – The model can be used to find cost drivers, as well as to perform sensitivity analysis to find parameters that have a large influence on the result. Largest influence on cost during the operation phase is larger replacement.

Research limitations/implications – The model has been tested on data that so far not has been verified. In the model it is assumed that the number of maintenance actions is linear with million gross tonnage per year, this does not take into consideration that maintenance strategies change with different types of traffic situation.

Practical implications – An LCC model can be used to evaluate different maintenance strategies.

Originality/value – LCC has been used for track in several of the European countries. A specialized model for S&Cs has not been presented before. This paper contributes with a LCC model based on NHPP and also shows the possibility to use Monte Carlo simulations.

This article contributes to the understanding on how an LCC model for S&Cs can be built and used. The reliability model, from journal article 2, based on Non Homogenous Poisson Process (NHPP) is implemented. Annual maintenance and maintenance with longer interval than one year and inspections can be inputted separately. By the model it is possible to find cost drivers and by this start to discuss how a better design or maintenance strategy can reduce the LCC value.

7.4 Journal paper 4 – Track condition data for S&Cs

This article presents a way of using track recording data in such a way that trends can be followed for individual S&Cs. The article also discusses the possibility of comparing types of S&Cs in the same track section by using a quality index.

Title – Condition data for Railway Switches and Crossing from Track Recording Cars

Paper type – Research paper, case study

Purpose – To explore the possibility to use track condition data for making decision about tamping and renewal

Approach – Data from the track recording car has been used to identify and characterize individual S&Cs. The data has been filtered to identify the crossing of the S&C. Trends based on standard deviation has been used to establish a quality index.

Findings – Several recordings for each S&C are needed to see trends on level and alignment of the individual S&Cs. The alignment signal is not recorded each time and therefore generally not possible to use. The level signal is increasing by time until a maintenance action is taken. Normal standard deviation calculation cannot be used for S&Cs and new ways to calculate standard deviation is necessary.

Research limitations/implications – Today's way of sampling data from the track recording car limits the possibility to use the alignment signal. A new generation of track recording cars might give better possibilities by, for instance, separate the lateral accelerometer signal from the lateral position measured by laser.

Practical implications – A quality index can be used for taking decisions on future maintenance actions.

Originality/value – A new method for studying the track recording data has been explored. The possibility to identify the position of the crossing is based on earlier research done by Eric Berggren, Banverket.

This journal paper contributes to a better use of track recording data. Previously all decisions for tamping S&Cs at Banverket have been based on either looking on The S&C at site or reading curves on a paper sheet without a good possibility to compare different recordings. A new way is outlined by suggesting the use of trending of the standard deviation of the level signal.

8 Discussion and conclusions

The results obtained from this study are going to be tested and eventually implemented by Banverket to enhance the effectiveness of the operation and maintenance management of S&Cs. In this section, some of the results are discussed. The author has noticed an increasing awareness about RAMS and LCC analyses and their applications within Banverket and other infrastructure managers (IMs) during the last two years. Different groups of technicians and engineers at Banverket are studying the data available in the database for maintenance. These databases have information which can become very useful input to RAMS and LCC analyses of S&Cs. The results obtained are verified within the Framework of EU FP 6 project INNOTRACK. For S&Cs, an LCC model based on the power law concept for a repairable system has been developed.

LCC analyses will give a better understanding of what type of changes in design and maintenance routines can be planned to lower the life cycle cost. The challenge in making a LCC model for S&Cs is neither the cost breakdown structure nor the product breakdown structure. Instead, a problematic issue is the long technical lifetime, TLT, in combination with the discount rate. The TLT is dependent on the traffic situation, and Banverket does not have good enough data to support any precise description of how much load is acceptable for an S&C. A realistic value of TLT is about 500 MGT for S&Cs. ORE D 161 presented a degradation model for rail. Data showing how degradation rate and TLT for S&Cs is affected by traffic load per year, speed and axle weight has so far not been published. Still, the LCC model has incorporated the same feature for rail by using the power law concept (ERRI 2002).

Another issue is to identify the maintenance activities in a correct way. It is especially the maintenance done very seldom that must be described. As component life time is a function of initial design, operational load, environment and maintenance activities it will be difficult to find precise figures on this even if several years' data is used.

During the work with the LCC model, cost driver and sensitivity analyses are made. This information is used to find key parameters that should be estimated as accurately as possible. During the work the following parameters have been found:

- Replacement rate of crossings and switch blades
- TLT
- Traffic load
- Inspection cost
- Discount rate
- Need for grinding
- Need for tamping

8.1 Research objectives

The research objective set out in this study has been achieved, as an LCC model for S&C for Banverket has been developed and is going to be implemented. The tool is intended to be used for decision making concerning S&Cs. The implementation of the tool is planned for 2010. Some features of the model, such as cost of snow removal, still need to be added.

8.2 Research questions and related papers

Research question 1 *Maintenance Actions*

   A) How to identify/define maintenance actions for S&C? - Journal paper 2

   B) How to identify the frequency of maintenance actions (reliability) for S&C? - Journal paper 2

Maintenance actions are stored in the maintenance system either as failure reports (corrective maintenance) or as inspection remarks (preventive maintenance). The reports can be used to identify which types of S&C as well as which subsystem that causes the problem. Frequencies of failure are established by grouping a number of S&Cs and calculating an average over a longer time period (for instance 3 years). Maintenance rate for preventive maintenance is calculated in the same way, but fewer S&Cs are needed, as the number of inspection remarks is much higher than failures. Banverket is recommended to improve the data quality to make more specific analysis, useful for different operational scenarios. However, the quality of the stored data and information is enough for the purpose of this research study as most LCC work is undertaken as a relative comparison and the exact value is not very important.

Research question 2 *Maintenance Cost*

   A) How is the cost related to the most important maintenance actions? - Journal paper 2 and 3

   B) How is the cost estimated for chosen maintenance actions? - Journal paper 1

Cost is not stored for individual S&Cs and therefore most of the cost estimation must be made indirectly. On track section level the cost is stored as preventive maintenance, corrective maintenance, tamping and so on. By using data of individual S&Cs, such as number of maintenance actions, the total cost can be distributed on all S&Cs of the track section. Another method is to use maintenance repair time and assuming certain delay times.

Research question 3 *LCC model*

   A) Which are essential elements in an LCC model for S&Cs? - Journal paper 3

   B) How is residual life value estimation and maintenance for prolonged usage after technical life reached? – This question has been dealt with within the INNOTRACK project, see also section 6.3

   C) Can the LCC model provide decision making support during upgradating and modifications of S&C (See question 5)? - Journal paper 3

In the LCC model three different structures are built. Product, maintenance work and cost breakdown structures are defined.

The product break down structure (PBS) is defined for the most important subsystems. In paper 3, these were:

- Ballast/Sleeper
- Crossing
- Control device
- Heating system
- Rail
- Switch blade
- Switch device

Later ballast/sleeper has been omitted and monitoring system has been added.

The maintenance work breakdown structure (WBS) has been divided into:

- Adjust
- Repair
- Replace
- Large replacement (restoration)
- Grinding
- Tamping

Cost breakdown structure (CBS) has been defined as:

- Acquisition cost
  - Material cost
  - Installation cost
  - Transportation cost
  - Preparation and planning cost
- Operation and maintenance cost
  - Operation cost
  - Maintenance cost
  - Consequence cost
- Termination cost or residual value
  - Termination cost
  - Residual value

Research question 4   *Asset health condition assessment*

A) How can asset health data be used to identify a specific S&C for replacement decision making? - Journal paper 1, 3 and 4

Comparing costs between the alternatives of replacing the S&C or prolonging their life time is possible. The most important cost element in papers 1 and 3 is the cost for larger replacements. This type of estimation is difficult to make from the maintenance system. Journal paper 4 indicates that the condition of the individual S&C can be established.

Research question 5   *Designed aspect*

A) If a group of S&Cs should be modernised, what type of S&C should be used is given traffic data, how deviating track is used considering from the LCC value and traffic volume? – not discussed in any journal paper

This question has not been dealt with so far. Banverket has recommendations mostly based on capacity and spare part supply when renewing an S&C.

B) What data and information are needed as input to the LCC model during investment projects in selection of S&C type for a defined task? – Journal paper 2 and more work needs to be done.

Type of information has been discussed as part of the answer to research question 1A. In section 6.2 the detailed information that is asked for by the model is shown. It is not obvious if Banverket can identify that 60 kg rail should be used in all main track or if 50 kg rail could be used for S&Cs with less load than, for instance, 8 MGT/year. In the internal standard (Banverket 2007) this is not stated, instead each project must make such a decision. To be able to satisfactorily answer this question it will be necessary to study the degradation of

some of the subsystems such as switch blades, check rails and crossings on these types of S&Cs.

8.3 Conclusions

In this research study, reliability and maintainability characteristics of switches and crossings are analysed using real data from Banverket. An LCC model has been built and used to enable effective maintenance decisions. Based on the study it can be concluded that adequate data is available in the Banverket database but the quality of reporting and registering must be improved so as to render them easy to use for analyses and decision making. Nevertheless an LCC analysis can be performed if the purpose is to compare different alternatives and not to establish a correct cost of the whole life cycle. Part of the research work has been performed within the European Framework of FP 6 IP Project INNOTRACK, and three examples of calculations have been made to show the positive effect of new approaches. Parameters that influence the result of the analysis have been identified by sensitivity analysis, and these parameters must be checked by, for instance, an expert group before the value is decided. Another method is to use distributions instead of discrete input values and by Monte Carlo simulations generate a probabilistic output. The model developed can be used to evaluate new S&C designs and also to take decisions regarding alternatives for S&C specification to be used under different traffic situations. Thus, by considering LCC as basis for decision making, it is expected that the decision makers in the future will be able to make more cost effective decisions.

9 Contributions and scope for future work

9.1 *Contributions*

The author of this thesis has been exploring failure and preventive maintenance statistics available at Banverket's databases for S&Cs and has converted this into useful information. This information is vital as input into the model and as foundation for maintenance decisions. In this research work, some activities are undertaken that are new, at least for Banverket and in some cases also for Europe. Some of the contributions of this research work can be summarised as:

- The use of different maintenance databases for maintenance to extract information on individual level and on group level down to component level
  - An example of this is that today the type of S&C is not registered by the failure database, by combining individual S&Cs in the asset register and in the failure database, the failure rate for types of S&Cs could be estimated for a number of track sections
  - Another example is that the type of switch position detector has been changed during 2004-2007. In failure or inspection reports, it is not stated which type of switch position detector is used, and by marking all S&Cs with the new type, it was possible to show a decrease in failure rate after the introduction of the new type
- During the work, the author has proposed an LCC model based on aging of the system by using a NHPP assumption
- During the study, it has been shown that Monte Carlo simulation can be incorporated into the LCC model by using macro programming in Excel.
- In this study, an approach for using track condition data to develop an individual quality index for S&Cs have been presented.

9.2 *Scope for future work*

To improve the application of RAMS and LCC in day-to-day decision making, the following activities could be scope for further research:

- Verification of the benefits of using an LCC model as a decision tool
- Developing the use of Monte Carlo simulation to enhance uncertainty and sensitivity analysis
- Developing and studying of a quality index for S&Cs and correlating it to the need of maintenance
- Establishing a system that can provide information on traffic that passes each S&C

10 References

1. Andersson, M. (2007). Fixed Effects Estimation of Marginal Railway Infrastructure Costs in Sweden, *Empirical Essays on Railway Infrastructure Costs in Sweden*, Chapter 3, Doctoral Thesis, Trita-TEC-PHD, 1653-4468, 07:002, ISBN: 91-85539-18-X. Division of Transport and Location Analysis, Department of Transport and Economics, Royal Institute of Technology, Stockholm

2. AAR (1993). *Development of a Comprehensive Life-cycle Costing Model for Railroad Turnouts*, R-854, Association of American Railroads, Washington

3. Backman, J. (1998). *Rapporter och uppsatser*, (*Reports and theses*), Studentlittertur, Lund

4. Banverket (2007). *Växelprojektering (Design guide for S&Cs)*, BVS 586.45, HK06 2772/BA40, Borlänge

5. Banverket (2008). *Banverkets Årsredovisning 2008*, (*Banverket's Annual report 2008*), http://www.banverket.se/pages/1493/BANVERKET_ÅR08_WEBB_tillg_2.pdf (accessed October 27, 2009)

6. Banverket (2009a). Mål och vision, (Goal and vision) http://www.banverket.se/sv/ Amnen/Om-Banverket/Verksamheten/Banverkets-mal.aspx (accessed October 27, 2009)

7. Banverket (2009b). *Nationell Plan för Transportsystemet 2010-2021 (National Plan for the Transport system 2010-2021)*, http://banportalen.banverket.se/Banportalen/pages/ 7571/ntp_kortversion_090828.pdf (accessed October 27, 2009)

8. Bonaventura, C.S., Zarembski, A.M. and Palese, J.W. (2008). Switch and crossing inspections and maintenance management using handheld computers, *IET Seminar Digest 2008* (12216)

9. Chattopadhyay, G. and Kumar, S. (2009). Parameter estimation for rail degradation model, 2009, *International Journal of Performability Engineering*, 2009, **5** (2), pp. 119-130

10. Emblemsvåg, J. (2003). *Life-cycle Costing Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks*, John Wiley & Sons, Hoboken, New Jersey

11. ERRAC (2007). *Strategic Rail research Agenda 2020*, Publishes by European Rail Research Advisory Council (ERRAC), http://www.errac.org/docs/ERRAC_brochure_ 2020.pdf (accessed October 27, 2009)

12. ERRI (2002). *Ecoswitch - Switches and Crossings Management System*, ERRI D251/RP1 (August 2002), Feasibility Study Appendices

13. Espling, U. and Kumar, U. (2007). Benchmarking of the Maintenance Process at Banverket (the Swedish National for Rail Administration), Chapter 23 in *Handbook on Maintenance of Complex System*, Springer, London

14. García Márquez, F.P., Lewis, R.W., Tobias, A.M. and Roberts, C., (2008). Life cycle costs for railway condition monitoring, *Transportation Research Part E: Logistics and Transportation Review*, November 2008, **44 (**6), pp 1175-1187

15. García Márquez, F.P., Schmid, F. and Collado, J.C.A (2003). Reliability centered approach to remote condition monitoring. A railway points case study, *Reliability Engineering and System Safety*, 2003, **80** (1), pp. 33-40

16. Gummesson, E. (2000). *Qualitative Methods in Management Research*. Sage publications limited, ISBN 0-7619-2013-7, Thousand Oaks, California

17. Granström, R. and Söderholm, P. (2005). Punctuality measurements effect on the maintenance process: a study of train delay statistics for the Swedish railway. *Proceedings of the 8th international conference and exhibition of Railway Engineering*, 29th-30th June 2005, London

18. Hedström, R. (2001). *Kriterier för byte alternativt fortsatt underhåll av spårväxlar* (*Criteria for replacement or extended maintenance of switches and crossings*), VTI notat-20-2001, Väg och transportforskningsinstitutet, Linköping

19. Hokstad, P. (1998). *Life Cycle Cost Analysis in Railway Systems*, SINTEF, Trondheim, STF 38, A98424, http://www.sintef.no/upload/Teknologi_og_samfunn/Sikkerhet%20 og%20pålitelighet/Rapporter/STF38%20A98424.pdf (accessed 15 October, 2009)

20. Holmgren, M. (2006). Maintenance-related losses at the Swedish Rail, *Journal of Quality in Maintenance Engineering*, 2006, **11** (1), 2006, pp. 5-18

21. IEC (2004). *Dependability management - Part 3-3: Application guide - Life cycle costing*, IEC 60300-3-3 2nd edition, International Electrotechnical Commission, 3, rue de Varembé, PO Box 131, CH-1211 Geneva 20, Switzerland

22. INNOTRACK (2008). *D3.3.1 – List of key parameters for switch and crossing monitoring*, Project no. TIP5-CT-2006-031415, http://www.INNOTRACK.net/ docs/deliverables/d331-f3p-key_parameters_switch_crossing_monitoring.pdf (accessed 27 October, 2009)

23. INNOTRACK (2009). *D6.3.3 Necessary developments of RAMS technologies*, Project no. TIP5-CT-2006-031415, http://www.INNOTRACK.net/docs/deliverables/d633.pdf (accessed 27 October, 2009)

24. Johansson, G. (2006). *On the Modeling of Large Ratcheting Strains and Anisotropy in Pearlitic Steel*, Doctoral Thesis ISSN 0346-718X, no 2495, Chalmers University of Technology, Gothenburg.

25. Jönsson, P.-A. (2007). *Dynamic Vehicle-Track Interaction of European Standard Freight Wagons with Link Suspension*, Doctoral Thesis Trita-AVE 2007:036, KTH (Royal Institute of Technology), Aeronautics and Vehicle Engineering, Stockholm

26. Kassa, E., Andersson, C. and Nielsen, J. (2006). Simulation of dynamic interaction between train and railway turnout, *Vehicle System Dynamics*, 2006, **44** (3), pp. 247-258.

27. Kassa, E. and Nielsen, J.C.O. (2008). Dynamic interaction between train and railway turnout: Full-scale field test and validation of simulation models, *Vehicle System Dynamics*, 2008, **46** (SUPPL.1), pp. 521-534

28. Kumar, U. and Akersten, P A. (2008). Availability and maintainability, *Encyclopedia of Quantitative Risk Analysis and Assessment*, editor E. Melnik and B. Everitt, Wiley, 2008, pp. 77-84, Chichester

29. Larsson, D. (2004). *A Study of the Track Degradation Process Related to Changes in Railway Traffic*, Licentiate Thesis 2004:48, 2004, Luleå University of Technology, Luleå

30. Li, Z., Zhao, X., Dollevoet, R. and Molodova, M. (2008). Differential wear and plastic deformation as causes of squat at track local stiffness change combined with other track short defects, *Vehicle System Dynamics*, 2008, **46** (SUPPL.1), pp. 237-246

31. Lichtberger, B. (2005). *Track Compendium: Formation, Permanent Way, Maintenance, Economics*. Eurailpress, Hamburg.

32. Ling, D.J., Roy, R., Shehab, E., Jaiswal, J. and Stretch, I. (2006). Modelling the cost of railway asset renewal projects using pairwise comparisons, Proceedings of the Institution of Mechanical Engineers, Part F: *Journal of Rail and Rapid Transit*, 2006, **220** (4), pp. 331-346

33. Link, H. and Maibach, M. (1999). *Calculating transport infrastructure costs*, Report of European Commission, Railway Working Group 1, April 28, available at: http://ec.europa.eu/transport/infrastructure/doc/infrastr-cost.pdf (accessed 15 October, 2009)

34. Modarres, M. (2006). *Risk Analysis in Engineering: Techniques, tools, and Trends*, CRC Press, Boca Raton, Palm Beach

35. Nicklish, D., Nielsen J., Ekh, M., Pålsson, B., Reinicke, J. M. and Zoll, A. (2009). Simulation of Wheel-Rail Contact Forces and Subsequent Material Degradation in Switches & Crossings, send for publication

36. Nissen, A. (2005). *Analys av Statistik om Spårväxlars Underhållsbehov* (*Maintenance Reliability Analysis of Railway Turnouts*), Licentiate Thesis 2005:86, ISSN:1402-1757, Luleå University of Technology, Luleå

37. Nummelin, M. (2004). *Railway Turnouts – Rautatievaihteet*, Finnish Rail Administration (RHK) , ISBN 952-445-096-8, Helsiniki

38. ORE D161 (1988). *Dynamic Vehicle / Track Phenomena, from the Point of View of Track Maintenance*, Report No. 3, Final Report, Office for Research and Experiments of the International Union of Railways, Utrecht.

39. Patra, A., Söderholm, P. and Kumar U. (2009). Uncertainty estimation in railway track life-cycle cost: a case study from Swedish National Rail Administration, Proceedings of the Institution of Mechanical Engineers, Part F: *Journal of Rail and Rapid Transit*, 2009 **223** (3), pp. 285-293

40. Reddy, V., Chattopadhyay, G., Larsson-Kråik, P.-O. and Hargreaves, D. J. (2007). Modelling and Analysis of Rail Maintenance Cost, *International Journal of Production Economics*, 2007, **105** (2) pp 475–482

41. Stichel, S. (2004). *Ökade laster med hänsyn till spårnedbrytning* (*Increased loads and the correlation to superstructure degradation*), Report 0506C, KTH (Royal Institute of Technology), Stockholm

42. UIC (2008). Best Practise Guide for Optimum Track Geometry Durability, UIC Internal document, 2008, Paris

43. Veit, P. (2007). Track Quality – Luxury or Necessity?, *RTR Special 2007*, ISBN 978-3-7771-0367-9, Eurailpress, Hamburg

44. Zhao, I., Chan, A. H. C., Roberts, C. and Stirling, A. B. (2006). Assessing the economic life of rail using a stochastic analysis of failures, Proceedings of the Institution of Mechanical Engineers, Part F: *Journal of Rail and Rapid Transit*, 2006, **220** (F2), pp 103–110

45. Zoeteman, A. (2004). *Railway Design and Maintenance from a Life Cycle Cost Perspective*, Doctor thesis, ISBN 90-9018691-3, TU Delft

46. Zwanenburg, W.-J. (2006). Modelling degradation processes of switches & crossings for maintenance & renewal planning on the Swiss railway network, *Swiss Transport Research Conference*, STRC 2006

47. Zwanenburg, W.-J. (2008). A model for the life expectancy of railway switches and crossings for maintenance and renewal planning in asset management systems, *WIT Transactions on the Built Environment: Computers in Railways XI*, 2008, **103**, pp. 765-773

48. Öberg J. (2006). Track *Deterioration of Ballasted Tracks*, Licentiate Thesis TRITA AVE 2006:88, KTH (Royal Institute of Technology), Rail Vehicles, 2006, Stockholm

Appendix A Basic data from the asset register, BIS

Track section	Km Start	+m	Km End	+m	Length	Type of track	Track no.	Station	S&C No.	S&C Type	Put in place year	Vendor	Manufactured year	Speed in deviating track	Sleeper type	Type of fasteners	Ballast type	Heating effect	Remark 1	Remark 2	Length of switch blade	Deviating track	Owner	New/Old when replaced
512	242	784	242	813	28.9	U	2-3	Fa	35a	EV-UIC60-760-1:15	2005	COGI	0	80	B		M1	13.8			21.5	V	BV	B
512	242	857	243	12	97.2	U	1.1-2	Fa	21b	EV-UIC60-1200-1:18,5	2005	COGI	2005	100	B		M1	15.6			23.3	V	BV	N
512	243	31	243	97	97.2	N	1-2.2	Fa	21b	EV-UIC60-1200-1:18,5	2005	COGI	2005	100	B		M1	15.6			23.3	V	BV	N
512	243	220	243	285	97.2	N	2.2-1	Fa	22a	EV-UIC60-1200-1:18,5	2005	COGI	2005	100	B		M1	15.6			23.3	H	BV	N
512	243	302	243	367	97.2	U	1.2-1	Fa	22b	EV-UIC60-1200-1:18,5	2005	COGI	2005	100	B		M1	15.6			23.3	H	BV	N
512	251	105	251	170	97.2	U	1.1-2	Gdo	21b	EV-UIC60-1200-1:18,5	1998	COGI	1998	100	B	P-Ec	M1	15.6	Korsning Vae-Jez 98-n-187		23.3	H	BV	N
512	251	189	251	254	97.2	U	1-2.2	Gdo	21b	EV-UIC60-1200-1:18,5	1998	COGI	1998	100	B	P-Ec	M1	15.6	Vae-Jaz 98-N-1621-5237 N		23.3	H	BV	N
512	251	384	251	448	64.8	U	2	Gdo	21b	EV-UIC60-1200-1:18,5	1998	COGI	1998	100	B	P-Ec	M1	15.6	Korsning Vae-Jaz 03-98-n-		23.3	H	BV	N
512	252	410	252	439	46.5	E	4.3	Gdo	34	EV-BV50-225/190-1:9	2005	COGI	0	40	B		M1	7.2			11	V	BV	N
512	252	495	252	528	33.2	U	2	Gdo	32b	EV-UIC60-300-1:9	2005	COGI	2005	50	B		M1	10.2			13	V	BV	N
512	252	597	252	662	97.2	N	2.2-1	Gdo	22a	EV-UIC60-1200-1:18,5	1999	COGI	1998	100	B	P-Ec	M1	15.6	Korsning Vae-Jez VII-98-N		23.3	V	BV	N
512	252	682	252	747	97.2	N	2.1-1	Ai	22b	EV-UIC60-1200-1:18,5	1998	COGI	1998	100	B	P-Ec	M1	15.6	Korsning Vae-Jez VII-98N2		23.3	H	BV	N
512	259	662	259	727	97.2	N	3.3-2	Ai	21b	EV-UIC60-1200-1:18,5	1998	COGI	1998	100	B	P-Ec	M1	15.6	Höger. Utlg.nr:4701 Ej krö65st		23.3	H	BV	N
512	259	729	259	794	97.2	U	2.3-2	Ai	22a	EV-UIC60-1200-1:18,5	1998	COGI	1998	100	B	P-Ec	M1	15.6	Höger. Utlg.nr:4701 Ej krö31st korsnsk-bks		23.3	V	BV	N
512	260	898	260	963	97.2	U	2.2-3	Ai	22b	EV-UIC60-1200-1:18,5	1998	COGI	1998	100	B	P-Ec	M1	15.6	Vänster. Utlg.nr:4701 Ej kri-94,11st efter bks.		23.3	V	BV	N
512	260	966	261	33	97.2	U	2-3.3	Ai	22b	EV-UIC60-1200-1:18,5	1998	COGI	1998	100	B	P-Ec	M1	15.6	Vänster. Utlg.nr:4701 Ej kri-94,32st;från kosrsnsk oct		23.3	V	BV	N
512	266	-8	266	46	83.1	U	3.3-2	Sie	21a	EV-UIC60-760-1:15	1992	COGI	1992	80	B	P-Ec	M1	13.8	Vänstervxl. Ej krökt	Korsning bytt 06.05.31	21.5	V	BV	N
512	266	56	266	111	83.1	N	3-2.2	Sie	31a	EV-UIC60-760-1:15	1992	COGI	1992	80	B	P-Ec	M1	13.8	Vänstervxl. Ut.lg.nr:9-5112		21.5	V	BV	N
512	266	131	266	164	33.2	N	2	Sie	31a	EV-UIC60-300-1:9	1989	COGI	1989	50	B	P-Ec	M1	10.2	Vänster. Ut.lg.nr:9-511200		13	V	BV	N
512	266	915	266	948	33.2	N	2.2-3	Sie	32b	EV-UIC60-300-1:9	1992	COGI	1992	50	B	P-Ec	M1	10.2	Höger Ut.lg.nr:9-511200 Ej		13	H	BV	N
512	266	982	267	35	83.1	U	2.2-3	Sie	22a	EV-UIC60-760-1:15	1992	COGI	1992	80	B	P-Ec	M1	13.8			21.5	H	BV	N
512	267	46	267	101	83.1	U	2.3-3	Sie	22b	EV-UIC60-760-1:15	1992	COGI	1992	80	B	P-Ec	M1	13.8	Högervxl. Ut.lg.nr:9-511218		21.5	H	BV	N
512	273	829	273	884	83.1	N	1.1-2	T	21a	EV-UIC60-760-1:15	1987	COGI	1987	80	B	P-Ec	M1	13.8	Höger. Ut.lg.nr:9-511218 E		21.5	H	BV	N
512	273	893	273	950	83.1	U	1-2.2	T	21b	EV-UIC60-760-1:15	1987	COGI	1987	80	B	P-Ec	M1	13.8	Höger. Ut.lg.nr:9-511218 E	Korsn.utbytt okt-94 manga	21.5	H	BV	N
512	273	963	273	996	33.2	U	2	T	33	EV-UIC60-300-1:9	2000	COGI	2000	50	B	P-Ec	M1	0	Ballast från Forserumsten		13	H	BV	N
512	274	160	274	214	54.2	U	2	T	31a	EV-UIC60-760-1:14	1998	COGI	1997	80	B	P-Ec	M1	13.8			21.5	H	BV	N
512	275	191	275	256	64.8	U	2	T	32b	EV-UIC60-1200-1:18,5	1998	COGI	1998	100	B	P-Ec	M1	15.6	Vänster. Ut.lg.nr:4831 Ej k		23.3	V	BV	N
512	275	278	275	332	83.1	U	2.2-1	T	22a	EV-UIC60-760-1:15	1998	COGI	1998	80	B	P-Ec	M1	13.8			21.5	V	BV	N
512	275	341	275	395	83.1	N	1.2-1	T	21a	EV-UIC60-760-1:15	1998	COGI	1998	80	B	P-	M1	13.8	Vänster. Ut.lg.nr: ? Ej k		21.5	V	BV	N
512	285	533	285	578	70.8	N	3.3-2	Mh	21a	EV-SJ50-12-1:15	1982	DOMN	1981	70	B	Klämpl	M1	7.4	Högervxl. Ut.lg.nr:4821 Ej		12	H	BV	N
512	285	592	285	637	70.8	N	2.3-2	Mh	21b	EV-SJ50-12-1:15	1982	DOMN	1982	70	B	Klämpl	M1	7.4	Högervxl. Ut.lg.nr:4821 Ej		12	H	BV	N

Selected data from the Asset Register (BIS), track section 512. In year 2009 there were 12 809 records of S&Cs (not all belonging to Banverket).

BIS has in total 32 columns of which 18 have been used:

- Track section
- Km+m Start (2 columns)
- Km+m End (2 columns)
- Length
- Type of track
- Track no.
- Station
- S&C No.
- S&C Type
- Put in place year
- Manufactured year
- Sleeper type
- Ballast type
- Remark 1
- Remark 2
- Owner

Example of data treatment:

Information on for instance curves and bridges is not linked to the S&C and must be correlated by using the Km+m information.

Appendix B Basic data from the maintenance database, Ofelia

Report No	Delayed trains	Delay time (sum)	Status	Reported date&time	Time for calling maintenance	Track section	Place (from)	Place (from) abbrev.	Symptom reported from system	Description	System failed	Asset no.
FR00456723			Avslutat	2008-01-27 11:26	2008-01-28 07:04	512	Finnerödja	FA	Spårväxelfel	larm växelvärmefel., larm	Spårväxel	22B
FR00456744	1	6	Avslutat	2008-01-27 15:41	2008-01-27 15:43	512	Slätte	SLE	Spårväxelfel	vx 31 ur kontroll	Spårväxel	31B
FR00459802			Avslutat	2008-02-15 05:47	2008-02-15 07:02	512	Töreboda	T	Spårväxelfel	Klotväxeln bör smörjas d	Spårväxel	
FR00463465	5	29	Avslutat	2008-03-11 17:48	2008-03-11 18:08	512	Töreboda	T	Spårväxelfel	korsningen i vx 22 b är s	Spårväxel	22B
FR00463562	12	70	Avslutat	2008-03-12 11:40	2008-03-12 11:41	512	Älgarås	ÄL	Spårväxelfel	Älgarås vx 21a spricka i	Spårväxel	21A
FR00465291	3	24	Avslutat	2008-03-25 14:23	2008-03-25 14:25	512	Slätte	SLE	Spårledning	Spårbeläggning mellan	Spårväxel	22A
FR00467516	3	34	Avslutat	2008-04-09 00:23	2008-04-09 00:32	512	Slätte	SLE	Spårledning	Spl belagd i vxl 31	Spårväxel	21B
FR00468230			Avslutat	2008-04-14 08:01	2008-04-14 08:03	512	Moholm	MH	Annan orsak	Moholm ligger en stock i	Spårväxel	21B
FR00468390			Avslutat	2008-04-15 05:24	2008-04-15 07:02	512	Finnerödja	FA	Spårväxelfel	Växelvärme larmar	Spårväxel	*Ingen lä
FR00469478			Avslutat	2008-04-21 17:01	2008-04-21 17:02	512	Moholm	MH	Spårväxelfel	Vx 21 går ej i kontroll i h	Spårväxel	
FR00469601			Avslutat	2008-04-22 10:40	2008-04-22 10:41	512	Gårdsjö	GDÖ	Spårväxelfel	Vx 31 svår att få i kontro	Spårväxel	
FR00470287	1	8	Avslutat	2008-04-25 18:10	2008-04-25 18:11	512	Moholm	MH	Spårväxelfel	Vx 21 ur kontroll i höger	Spårväxel	
FR00475874			Avslutat	2008-05-30 19:41	2008-05-30 19:43	512	Älgarås	ÄL	Spårväxelfel	Ej vänsterläge	Spårväxel	22A
FR00477242	1	6	Avslutat	2008-06-06 13:19	2008-06-06 13:25	512	Gårdsjö	GDÖ	Spårväxelfel	vx 31 och 31 b ur kontr	Spårväxel	31A
FR00485677	1	9	Avslutat	2008-07-28 16:14	2008-07-28 16:16	512	Älgarås	ÄL	Spårväxelfel	Vx 22 ej vänster	Spårväxel	22B
FR00496110			Avslutat	2008-10-03 10:33	2008-10-03 10:34	512	Slätte	SLE	Spårväxelfel	ur kontroll	Spårväxel	22A
FR00498112	1	6	Avslutat	2008-10-16 07:41	2008-10-16 07:44	512	Töreboda	T	Spårväxelfel	Vx 22 trög ur kontroll en	Spårväxel	22A
FR00498186	2	19	Avslutat	2008-10-16 13:40	2008-10-16 13:41	512	Töreboda	T	Spårväxelfel	Vx 22 ur kontroll	Spårväxel	22B
FR00500521	2	17	Avslutat	2008-10-31 05:52	2008-10-31 05:52	512	Gårdsjö	GDÖ	Spårväxelfel	ej i kontroll	Spårväxel	31A
FR00502259			Avslutat	2008-11-11 08:08	2008-11-11 08:09	512	Gårdsjö	GDÖ	Spårväxelfel	Växel 34 är trög i omläg	Spårväxel	34
FR00502327	2	10	Avslutat	2008-11-11 13:58	2008-11-11 14:00	512	Älgarås	ÄL	Spårväxelfel	Växel 22 går ur kontroll	Spårväxel	22A
FR00504532			Avslutat	2008-11-24 15:17	2008-11-24 15:20	512	Slätte	SLE	Spårväxelfel	Växel 31 går ej i kontroll	Spårväxel	31A
FR00504653			Avslutat	2008-11-25 02:57	2008-11-25 07:03	512	Moholm	MH	Spårväxelfel	Vxl 21 går ej att lägga o	Spårväxel	21B

Report No	Sub system	Com- ponent	Unit	Failure	Description on of failure	Cause	Description of cause	Action	Description of action
FR00456723				Avbrott		Materialutmattning/Åldrande	komponent trasig	Utbyte av enhet	
FR00456744				Avbrott		Främmande föremål	Makadamsten mellan tunga och stödräl	Rengöring	
FR00459802				Rost		Rost/Ärgning		Smörjning	
FR00463465				Materialbrott		Materialutmattning/Åldrande		Hastighetsnedsättning	
FR00463562				Materialbrott		Materialutmattning/Åldrande		Hastighetsnedsättning	
FR00465291				Kortslutning		Olämplig konstruktion		Justering	
FR00467516	Snöskydd			Kortslutning		Lossad detalj		Reparation	
FR00468230				Avbrott		Träd		Rensning	
FR00468390	Växelvärme	Lågspänningsfördelning		Isolationsfel		Opäräknad elektrisk påkänning		Utbyte av enhet	
FR00469478				Avbrott		Rost/Ärgning		Justering	
FR00469601				Avbrott		Rost/Ärgning		Justering	
FR00470287				Avbrott		Främmande föremål		Rengöring	
FR00475874				Inget fel		Ingen känd orsak		Kontroll	
FR00477242	Kontrollanordning	Kontaktdon elektronisk		Avbrott		Materialutmattning/Åldrande		Utbyte av enhet	Byte tkk4
FR00485677	Kontrollanordning	Kontaktdon elektronisk		Avbrott		Materialutmattning/Åldrande		Utbyte av enhet	Byte tkk 4
FR00496110	Kontrollanordning			Avbrott		Rost/Ärgning		Utbyte av enhet	
FR00498112	Kontrollanordning			Inget fel		Ingen känd orsak		Kontroll	
FR00498186	Kontrollanordning	Kontaktdon elektronisk		Avbrott		Materialutmattning/Åldrande		Utbyte av enhet	
FR00500521				Avbrott		Snö eller is		Rengöring	Växelvärmen ej påslagen
FR00502259				Inget fel		Ingen känd orsak		Kontroll	
FR00502327				Avbrott		Materialutmattning/Åldrande		Utbyte av enhet	
FR00504532				Avbrott		Opäräknad elektrisk påkänning	Trasig säkring	Utbyte av enhet	
FR00504653				Avbrott		Snö eller is		Rengöring	

Corrective maintenance data from maintenance system 0felia. Each year 8000 – 10 000 records is made for S&Cs. 0felia has 34 columns of data and two are added here to show number of delayed train and total delaying time. This information is available in 0felia search engine but needs to be putted in separately in the sheet. Of these 36 columns 23 columns are used or read if needed.

- Report No
- Delayed trains
- Delay time (sum)
- Reported date&time
- Time for calling maintenance
- Maintenance started

- Maintenance ended
- Time to start maintenance
- Route
- Track section
- Place (from) abbrev.
- Place (to) abbrev.

- Description
- System failed
- No of system
- Sub system
- Component
- Failure

- Description of failure
- Cause
- Description cause
- Action
- Description of action

Example of data treatment:

In the report it is not necessary to fill in the asset number. Rows 11-13, for example, have no asset number and are therefore not automatically searchable. The asset number is written in the description and can manually be written in during analysis, which has been done for some analysis.

The asset type is not written into the database, so this information needs to be added by using station and asset number and seeking the asset type in the asset register

Appendix C Basic data from the inspection report database, Bessy

Year	Track Section	No.	Priority	Date of action	Date of inspection	Station	Track type	Km+m (from)	Km+m (to)	Asset No.	Asset Type	Inspection point	Component level
2006	512	8	V	2006-01-12	2006-01-11	gdö-gdö	n	251 + 105	251 + 138	21a	Spårväxel-EV-UIC60-1200-1:18,5	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	25	V	2006-01-18	2006-01-13	t-t		275 + 224	275 + 256	32b	Spårväxel-EV-UIC60-1200-1:18,5	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	79	M		2006-03-13	gdö-gdö	n	251 + 105	251 + 138	21a	Spårväxel-EV-UIC60-1200-1:18,5	Enligt notering	\Övrigt\Enligt notering
2006	512	80	M		2006-03-13	gdö-gdö	u	251 + 189	251 + 222	21b	Spårväxel-EV-UIC60-1200-1:18,5	Enligt notering	\Övrigt\Enligt notering
2006	512	87	M		2006-03-13	gdö-gdö	u	252 + 512	252 + 528	32b	Spårväxel-EV-UIC60-300-1:9	Enligt notering	\Övrigt\Enligt notering
2006	512	90	M		2006-03-13	gdö-gdö	n	252 + 715	252 + 747	22b	Spårväxel-EV-UIC60-1200-1:18,5	Enligt notering	\Övrigt\Enligt notering
2006	512	91	V	2006-03-27	2006-03-14	al-al	n	259 + 662	259 + 695	21a	Spårväxel-EV-UIC60-1200-1:18,5	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	93	V	2006-03-27	2006-03-14	al-al	u	259 + 729	259 + 762	21b	Spårväxel-EV-UIC60-1200-1:18,5	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	101	V	2006-03-27	2006-03-14	al-al	u	260 + 930	260 + 963	22a	Spårväxel-EV-UIC60-1200-1:18,5	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	125	V	2006-04-03	2006-03-20	t-t	u	273 + 829	273 + 855	21a	Spårväxel-EV-UIC60-760-1:15	Växeldriv	\Omläggningsanordning\Växeldriv,2\Växeldriv,2
2006	512	133	V	2006-04-03	2006-03-22	t-t	u	275 + 224	275 + 256	32b	Spårväxel-EV-UIC60-760-1:15	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	136	V	2006-04-03	2006-03-22	t-t	u	275 + 278	275 + 303	22a	Spårväxel-EV-UIC60-760-1:15	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	369	V	2006-06-19	2006-06-16	sle-sle	n	266 + 932	266 + 948	32b	Spårväxel-EV-UIC60-300-1:9	Mätkod i	\Mätpunkter EV\Mätkod i
2006	512	392	V	2006-06-30	2006-06-20	t-t	n	273 + 829	273 + 855	21a	Spårväxel-EV-UIC60-760-1:15	Växeldriv	\Omläggningsanordning\Växeldriv,2\Växeldriv,2
2006	512	393	V	2006-06-30	2006-06-20	t-t	u	273 + 963	273 + 979	33	Spårväxel-EV-UIC60-300-1:9	Växeldriv	\Omläggningsanordning\Växeldriv,Driv 2\Växeldriv,Driv,Driv
2006	512	394	V	2006-06-30	2006-06-20	t-t	u	273 + 963	273 + 979	33	Spårväxel-EV-UIC60-300-1:9	TKK	\Kontrollanordning,4\TKK(Kontrollanordning,4)
2006	512	402	V	2006-06-30	2006-06-20	t-t	n	274 + 160	274 + 187	31a	Spårväxel-EV-UIC60-760-1:14	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	540	V	2006-08-02	2006-07-31	gdö-gdö	u	251 + 189	251 + 222	21b	Spårväxel-EV-UIC60-1200-1:18,5	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	583	V	2006-08-22	2006-08-14	t-t	n	273 + 829	273 + 855	21a	Spårväxel-EV-UIC60-760-1:15	Växeldriv	\Omläggningsanordning\Växeldriv,2\Växeldriv,2
2006	512	686	V	2006-09-22	2006-09-13	fa-fa	u	243 + 335	243 + 367	22b	Spårväxel-EV-UIC60-1200-1:18,5	Växeldriv	\Omläggningsanordning\Växeldriv,2\Växeldriv,2
2006	512	698	V	2006-10-16	2006-10-12	sle-sle	u	265 + 980	266 + 17	21a	Spårväxel-EV-UIC60-760-1:15	Växeldriv	\Omläggningsanordning\Växeldriv,2\Växeldriv,2
2006	512	807	M	2007-03-30	2006-12-12	mh-mh	u	285 + 618	285 + 637	21b	Spårväxel-EV-S.J50-12-1:15	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	815	V	2006-12-21	2006-12-15	al-al	n	259 + 662	259 + 695	21a	Spårväxel-EV-UIC60-1200-1:18,5	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1
2006	512	819	V	2006-12-21	2006-12-18	gdö-gdö	n	251 + 105	251 + 138	21a	Spårväxel-EV-UIC60-1200-1:18,5	Växeldriv	\Omläggningsanordning\Växeldriv,1\Växeldriv,1

Preventive maintenance data from inspection report system Bessy. Each year 80 000 records are registered for S&Cs. Bessy has 31 columns of data and 24 columns are used or read if needed.

- Report No.
- Year
- Track Section
- No.
- Priority
- Date of action
- Date of inspection
- Station

- Track type
- Km+m (from)
- Km+m (to)
- Asset No.
- Asset Type
- Inspection point
- Component level
- Remark

- Value
- Min
- Max
- Status
- Changed
- Proposed action
- Note

- Proposed latest date for action

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Year	Track Section	No.	Remark	Value	Min	Max	Status	Changed	Proposed action	Note	Proposed latest date for action	Text	Tech-nology
2006	512	8	Bryter för 5 mm				Åtgärdad	2006-01-18 08:44	Justeras	h sida.	2006-01-25	Inget fel	signal
2006	512	25	Bryter för 5 mm				Åtgärdad	2006-01-23 08:14	Justeras	voh sida	2006-01-27		signal
2006	512	79	Enligt notering				Åtgärdas ej	2006-06-13 08:41	Enligt notering	ej bedömd pga is o snö	2006-06-11		ban
2006	512	80	Enligt notering				Åtgärdas ej	2006-06-13 08:41	Enligt notering	ej bedömd pga is o snö	2006-06-11		ban
2006	512	87	Enligt notering				Åtgärdas ej	2006-06-13 08:41	Enligt notering	ej bedömd pga is o snö	2006-06-11		ban
2006	512	90	Enligt notering				Åtgärdad	2006-06-13 08:41	Enligt notering	ej bedömd pga is o snö	2006-06-11		signal
2006	512	91	Bryter för 5 mm				Åtgärdad	2006-03-28 19:24	Justeras	h sida	2006-03-28		signal
2006	512	93	Bryter för 5 mm				Åtgärdad	2006-03-28 19:25	Justeras	voh sida	2006-03-28		signal
2006	512	101	Bryter för 5 mm				Åtgärdad	2006-03-28 19:22	Justeras	v sida	2006-03-28		signal
2006	512	125	Bryter för 5 mm				Åtgärdad	2006-04-04 10:31	Justeras	båda sidor.	2006-04-03	Inget fel	signal
2006	512	133	Ej kontroll för 3 mm				Åtgärdad	2006-04-04 10:34	Justeras	v sida.	2006-04-05	Inget fel	signal
2006	512	136	Bryter för 5 mm				Åtgärdad	2006-04-04 10:34	Justeras	v sida.	2006-04-05	Inget fel	signal
2006	512	369		1391 mm	1392	1398	Åtgärdad	2006-06-19 12:12			2006-06-30	peder	ban
2006	512	392	Ej kontroll för 3 mm				Åtgärdad	2006-07-04 12:26	Justeras	v sida	2006-07-04	Inget fel	signal
2006	512	393	Ej kontroll för 3 mm				Åtgärdad	2006-07-04 12:26	Justeras		2006-07-04	Inget fel	signal
2006	512	394	Ej kontroll för 10 mm				Åtgärdad	2006-07-04 12:26	Justeras		2006-07-04	Inget fel	signal
2006	512	402	Bryter för 5 mm				Åtgärdad	2006-07-04 12:26	Justeras	h sida.	2006-07-04	Inget fel	signal
2006	512	540	Ej kontroll för 3 mm				Åtgärdad	2006-08-02 13:26	Justeras	h sida.	2006-08-15		signal
2006	512	583	Bryter för 5 mm				Åtgärdad	2006-08-25 07:30	Justeras	båda sidor.	2006-08-28	L-O H.	signal
2006	512	686	Ej kontroll för 3 mm				Åtgärdad	2006-09-25 08:56	Justeras	h sida	2006-10-02		signal
2006	512	698	Ej kontroll för 3 mm				Åtgärdad	2006-10-20 14:39	Justeras	v sida.	2006-10-26		signal
2006	512	807	Bryter för 5 mm				Åtgärdad	2007-04-02 08:34	Justeras	v sida.	2007-03-12		signal
2006	512	815	Bryter för 5 mm				Åtgärdad	2006-12-22 07:52	Justeras	h sida	2006-12-29	Inget fel	signal
2006	512	819	Ej kontroll för 3 mm				Åtgärdad	2006-12-22 07:51	Justeras	v sida	2007-01-01	Inget fel	signal

Example of data treatment

The way of describing asset type is different in this database "Spårväxel-" is written before the asset type.

The place is here written combined of both the station where the S&C "starts" and the station where the S&C "ends", normally this is the same and therefore, "gdö-gdö" is the same as "gdö" in the asset register.

Appendix D Basic data from the track recording car, Strix

Track section	Km	+m	Track Category	Track type	Level Short wave Left [1/100 mm]	Level Middle wave Left [1/100 mm]	Level Long wave Left [1/100 mm]	Level Short wave Right [1/100 mm]	Level Middle wave Right [1/100 mm]	Level Long wave Right [1/100 mm]	Alignment Short wave Left [1/100 mm]	Alignment Middle wave Left [1/100 mm]	Alignment Long wave Left [1/100 mm]	Alignment Short wave Right [1/100 mm]	Alignment Middle wave Right [1/100 mm]	Alignment Long wave Right [1/100 mm]	Gauge deviation [1/100 mm]	Curvature *1.99E-5 [m^{-1}]	Cant [mm]	Speed [1/100 km/h]
124	966	292	1	E	-27	-562	-1062	-31	-574	-1062	11	23	14	-82	-54	-6	152	1	107	9625
124	966	292	1	E	-46	-593	-1097	-31	-585	-1074	39	46	21	-74	-42	-4	121	1	115	9625
124	966	292	1	E	-58	-617	-1125	-31	-597	-1089	50	58	23	-74	-50	-5	93	1	89	9625
124	966	292	1	E	-42	-613	-1121	-31	-601	-1097	70	78	28	-74	-46	-5	109	1	107	9625
124	966	293	1	E	-27	-609	-1117	-27	-609	-1105	66	74	27	-70	-46	-4	85	1	89	9625
124	966	293	1	E	-15	-609	-1121	-3	-593	-1089	70	74	28	-50	-27	0	62	1	107	9625
124	966	293	1	E	0	-597	-1109	3	-589	-1085	46	54	22	-50	-31	0	54	2	97	9625
124	966	293	1	E	23	-582	-1097	31	-566	-1070	15	19	13	-35	-15	2	35	2	89	9632
124	966	293	1	E	27	-589	-1105	39	-566	-1070	0	0	9	-23	-3	6	39	2	97	9632
124	966	294	1	E	54	-570	-1085	62	-550	-1054	-11	-11	5	-3	7	10	50	2	97	9632
124	966	294	1	E	39	-593	-1113	62	-558	-1062	-19	-15	3	7	23	14	78	2	86	9632
124	966	294	1	E	74	-566	-1085	70	-550	-1058	-31	-31	0	11	31	16	128	2	89	9632
124	966	294	1	E	50	-593	-1117	74	-554	-1062	-58	-58	-7	0	11	11	160	2	75	9632
124	966	295	1	E	54	-601	-1125	70	-566	-1074	-62	-62	-8	0	15	12	183	2	61	9625
124	966	295	1	E	54	-605	-1128	66	-574	-1085	-78	-82	-13	-3	7	10	210	2	86	9625
124	966	295	1	E	23	-644	-1167	58	-582	-1097	-58	-66	-8	-3	7	10	226	2	46	9625
124	966	295	1	E	31	-640	-1167	54	-589	-1105	-54	-62	-7	0	7	11	242	2	68	9625
124	966	296	1	E	-11	-699	-1222	39	-609	-1125	-50	-58	-6	0	11	12	246	2	21	9625
124	966	296	1	E	-3	-695	-1222	27	-621	-1136	-23	-31	0	3	19	14	253	2	28	9625
124	966	296	1	E	-42	-734	-1261	15	-632	-1152	-7	-19	3	11	27	15	242	2	10	9625

Track recording data is stored in binary files. During one day a 200 MB of track recording data can be produced. To retrieve information about S&Cs Matlab and Pascal program has been used. The information is stored as integers and needs to be recalculated to be presented with correct unit (normally mm). Recording is done every 25 cm so storing 16 measurements for 23 S&Cs including analysis in Excel takes 90 MB of storage.

Appendix E Data from wayside condition monitoring system

Place	Detector type	Direction	Time stamp	Alarm/ Passage	Train no.	Axles	Speed	Operator
Kilvo	FUESXML	U	2009-10-01 02:32	Passage	9951	220	56	MTAB
Kilvo	FUESXML	J	2009-10-01 05:31	Passage	6076	84	77	TGC AB
Kilvo	FUESXML	J	2009-10-01 05:55	Passage	9952	284	72	MTAB
Kilvo	FUESXML	J	2009-10-01 06:06	Passage	9964	284	72	MTAB
Kilvo	FUESXML	U	2009-10-01 07:23	Passage	4005	98	81	GC AB
Kilvo	FUESXML	U	2009-10-01 07:40	Passage	7001	20	92	SJ AB
Kilvo	FUESXML	J	2009-10-01 07:54	Passage	4019	70	78	GC AB
Kilvo	FUESXML	J	2009-10-01 08:18	Passage	94	28	87	SJ AB
Kilvo	FUESXML	J	2009-10-01 08:28	Passage	9954	180	54	MTAB
Kilvo	FUESXML	J	2009-10-01 08:40	Passage	67694	34	81	GC AB
Kilvo	FUESXML	U	2009-10-01 10:35	Passage	9955	284	61	Saknas
Kilvo	FUESXML	U	2009-10-01 11:10	Passage	69870	3	79	Saknas
Kilvo	FUESXML	J	2009-10-01 11:46	Passage	9957	216	54	MTAB
Kilvo	FUESXML	J	2009-10-01 12:33	Passage	96	16	92	SJ AB
Kilvo	FUESXML	J	2009-10-01 15:02	Passage	9959	284	60	MTAB
Kilvo	FUESXML	U	2009-10-01 15:31	Passage	95	16	91	SJ AB
Kilvo	FUESXML	U	2009-10-01 15:44	Passage	6083	42	84	GC AB
Kilvo	FUESXML	J	2009-10-01 17:51	Passage	9960	284	72	MTAB
Kilvo	FUESXML	J	2009-10-01 18:08	Passage	4016	68	76	GC AB
Kilvo	FUESXML	J	2009-10-01 18:48	Passage	7000	20	98	SJ AB
Kilvo	FUESXML	J	2009-10-01 19:13	Passage	93	28	88	SJ AB
Kilvo	FUESXML	J	2009-10-01 19:28	Passage	43070	26	81	TGOJ
Kilvo	FUESXML	J	2009-10-01 19:49	Passage	84824	8	87	Saknas
Kilvo	FUESXML	U	2009-10-01 20:08	Passage	6071	96	82	GC AB
Kilvo	FUESXML	U	2009-10-01 20:43	Passage	4004	96	81	GC AB
Kilvo	FUESXML	J	2009-10-01 21:30	Passage	9965	284	61	MTAB
Kilvo	FUESXML	U	2009-10-01 22:25	Passage	43071	38	78	TGOJ
Kilvo	FUESXML	J	2009-10-01 22:40	Passage	9964	284	71	TGOJ

Place	Detector type	Direction	Time stamp	Alarm/ Passage	Train no.	Axles	Speed	Operator
Kilvo	FUESXML	U	2009-10-02 02:42	Passage	9951	284	62	Saknas
Kilvo	FUESXML	J	2009-10-02 03:29	Passage	6076	78	75	GC AB
Kilvo	FUESXML	J	2009-10-02 03:46	Passage	37000	6	76	Saknas
Kilvo	FUESXML	J	2009-10-02 05:50	Passage	9952	284	72	MTAB
Kilvo	FUESXML	U	2009-10-02 05:59	Passage	4005	94	79	GC AB
Kilvo	FUESXML	U	2009-10-02 07:31	Passage	7001	20	97	SJ AB
Kilvo	FUESXML	J	2009-10-02 07:57	Passage	4019	72	79	GC AB
Kilvo	FUESXML	J	2009-10-02 08:11	Passage	9954	216	60	MTAB
Kilvo	FUESXML	J	2009-10-02 08:36	Passage	94	28	98	SJ AB
Kilvo	FUESXML	J	2009-10-02 08:56	Passage	67694	48	82	GC AB
Kilvo	FUESXML	U	2009-10-02 09:44	Passage	S7405	4	75	
Kilvo	FUESXML	U	2009-10-02 10:03	Passage	37225	46	80	
Kilvo	FUESXML	J	2009-10-02 10:25	Passage	9956	284	68	MTAB
Kilvo	FUESXML	J	2009-10-02 10:39	Passage	9955	284	63	Saknas
Kilvo	FUESXML	J	2009-10-02 11:24	Passage	9957	220	54	MTAB
Kilvo	FUESXML	J	2009-10-02 12:36	Passage	96	16	88	SJ AB
Kilvo	FUESXML	J	2009-10-02 13:51	Passage	88	4	88	
Kilvo	FUESXML	U	2009-10-02 15:04	Passage	9959	284	60	MTAB
Kilvo	FUESXML	U	2009-10-02 15:33	Passage	95	16	87	SJ AB
Kilvo	FUESXML	U	2009-10-02 15:45	Passage	6083	54	86	GC AB
Kilvo	FUESXML	U	2009-10-02 17:54	Passage	6071	82	81	GC AB
Kilvo	FUESXML	J	2009-10-02 18:08	Passage	9960	284	72	MTAB
Kilvo	FUESXML	J	2009-10-02 18:50	Passage	7000	20	97	SJ AB
Kilvo	FUESXML	U	2009-10-02 19:16	Passage	10093	28	86	SJ AB
Kilvo	FUESXML	U	2009-10-02 19:26	Passage	43070	38	77	Saknas
Kilvo	FUESXML	J	2009-10-02 20:00	Passage	4004	96	68	GC AB
Kilvo	FUESXML	J	2009-10-02 20:46	Passage	9962	220	62	MTAB
Kilvo	FUESXML	J	2009-10-02 21:40	Passage	9965	284	55	MTAB
Kilvo	FUESXML	J	2009-10-02 22:43	Passage	9964	284	72	MTAB
Kilvo	FUESXML	U	2009-10-02 22:51	Passage	43071	42	84	TGOJ

Wayside detectors are used for identify failures on the train and stop them before these failures leads to accidents. Three major type of detector data is stored in a system called Detector PC.

- Wheel impact load detectors
- Hot wheel detector (controlling unreleased brakes)
- Hot bearing detector (controlling bad bearings)
- Carbon contact strip (controlling the contact between train and contact wire)

The data retrieved is

- Place
- Detector type
- Direction
- Time stamp
- Alarm/ Passage
- Train no.
- Axles
- Speed
- Operator

It is possible to get data for the measured value of each axle on temperature (hot wheel/bearing detector) or vertical force (Wheel impact load detector), but this has not used in this project.

Example of data treatment

For each track section it is possible to count the number of axles passing by. By using train number and operator to distinguish between freight trains and passenger trains it is possible to sum the number of axles given in the column "axles".

Journal Paper 1

Classification and cost analysis of switches and crossings for the Swedish railway: a case study

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Abstract

Purpose – Switches and crossings (S&Cs) are an important component of Banverket's (the Swedish National Rail Administration's) infrastructure and are associated with 13 per cent of the total maintenance cost. Therefore, it is important that a detailed study of different aspects of the costs of S&Cs should be undertaken to analyze individual maintenance costs. This will in the future give the possibility of enhancing the management of infrastructure.

Design/methodology/approach – A case study is undertaken to study, identify and classify the costs of S&Cs for Banverket. Data are taken from Banverket's maintenance information systems and accounting system.

Findings – A rough estimation of the cost for individual S&Cs can be identified in this way. The cost varies very much and a more detailed study is needed to validate the cost on this level. The average cost of a group of S&Cs varies less and is therefore more likely to reflect the true cost. The cost varies depending on the amount and type of traffic. Moreover, the type of S&C seems to reflect the cost variation, but further investigation is needed to verify this conclusion.

Research limitations/implications – The accounting system does not store data for individual assets, and further research would be more fruitful if individual costs could be recorded by the entrepreneur. Larger repairs should be separated from annual maintenance tasks in a future study. Data from this study could be used to build a life cycle cost model for S&Cs.

Practical implications – Cost identification is a first step in finding a way to organize maintenance in a more cost-effective way.

Originality/value – The paper shows a way to distribute costs (in the accounting system) down to individual subsystems of the infrastructure. This enables analysts to find cost drivers and plan for modification of or reinvestment in the asset.

Keywords Railway engineering, Railway equipment, Maintenance costs, Life cycle costs, Sweden

Paper type Case study

Introduction

The railway is a complex technical system used for both freight and passenger transportation (Holmgren, 2005). The available infrastructure cost accounts for the rail sector distinguish usually between the costs for administration, operation and maintenance, traffic operation and reinvestment, and capital costs (Banverket, 2006, Table I). It should also

Costs for the railway network	M€	%
Administration	77	4
Operation and maintenance	282	16
Traffic operation	68	4
Reinvestments	165	9
New national investments	729	42
Other new investments	17	1
Contribution to other infrastructure managers	40	2
Capital cost	59	3
External consultancy	304	17
Total	1,742	

Source: Banverket (2006)

Table I.
Results for the costs,
including the investment
cost, of the railway
network of Banverket

be noted that infrastructure cost accounts for the rail sector concern not only tracks, but also other facilities such as stations and freight terminals. In this connection, the German rail infrastructure cost accounts, for example, draw a delimitation line in the following way: all the costs required to operate transport from A to B are counted as track costs (Link and Maibach, 1999).

In the Swedish railway system, the infrastructure owner's costs for maintenance and operation, together with reinvestment, amounted to €447m during 2006, see Table I (Banverket, 2006). The railway infrastructure of Sweden has in total 13,000 km of track and about 12,000 switches and crossings – S&Cs (Banverket, 2006). The costs for S&Cs stand for at least 13 per cent of the maintenance cost and S&C failures cause most of the train delays of the Swedish railway (Nissen, 2005). The high cost is caused by the degradation of the assets and the need for inspection to maintain a high-safety level to avoid the undesired risk of incidents and accidents. Added to this there is a demand for high dependability. Numerical simulation of the forces in the interaction between the vehicle and the S&Cs has been studied, and the largest disturbances causing high forces are due to the discontinuity in the switch panel and the crossing part of the S&Cs (UIC) and (Kassa et al., 2006). Dynamic vertical and lateral forces are believed to be one of the more important reasons for the mechanical degradation of this type of asset. Lateral forces of up to 78 kN have been simulated and measured at 100-2,000 Hz frequencies (Kassa et al., 2006). The individual costs of S&Cs have not yet been evaluated in Banverket and this paper intends to see if it is possible to establish a mean cost for the operation and maintenance of specific types of S&Cs. The problem of establishing this cost is due to a lack of information, since not all the maintenance actions are declared for an individual S&C. Even if the total cost is declared in the accounting system, there is no direct link between actions and costs, and the cost for individual S&Cs is not declared. This study is focused on presenting individual costs for S&Cs by using information available in different computerized systems.

S&Cs are used to enable trains to choose between different routes. This is possible by moving the switch blade either to the left (for the main track) or to the right (for a deviating track). On a ballasted track, S&Cs are laid on 30 cm of stone ballast. The asset can be subdivided into the following subsystems, (Figure 1):

- switch blades;
- stock rail;
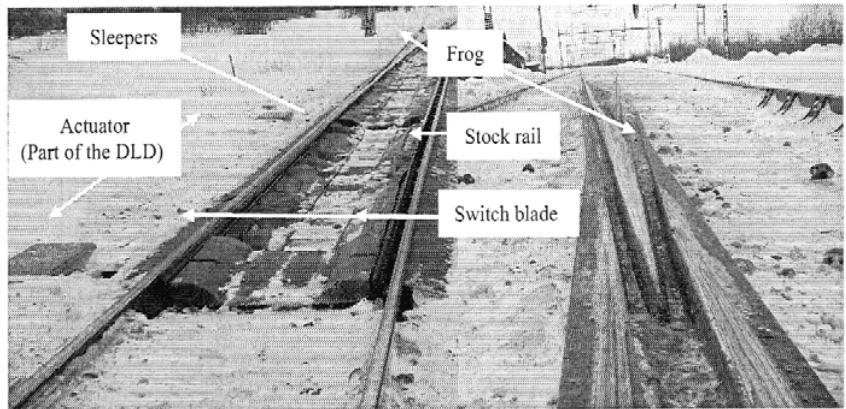
- frog;
- driving and locking devices, including switch blade position detectors;
- heating system;
- sleepers and fasteners; and
- ballast.

Similar studies have been performed by other infrastructure owners. Network Rail – NR (Great Britain) has presented the overall cost for maintenance (Roberts, 2008) and Deutsche Bahn – DB (Germany) has been studying one particular track section (Grönlund and Bauman, 2008). This information has been presented within the European Project Innotrack. The present study examines the types, classifications, failures and cost aspects of the S&Cs used for the Swedish railway. In addition, a case study has been undertaken to collect relevant data for studying, identifying and classifying the costs of S&Cs for Banverket.

In Table II, the most common S&Cs in Sweden are presented. The S&Cs covered by the study represent about 55 per cent of the types present on main track, where the speed is higher than 40 km/h.

Studies concerning S&Cs in Sweden have been performed by Kassa *et al.* (2006) and Johansson (2006) and Hedström (2001). Kassa *et al.* (2006) and Johansson (2006) have developed computerized models to simulate the forces involved, in order to calculate the wear of switch blades and frogs. Hedström (2001) has studied the criteria for replacement of S&Cs.

Types of S&Cs in Sweden

The S&Cs of Banverket have been studied in great detail for different types of tracks. S&Cs having single crossings have been in focus in the collection of data (96 per cent of all the S&Cs have single crossings). After analysis of the collected data, the most common S&Cs have been found to be of 12 different types, as given in Table II. In this table some basic data about these S&Cs is given, such as the weight of the rail, the length of the S&Cs, and their radius and frog nose angle. The types of S&Cs studied in detail have been marked in bold print. The data have been collected from Banverket's asset management system (BIS, 2007).

S&C types	Main track with speed > 40 km/h	Non-main track or < = 40 km/h	Total	Rail weight (kg/m)	Length of switch blade (m)	Total length (m)	Radius (m)	Angle of frog nose
DKV-SJ50-7,641/9,375-1:9	244	129	373	50	7.6 and 9.4	69.9		1:9
EV-SJ41-5,9-1:9	33	206	239	41	5.9	46.5	210/243	1:9
EV-SJ43-5,9-1:9	219	690	909	43	5.9	46.5	210/243	1:9
EV-SJ43-11-1:9	159	202	361	43	11	46.5	300	1:9
EV-SJ50-5,9-1:9	197	450	647	43	5.9	46.5	210/243	1:9
EV-SJ50-11-1:9	1,716	1,255	2,971	50	11	46.5	190/225	1:9
EV-SJ50-12-1:15	473	30	503	50	12	70.8	600	1:15
EV-BV50-225/190-1:9	238	120	358	50	11	46.5	190/225	1:9
EV-UIC60-300-1:9	628	14	642	60	13	49.8	300	1:9
EV-UIC60-760-1:15	747	2	749	60	21.5	83.1	760	1:15
EV-UIC60-1200-1:18,5	261	0	261	60	23.3	97.2	1,200	1:18.5
Others	1,507	1,279	2,786					
Total	6,422	4,377	10,799					

Table II.
Most important switches
on the Swedish railroad
according to the asset
information system

In the analysis of cost, the S&Cs have been grouped into types without taking into account other important factors, such as their location close to bridges and in curves and the year of installation. On a track section, very few S&Cs are placed in bad locations, and it is impossible to say if badly located S&Cs can be associated with a higher cost per action than other S&Cs. It has previously been concluded that such S&Cs need more maintenance and in the calculation here this will give a higher cost. Therefore, in this study no identification of the location has been made, since these S&Cs will have a higher cost than a "normal" S&C. For the average cost for one type of S&C on a whole track section, this will not greatly affect the value calculated. The installation year and the load of each group of S&Cs are shown in Table III. These types of factors have been discussed in greater detail in a previous study (Nissen, 2005). All these factors are important to consider from the infrastructure manager's viewpoint, especially when trying to find better strategies for maintenance. Infrastructure maintenance execution was separated from Banverket's operational activities in 1998 and is now purchased by contracts. Therefore, on a management level, not only maintenance strategies whose aim is to minimize degradation are discussed, but also how to write contracts with entrepreneurs, formulate the right kind of goals, and control goal achievement by maintenance indicators (Espling, 2007).

The degradation of the track and, therefore, the maintenance cost of the S&Cs depend on the traffic, which has already been shown in studies of ORE D161. The speed, axle weight and total amount of traffic in gross metric tonnes (MGT) have been considered as main factors (ORE D161, 1988):

$$E = kT^{\alpha}P^{\beta}V^{\gamma} \tag{1}$$

where, E – amount of degradation since last restoration; k – constant; T – total tonnage since last restoration in MGT; P – dynamic axle load; V – speed; α, β, γ – exponents in the order of 1-3.

Maintenance at Banverket

Maintenance can be subdivided into different categories. The main categories are corrective and preventive maintenance (PM) according to EN-13306 (CEN, 2001). PM can be subdivided into condition-based and predetermined maintenance. At Banverket corrective maintenance is recorded in one computerized system and condition-based maintenance is recorded in another system.

Failures are reported directly to the central train traffic control office, which orders the maintenance personnel to correct the problem. A failure can sometimes be a train stoppage, which is shown separately in the graphs.

Predetermined maintenance is time-, km- or tonnage-based maintenance stipulated by the supplier or Banverket's regulations. For S&Cs predetermined maintenance is:

- adjustment and cleaning of insulated rail joints; and
- greasing of slide chairs and parts of the actuators.

As Banverket does not keep a separate record of these activities, the cost for this has been included in the heading "Inspection and predetermined maintenance". The cost for inspection dominates and the cost for predetermined maintenance is a minor part (estimated to be 25 per cent by the author).

Type of S&C	111 Riksgränsen-Kiruna C	119 Luleå-Boden	Track section 512 Laxå-Falköping	611 Falköping-Alingsås	612 Alingsås-Partille	910 Hässleholm-Höör	Total
EV-SJ50-11-1.9							
Number	10		4	1	7	1	23
Age	30.6		22.3	23	23	25	26.3
Load	630.4		184.7	184	211.6	257.5	389.8
EV-SJ50-12-1.15							
Number			14	4	18	8	44
Age			26.1	24	22.9	24.5	24.3
Load			217	192	210.6	252.4	218.5
EV-UIC60-300-1.9							
Number	7	8	13	3	1	1	33
Age	11.1	12.1	10.1	8.3	2	15	10.5
Load	229.5	218.3	83.6	66.7	18.4	154.5	145.8
EV-UIC60-760-1.15							
Number	8	5	33	10	6		62
Age	6.1	8.2	10.9	8.6	16		10.2
Load	126.2	147.6	90.3	68.8	147.2		101.6

Note: Italics values show that there are fewer than five S&Cs in the group, which affects the possibility of comparison

Table III.
Number and average age
of S&Cs on each track
section

Condition-based maintenance is performed as a consequence of inspection or measurement (non-destructive testing, by ultrasonic track recording vehicles and measurement performed by personnel walking along the track). The maintenance is then planned for and most of the remarks from inspections or measurements prescribe actions to be taken within a month or longer, for instance larger replacements, tamping, vegetation removal and grinding. Actions with this type of priority have been classed as long-range planned actions in this paper.

Maintenance actions prioritized as having to be done within 2 weeks or immediately (because there is a high probability that a failure that might affect health or safety will occur within days) are seen as corrective maintenance within Banverket and have been classed as short-range planned actions in this paper.

The cost data have separate headings in the accounting system for long- and short-range planned actions. The decision to prioritize maintenance actions as long- or short-range actions is taken by the inspector. Clearly, there is variation in these judgments between different inspectors and different track sections. The prioritization may also be overridden by a planner or the infrastructure manager, which results in some of the short-range planned actions not being carried out within 2 weeks. (A frequent inspection or a minimal repair may be performed instead of a replacement.) This can explain why in one track section the number of short-range planned actions seems to be high, at the same time as the cost for these actions is not so high. On another track section, the opposite may be the case, i.e. the number of actions may be few and the cost may be high. The difference between the short- and long-range planned actions is not very clear and caution must be taken when drawing conclusions. The parameters chosen for each track section (Table III), may provide some understanding concerning this matter. The sum of the mean cost of short- and long-range planned maintenance on a whole track section should be representative of the track section in question and possible to compare with other track sections.

Case study
Methodology
A case study has been undertaken based on data from 2004 to 2006. Some track sections with different kinds of traffic have been selected. Information gathered in different databases has been used in the work involved in identifying costs for individual S&Cs.

The following sources have been used:

- Agresso, accounting system (Espling, 2007).
- BIS, asset management system (Nissen, 2005).
- Ofelia, failure report system (Granström, 2008).
- TFÖR, train time and train delay report system (Granström, 2008).
- Bessy, inspection remark report system (Nyström, 2008).

Information from accounting system
The cost identification for S&Cs has been based on the accounted cost for six different track sections of the Swedish network. For the years 2004-2006, the information from the accounting system has been compared with information from different maintenance systems to establish the cost down to individual S&Cs. The accounted costs have four different headings which have enabled the sorting of the information:

(1) action code;

(2) asset type;

(3) type of work; and

(4) work order information.

These headings have been treated in the following way:

Action code. Operation and maintenance.

Asset type. S&Cs and 35 per cent of the "no asset specified" entries. Two different headings have been used. "S&Cs" is one heading and a heading for the superstructure in general, called "no asset specified", is the other. On the Western Mainline about 35 per cent of the total cost could be attributed to S&Cs if "no asset specified" was omitted. The assumption of the author is that this heading should be included because it concerns unspecified work that should be allocated to the asset and is not a special heading.

Type of work.

- Failures.

- Inspection and predetermined maintenance.

- Short-range planned actions after inspections.

- Long-range planned actions after inspections.

- Tamping.

Damages and snow clearance have been omitted, since these cannot be attributed to the design of the S&Cs and differ very much over the country.

Work order information. This has been used to understand if the cost is a yearly cost or a cost specific to a particular year. One example of a cost that has been omitted is the cost for taking away leaves, which in some cases is a cost without a specified asset.

However, there are additional costs that the accounting system does not provide, for instance the grinding and heating costs for S&Cs, which are paid from a central account and are not registered on the track section level. The cost of grinding has been added to the cost of S&Cs. The heating cost has not been included in the operation cost of the S&Cs.

Information from maintenance systems

Information as to when tamping and grinding were performed has been taken from BIS. Information about actions taken after failures and inspection has been taken from Ofelia and Bessy. The connection between the databases is the name of the place and the identification number of the S&Cs. From Ofelia and Bessy, data from the years 2004 to 2006 has been used. In the case of tamping and grinding, a longer time than 3 years has been used, since it is normal to have several years between these actions, and the records normally used in this study are from 2001 to 2007.

Traffic descriptions

In Table IV, the traffic is described. On the Iron Ore Line, traffic with an axle load of 30 metric tonnes is allowed (Figure 2), although in practice track section 111 had a 25 tonne axle load until 2007. The normal axle load on the other lines is 12.5-22.5 tonnes (Figure 3).

Line	Track section no.	Track section	Passenger trains/day	Freight trains/day	Total	Million gross tonnes/year (assumed)
Iron Ore	111	Riksgränsen-Kiruna C	4	27	31	20.6
Iron Ore	119	Luleå-Boden	10	31	41	18.0
Western Mainline	512	Laxå-Skövde	58-63	48-50	106-113	8.3
Western Mainline	512	Skövde-Falköping	92	41	133	8.3
Western Mainline	611	Falköping-Alingsås	60	44-46	104-106	8.0
Western Mainline	612	Alingsås-Partille	143	46	189	9.2
Southern Mainline	910	Hässleholm-Höör	73	63	136	10.3

Table IV.
Traffic description – as stated by Banverket (2001)

Source: BIS (2007)
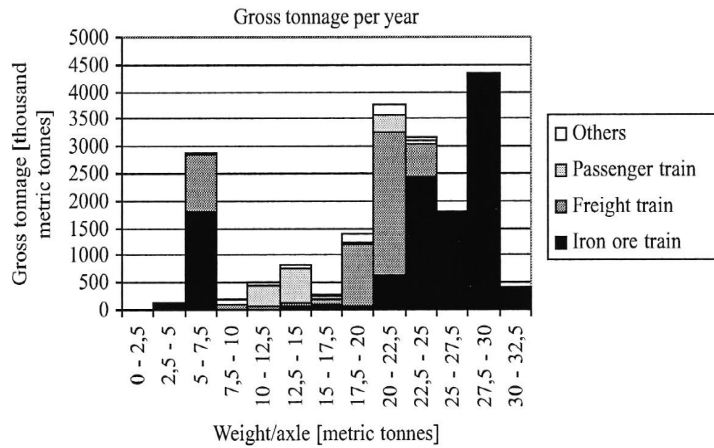
Figure 2.
Gross weights on track section 119

Source: Nissen *et al.* (2006)

Results

The results are presented as the maintenance cost per million MGT for different types of S&Cs. Most of the cost elements are clearly dependent on how much traffic there is, and it is easier to compare different track sections using cost per MGT instead of the maintenance cost per year. In Table VI, the latter is given within parentheses.

Cost parameters

Each action is associated with a cost. This cost has been adjusted for each track section, so that the total cost for each category has been the same as the cost in the accounting system. Finally, the result has been presented for each individual S&C.

In Table V, it is shown that the cost for the different types of actions varies considerably between the track sections. There are several reasons for this. The most

Gross weight in Line 611 (Odensberg)

Gross weight [million metric tonne]

- □ Passenger train
- ▨ X2000
- □ Post train
- ■ System train
- ▨ Freight train

Axle weight [metric ton]
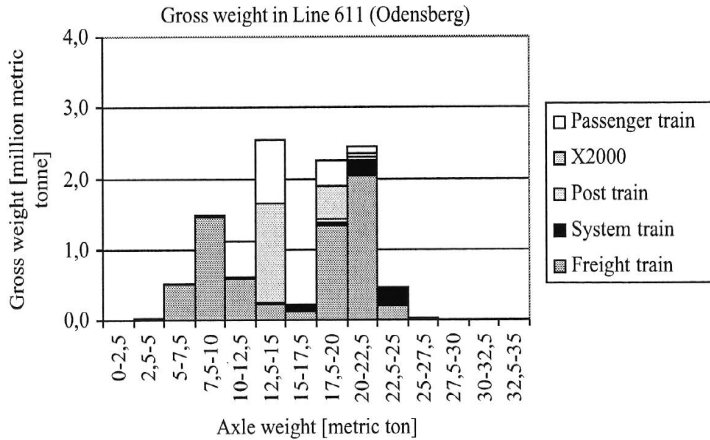
Note: Data from wheel impact load detectors, DPC-II and traffic operation system Opera (2007)

Figure 3.
Gross weights on track section 611

S&C	€	Train-delaying failure	Failure	Inspection	Short-range planned action	Long-range planned action	Tamping	Grinding
111	Cost/event	560	560		630	560		
	Cost/S&C		0	3,420	0	0	3,240	3,160
119	Cost/event	350	350		470	350		
	Cost/S&C		0	2,210	0	0	2,100	3,160
512	Cost/event	580	580		630	720		
	Cost/S&C		*550*	1,400	0	0	3,790	3,160
611	Cost/event	480	480		630	950		
	Cost/S&C		0	1,240	0	*970*	3,250	3,160
612	Cost/event	390	390		630	950		
	Cost/S&C		0	2,250	*810*	*50*	2,920	3,160
910	Cost/event	350	350		470	350		
	Cost/S&C		0	2,210	0	0	2,100	3,160

Note: For values marked with italics, an additional cost term has been used

Table V.
Cost parameters used

obvious reason is that all the information is not available in the system and some of the actions were never recorded. The cost for individual actions may be very high (up to at least €20,000) and, therefore, the average cost can be affected if there are single events with a high cost. To avoid too high a cost being distributed to some individual S&Cs, the cost per action has been limited. Consequently, not all the cost is covered and, therefore, the rest of the cost is evenly distributed to all the S&Cs on that track section. In Table V, this is marked with a light grey background colour. The maximum cost for a single failure has been set to €560. For actions after inspections, it has been set to €950/long-range planned action and €630/short-range planned action (information provided by Ulla Juntti, Banverket).

Maintenance actions after failure and short-range planned actions after inspection are a more expensive way of performing maintenance than long-range planned actions. Therefore, one must explain why a higher associated cost is accepted for long-range planned actions. This is a consequence of the type of action that can be performed as a short-range planned action or as an action taken after a failure has occurred. Most of these actions concern adjustment and very seldom the replacement of costly items like crossings and switch blades. Costly, repairs are planned and, therefore, the cost for long-range planned maintenance is the highest per unit.

In some cases, these parameters do not vary much (e.g. the failure and grinding costs), but the cost for inspection and long-range planned actions varies to a great extent.

Cost

The highest cost per year for maintaining S&Cs is on track section 111 in the northern part of Sweden. The total MGT of 20.6 (Table IV), cold weather and a high-axle load (25 metric tonnes) are factors that can explain the high costs. When comparing the costs per MGT, track section 111 is on the same cost level as the track sections in the southern part of Sweden.

Cost of individual S&C

The maintenance cost for individual S&Cs can vary to a great extent, which is shown in Figures 4 and 5. At this stage of the investigation, no effort was made to find an explanation for the variation. In a previous study, it had been shown that the number of inspection remarks can vary depending on factors such as how the S&Cs are located (in a curve, on a bridge, etc.) or the usage of deviating track (Nissen, 2005). Figures 4-10 all have the same scale (the numbers are not given in the graph) to make it possible to compare different track sections. Neither in Table VI nor in Figures 4-8 has the indirect cost for train delays been added to the train-delaying failure cost, since this cost is very dependent on which track section the failure occurs on.

Cost for different types of S&Cs

In Figures 6-8, the cost for certain types of S&Cs is shown. This cost is the mean value of the S&Cs in the respective track sections. The cost here is larger than what could be expected, since some S&Cs have a high cost compared to the average value for the track section. In Figure 9, the result of a calculation without outliers is shown.
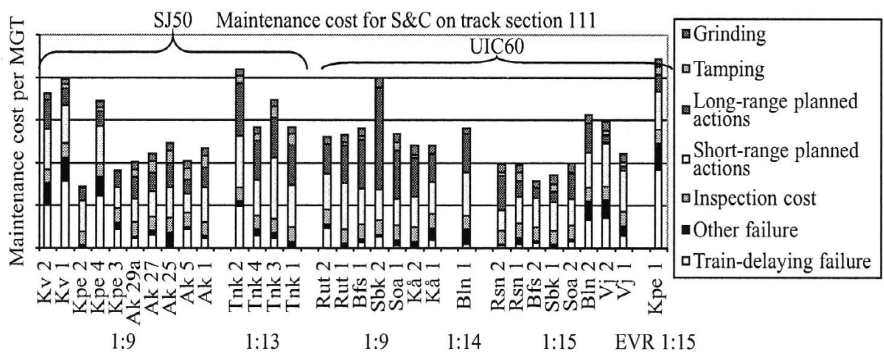
Figure 4.
Cost for individual S&Cs on track section 111

Note: Figures 4-10 have the same scale, but no number is given in the figures
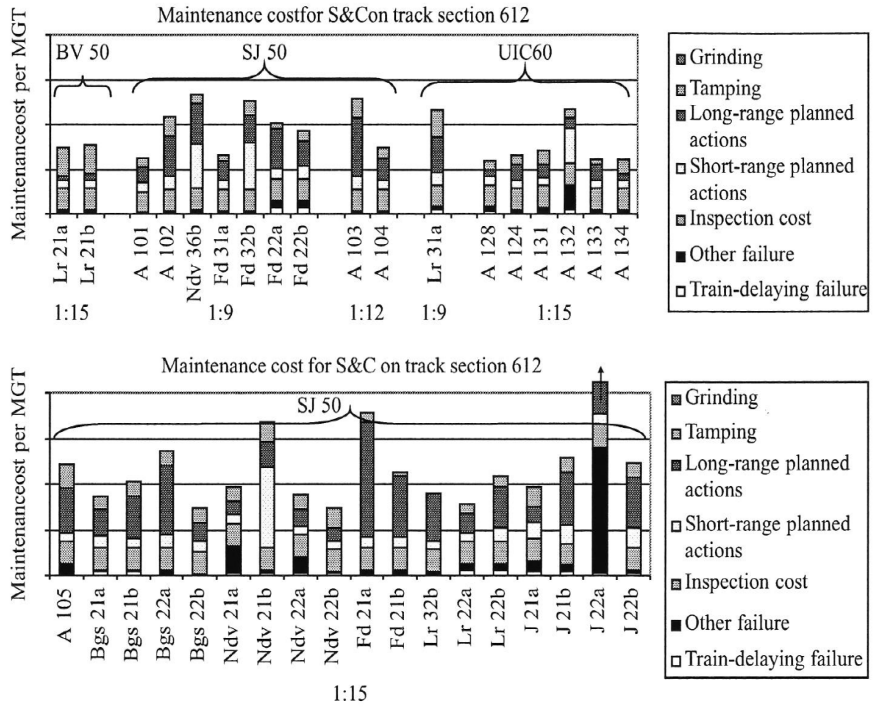
Figure 5.
Cost for individual S&Cs
on track section 612
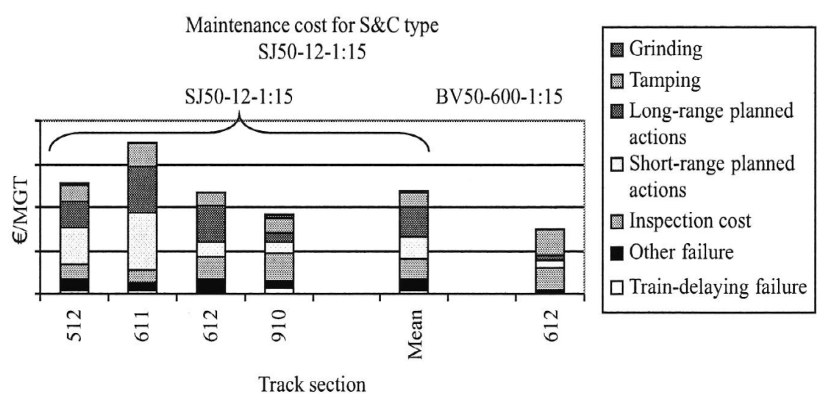
Figure 6.
Mean cost for S&Cs of the
SJ50-12-1:15 type on
different track sections

By omitting outliers with a cost that differed by more than 30 per cent from the average, a high or low value was calculated.

The BV50-600-1:15 type of S&C has been included in the graph, but as it is a modernization of the SJ50-type, it is not part of the average value.

Average cost for different S&C types, showing the variation, if the outliers are removed from the calculation. Low whisker – all the S&Cs with a cost higher than 130 per cent of the averages were omitted. High whisker – all the S&Cs with a cost lower than 70 per cent of the averages were omitted.

Maintenance cost for S&C type
EV-UIC60-760-1:15

Maintenance cost for different types of S&C

Figure 8.
Mean cost for different
S&C types

Maintenance cost for different types of S&Cs
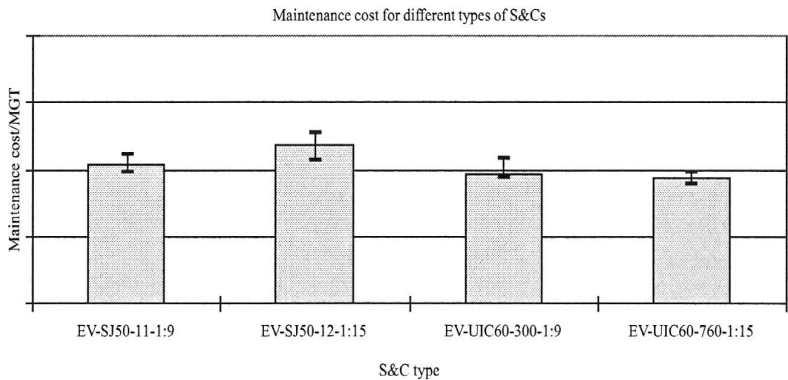
Figure 9.
Average cost for different
S&C types, showing the
variation

Maintenance cost for different types of S&C

€/MGT

Grinding
Tamping
Long-range planned actions
Short-range planned actions
Inspection cost
Other failure
Train-delaying failure

EV-SJ50-11-1:9
EV-SJ50-12-1:15
EV-UIC60-300-1:9
EV-UIC60-760-1:15
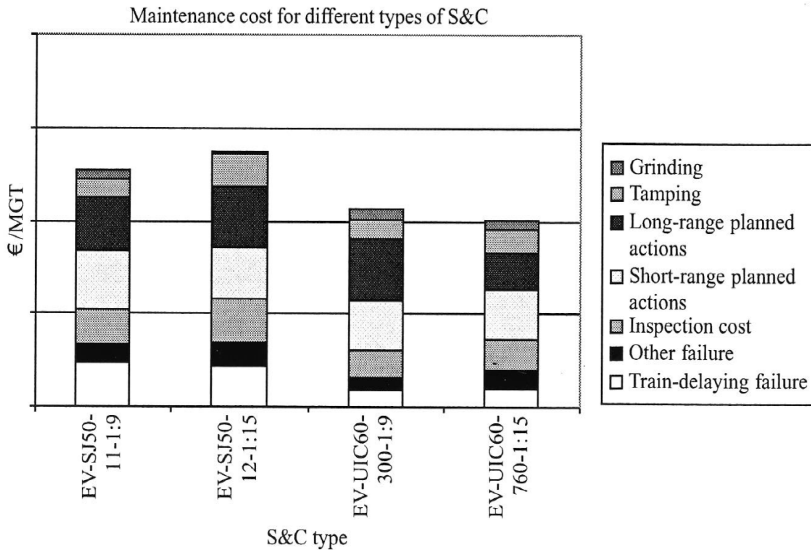
S&C type

Figure 10.
Mean cost for different
S&C types, including the
indirect cost for train
delays

To the cost for the train-delaying failures can be added the cost for the amount of delay time which they contribute to. A delay time of one minute is estimated to cost €55 (Corshammar, 2006). NR has used a delay cost of £4-230/min (an average of £32/min) depending on the traffic operator and where and when the delay occurs (oral information from Clive Roberts, Birmingham University). This can be calculated, but the cost for delayed trains is very dependent on the traffic intensity and how much of its capacity the track section concerned is using. The result of such a calculation is shown in Figure 10.

Discussion
The maintenance cost for an S&C is dependent on many factors that have still not been evaluated fully. The first question to be answered is which cost elements are essential to evaluate for a proper life cycle costing (LCC) analysis. In this paper, the costs for the following maintenance actions have been used:

- Condition-based maintenance.
- Inspection.
- Long-range planned actions resulting from inspection remarks.
- Tamping.
- Grinding (the amount of removal depends on the condition of the rail).
- Predetermined maintenance.
- Corrective maintenance.
- Failures.
- Train-delaying failures.
- Short-range planned actions resulting from inspection remarks. (According to Banverket's definition and the standard, this is condition-based maintenance).

Cost €/MGT (€/year)

Track section	EV-SJ50-11-1:9		EV-SJ50-12-1:15		EV-UIC60-300-1:9		EV-UIC60-760-1:15	
	No	€/S&C/MGT (€/S&C/year)	No	€/S&C/MGT (€/S&C/year)	No	€/S&C/MGT (€/S&C/year)	No	€/S&C/MGT (€/S&C/year)
111 Riksgränsen-Kiruna C	10	980 (20,100)				1,080 (22,200)	8	1,000 (20,500)
119 Luleå-Boden					8	720 (13,000)	5	760 (13,700)
512 Laxå-Falköping	4	*1,050 (8,700)*	14	1,280 (10,600)	13	1,050 (8,700)	33	940 (7,800)
611 Falköping-Alingsås	1	*1,740 (13,900)*	4	*1,750 (14,000)*	3	*1,110 (8,900)*	10	1,150 (9,200)
612 Alingsås-Partille	7	990 (9,100)	18	1,160 (10,700)	1	*1,160 (10,700)*	6	730 (6,700)
910 Hässleholm-Höör	1	1,770 (18,200)	8	870 (9,000)	1	1,150 (11,800)		

Note: Italic values mark groups where there were fewer than five S&Cs, which affects the possibility of comparison

Table VI.
Cost for maintaining
different types of S&Cs

There are other costs that are not very specific to the type of S&C or the traffic, such as costs for:

- damage (for instance when a wagon derails in an S&C, mostly through trying to run in a trailing direction on a non-trailable S&C);
- snow clearance; and
- heating.

The investment and reinvestment cost has not been included and the reason for this is that it has not been possible to establish the life length of any existing S&Cs. Recently, most S&Cs will be on the track for 30-40 years. Even a prolonged lifetime of up to 45 years can change the total cost. Another alternative is to take out the S&Cs at an age of 25 years, place them on a track section that is not so highly and frequently used, and calculate the remaining asset value as an income. The indirect cost for train delays can be added, but this is not necessary in a primary analysis of S&C cost, since it depends on the capacity utilization more than the traffic load in MGT.

The second question is how to establish the cost for single events when there is no detailed record in the accounting system. In the present paper, this has been achieved by using the mean cost and information about failures and inspection actions. This is not sufficient to obtain correct information for individual S&Cs. For the average cost of an S&C, it is a reasonable approach, but for individual S&Cs the next step should be to decide the cost for different types of actions. The cost for a larger repair is a great uncertainty in these calculations, since the replacement of a frog can cost €20,000 and in some cases it is undertaken without recording in the database when it was carried out. Therefore, larger replacements of frogs, switch blades, support rail and check rail should be investigated more thoroughly.

The cost for individual S&Cs can be established with the method used, and, even if the result not should be taken as exact, the method can be a first step in evaluating which S&Cs should be considered for replacement or other actions in order to lower the maintenance cost in the long run.

The cost on different tracks can be used to compare the different maintenance practices in use and learn the best way of maintaining an S&C. Regular grinding can be a way to lower the forces and thereby minimize the need for tamping. This is shown in Figures 6 and 7. The coding of short- and long-range planned actions is not so certain, but one question that can be asked is why the short-range planned maintenance is low on Track Sections 612 and 910 and not on the other track sections.

Cost drivers can be discussed on the basis of Figures 8 and 9. The cost for failures should be minimized, since they are unplanned events and lead to indirect costs which can be larger than those estimated here. The cost for inspection can be questioned, but inspection may not be a cost driver if it can help the planning of the actions taken afterwards. Moreover, it is possible through a new design to lower the inspection cost if the new design results in components with a higher reliability. The actions taken after inspections are cost drivers, since most of them are adjustments and minor work that could be omitted if the S&Cs were more reliable in their performance.

Tamping can be considered to be a cost driver at the same time as it can be considered not to be one. This depends on the maintenance strategy being used. Tamping was found to be responsible for around 16 per cent of the maintenance cost in this study, but if tamping was performed more seldom, the cost for actions after inspection remarks

would increase, since the forces would increase if the alignment were to become worse. Better alignment from the beginning and grinding are two key-factors for minimizing the need for tamping and, therefore, one can question why some track sections have less money spent on grinding than others, which is shown in Figure 8.

One cannot draw any clear conclusion concerning the cost difference between different types of S&Cs. One of the difficulties is shown in Table III, namely the fact that the age and the total load differ and, therefore, the older S&Cs should cost more than the newer ones. One way to compensate for this is to calculate the degradation according to the theory of the non-homogenous poisson process – NHPP (Rigdon and Basu, 2000). In this theory, the amount of maintenance increases according to the following formula:

$$n = c^* T^{\beta - 1} \tag{2}$$

n – number of actions; c – constant; T – total load since last restoration; β – coefficient.

In Figure 11, the low cost calculated in Figure 9 was used, together with the information in Table III. For corrective maintenance $\beta = 1.15$, for PM $\beta = 1.3$, and in all the other cases it was set to 1. The cost for an S&C of the EV-UIC60-760-1:15 type was set to 100 per cent for each track section. It is remarkable that the cost for the 1:9 S&Cs is not higher than that for the 1:15 S&Cs. The cost for an EV-SJ50-12-1:15 is higher in both cases shown here than that for the EV-UIC60-760-1:15, as expected. This calculation shows that more information is needed to gain a good understanding of the total cost of maintaining an S&C.

Conclusions

The individual maintenance costs of S&Cs, considering their usage life and type, constitute important factors to be considered from the LCC viewpoint. The accounting system does not provide this type of information. By using a lump sum for a total area of track and statistics of maintenance actions, it is possible to create a reasonable picture of how the cost is distributed for individual S&Cs, different types of S&Cs and different cost elements.
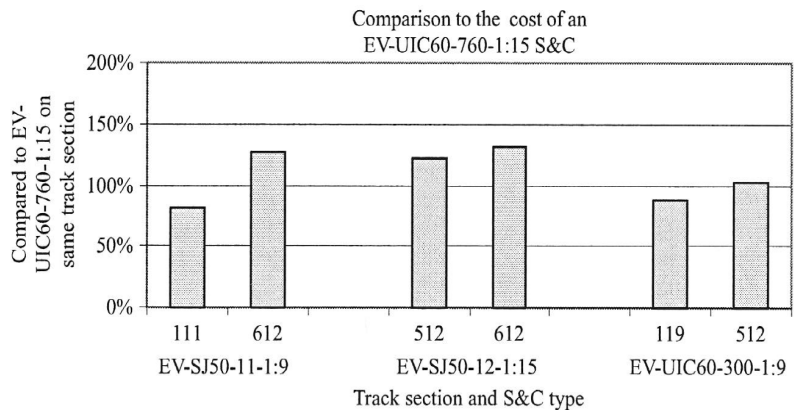
Figure 11.
Comparison with the cost of different types of S&Cs using an NHPP-model for degradation

Note: 100% is the cost for an EV-UIC60-1:15 in use on each track section

To make comparisons between different track sections, it is proposed that the cost per MGT should be used. The variation between individual S&Cs can be greater than -33 and $+50$ per cent from the mean cost, and in 29 of 162 studied S&Cs the cost was outside these boundaries (18 per cent). Figure 11 shows that the newer design of S&C (the EV-UIC60-760-1:15) has a lower maintenance cost than the old design (the EV-SJ50-12-1:15).

This paper can provide an insight into the cost of S&Cs for infrastructure managers and assist them in prioritizing their future course of actions from a strategic viewpoint for better management.

Future work
This study was based on only six track sections and it would be interesting to make a wider investigation.

Some maintenance information is not reported properly in the PM system. More specific information on larger repairs can be collected by using weld reports, as well as the number of replaced units provided by the spare parts store.

All the cost estimation was based on the mean unit cost, calculated by dividing the total cost by the number of actions. A more precise way would be to take the mean repair time and time spent after the failure was reported until the failure was repaired and multiply this by the mean cost for man hours. For PM, no repair times are reported and, therefore, interviews are necessary to establish these times.

References
Banverket (2001), "Nulägesbeskrivning av Statens Spåranläggningar – Underlagsrapport Banhållningsplan" ("Status description of the Swedish railway net"), *Internal Report Written for the Project Banhållningsplan (BHP)*, Report No. MA0874, Banverket, Borlänge.

Banverket (2006), *BanverketsÅrsredovisning 2006 (The Annual Report of Banverket 2006)*, Banverket, Borlänge.

BIS (2007), *Banverkets Information System, (Asset Management System for Banverket)*, Internal Database of Banverket.

CEN (2001), *EN 13306:2001, Maintenance Terminology*, European Committee for Standardization, Brussels.

Corshammar, P. (2006), *Perfekt Spår: Din Framgång i Järnvägsunderhåll och Driftsäkerhet (Perfect Track: Your Success in Maintenance and Dependability in the Railway System)*, Perfect Track, Lund.

Espling, U. (2007), "Maintenance strategy for a railway infrastructure in a regulated environment", doctoral thesis, Luleå University of Technology, Luleå.

Granström, R. (2008), "Management of condition information from railway punctuality perspectives", doctoral thesis, Luleå University of Technology, Luleå.

Grönlund, W. and Bauman, G. (2008), "Report on Cost drivers for goal directed innovation", Deliverable D3.1.2, UIC, Paris, available at: www.innotrack.net/docs/deliverables/d311-f4-key_param_cost_drivers.pdf (20 January 2009).

Hedström, R. (2001), "Kriterier för Byte Alternativt Fortsatt Underhåll av Spårväxlar" ("Criteria for replacement or prolonged maintenance for turnouts"), VTI notat 20-2001, VTI, Linköping.

Holmgren, M. (2005), "Maintenance-related losses at the Swedish rail", *Journal of Quality in Maintenance Engineering*, Vol. 11 No. 1, pp. 5-18.

Johansson, G. (2006), "On the modelling of large ratcheting strains and anisotropy in pearlitic steel", doctoral thesis, Chalmers University of Technology, Gothenburg.

Kassa, E., Andersson, C. and Nielsen, J. (2006), "Simulation of dynamic interaction between train and railway turnout", *Vehicle System Dynamics*, Vol. 44 No. 3, pp. 247-58.

Link, H. and Maibach, M. (1999), "Calculating transport infrastructure costs", Report of European Commission, Railway Working Group 1, April 28, available at: http://ec.europa.eu/trans port/infrastructure/doc/infrastr-cost.pdf (accessed 14 February 2008).

Nissen, A. (2005), "Analys av Statistik om Spårväxlars Underhållsbehov", Licentiate thesis, Luleå University of Technology, Luleå.

Nissen, A., Larsson, D. and Nyberg, J. (2006), "Measuring the use of deviating track", in Kumar, U., Parida, A. and Rao, R.B.K.N. (Eds), *Condition Monitoring and Diagnostic Engineering Management (COMADEM 2006*), Proceedings of the 19th International Congress, Luleå, 12-15 June, Luleå University of Technology, Luleå, pp. 701-10.

Nyström, B. (2008), "Aspects of improving punctuality: from data to decision in railway maintenance", doctoral thesis, Luleå University of Technology, Luleå.

ORE D161 (1988), "Dynamic vehicle/track phenomena, from the point of view of track maintenance", Report No. 3, Final Report, Office for Research and Experiments of the International Union of Railways, Utrecht.

Rigdon, S.E. and Basu, A.P. (2000), *Statistical Methods for the Reliability of Repairable Systems*, Wiley, New York, NY.

Roberts, C. (2008), "Requirement and functional description for S&C monitoring", D3.3.3 Delivarable within the European Project Innotrack, UIC, Paris.

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Journal Paper 2

RAM-analysis of Switches and Crossings for Swedish Railway: A case study

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Abstract: Switches and crossings are critical components within the railway system and contribute to many of the maintenance activities needed to keep the track section available for traffic. Sweden has about 12 000 switches and crossings. Cost benefit calculation based on reliability, maintainability and availability data can be used to make the maintenance actions more effective. The data has been obtained from Banverket's maintenance systems and evaluated. A reliability model based on non-homogenous Poisson process (NHPP) has been developed and used. The data available can be used to calculate maintenance cost of switches and crossings using an LCC-model. In this paper the availability of data to be used as input for an LCC-model is discussed. Such a model can be used to make strategic decisions of how to maintain or replace switches and crossings within the Swedish railway network.

1   Introduction

Banverket is the Swedish administrator of the Swedish railway net. Sweden has 12 000 km of track and about 12 000 switches and crossings. The cost of maintenance and reinvestment for Banverket is on an average of 24 000 €/km track/year [1].

In the standard SS-EN 50126:1999 [2], "Railway application – The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)"- how to work with RAM is described. RAM is an abbreviation used to describe the maintenance need of an asset, the letters standing for Reliability, Availability and Maintainability. Banverket has stated that it will use this standard in the work to enhance the performance of the railway system [3]. This study has been undertaken to analyse the RAM-level of S&Cs (switches and crossings) on different railway tracks in Sweden as well as the influence of different types of S&C. This case study is a demonstration of what is possible to find from historical data. By presenting quantified values, a better understanding of what type of changes in design and maintenance routines are required to lower the life cycle cost, can be planned.

Glossary

DLD	Drive and Locking Device
S&C	Switches and Crossings
Item	Any part, component, device, subsystem, functional unit, equipment or system that can be individually considered (IEV 191-01-01)
Reliability	Ability of an item to provide a required function under given condition for a given time interval (IEV 191-02-06)
Maintainability	Ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources (IEV 191-02-07)

| Availability | 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) |

Notation

λ – failure rate (maintenance rate)   t – global time
β – form parameter   i, k – indexes for subsystems
θ – scale parameter   j, l – indexes for maintenance actions
γ – covariates   T' – yearly tonnage

2   Switches and crossings

Switches and Crossings (S&Cs) are a subsystem in the railway system that allows traffic to change track and directions. They have two primary functional demands:

- Carry the load of the train in a safe way
- Allow traffic to pass in either a straight or diverting route

An S&C consists of three major parts: switch panel, closure panel and crossing panel. The switch panel is the movable part consisting of switch blade, bars, switch device and control device. The closure panel connects the switch blade with the crossing. The crossing panel has a crossing nose, wing rails and check rails, where all of them should withstand the high forces that occur when the wheel is transferring from one rail to the next at the crossing nose.

The S&C should also fulfill a number of secondary functions, such as:

- Allow movements of the switch panel
- Give information to the interlocking system that the end position is reached and the switch panel is locked
- Be able to function in winter conditions, i.e. keeping free from snow and ice by means of a heating system
- Withstand considerable impact loads with negligible wear and crack growth

3   Problem

Switches and Crossings (S&Cs) contribute to about 13% [4] of the maintenance budget for Banverket. The age of the S&Cs in main track is on average more than 20 years, and therefore in the reinvestment plan it is necessary to calculate for more than 200 new S&C' per year. A cost benefit analysis based on life cycle costing could be a good tool for finding which S&Cs are required to be replaced. Another use of life cycle costing is in the design stage or when choices between types of S&Cs must be made. In the European project Innotrack, life cycle costing and RAM-analysis have been used as a foundation to make choices. Banverket is involved in this European project as one of 8 infrastructure managers.

4   Data collection, sorting and classification

4.1   Selected data

Swedish S&Cs have been selected to be on the main track on three selected main routes. **Table 1** indicates the end stations of the main routes with their length, track density and number of switches that can be found on the main track. Track density is here used to describe a single track (track density = 1) or a double track (track density=2) or a mixture of both. The dominating types of switches on these lines are shown in **Table 2**.

Table 1: Data for 3 different routes

Main route	End stations *(Major cities)*	Length [km]	Track density	Number of switches in main track	Number of passenger train/day	Number of freight train/day	Million gross tonnes (MGT)/ track/ year
1	Älvsjö-Partille *(Stockholm - Gothenburgh)*	456	2	493	76	44	8
2	Järna-Arlöv *(Järna/Katrineholm - Malmö)*	534	1.8	471	68	54	10
21	Buddbyn-Riksgränsen *(Boden -Norweigian border)*	486	1	117	6	19	10-20

Table 2: Number of different types of S&Cs on the main track lines
EV= Single S&C, DKV=Double crossing S&C

S&C Type	Abbreviation Used in figures	Main track Route number				Side track
		1	2	21	Sum	
DKV-SJ50-7,641/9,375-1:9	D-SJ50 R190	8	15	3	26	34
EV-BV50-300-1:9	SJ50 R300X	5	1		6	14
EV-SJ50-11-1:9	SJ50 R225	46	89	22	157	381
EV-SJ50-12-1:15	SJ50 R600	105	85	18	208	20
EV-SJ50-300-1:9	SJ50 R300	12	1		13	17
EV-UIC60-1200-1:18,5	UIC60 R1200	25	25		50	
EV-UIC60-1200-1:18,5 BL33	UIC60 R1200X	13	82		95	
EV-UIC60-300-1:9	UIC60 R300	74	34	40	148	29
EV-UIC60-760-1:14	UIC60 R760X	9	6	3	18	2
EV-UIC60-760-1:15	UIC60 R760	157	73	14	244	2
Other types		39	60	17	116	408
Main track		493	471	117	1 081	
Side Track		301	487	119		907
Total		794	958	236	1 988	

Table 3: Data of the S&C-types studied

Type	Radius [m]	Length [m]	Length [m] including diverting track	Switch blade length [m]	Rail weight [kg]	Angle [°]
DKV-SJ50-7,641/9,375-1:9	190		64.4	9.4	50	6.3
EV-BV50-300-1:9	300	33.2	49.8	12.9	50	6.3
EV-SJ50-11-1:9	225/190	28.1	44.7	11.0	50	6.3
EV-SJ50-12-1:15	600	44.6	70.9	12.0	50	3.8
EV-SJ50-300-1:9	300	33.2	49.8	12.9	50	6.3
EV-UIC60-1200-1:18,5	1200	64.8	97.2	23.3	60	3.1
EV-UIC60-300-1:9	300	33.2	49.8	13.0	60	6.3
EV-UIC60-760-1:14	760	54.2	81.3	21.5	60	4.1
EV-UIC60-760-1:15	760	54.2	83.1	21.5	60	3.8

In **Table 3** the most important figures are presented for the most common S&C's within main track. Data in **Table 2 and 3** is taken from the asset register, BIS.

Maintenance data has been taken from the failure reporting system (0felia) and the inspection report system (Bessy) at Banverket, and has been coordinated, so that each S&C on a main route can be identified with a certain number of failures or preventive maintenance actions. Data from the period 2005-2007 was analysed in respect to the different subsystems involved.

4.2   Condition on different type of stations

On a track section between two larger cities, the traffic conditions can be assumed to be similar. On larger stations, trains slow down and stop more frequently and in some cases divert to another track section. To minimise statistical variation it is necessary to choose only S&Cs on crossover stations that is stations that are only used for changing track and do not have platforms for passengers or a terminal for freight-trains. Also, in a crossover station the S&Cs have different traffic conditions. In **Figure 1**, a typical crossover station is shown. In a double track system one train direction is dominating on each track. This station has an additional track for trains that stops to let other (faster) trains to overtake. So some switches are in trailing mode (A and C), where the train reaches the crossing panel first and travels further to the switch panel. Some other S&Cs are in facing mode (B and D). The S&C in position B and C are more used for diverting track as they direct the slow going trains to stop at the side track.
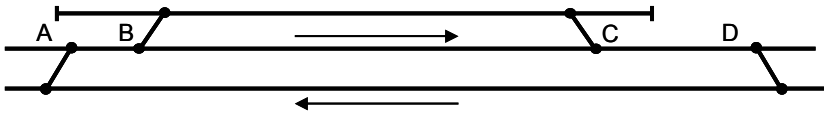
Figure 1: Typical cross-over station for a double track line

4.3   Test of independency of data

The number of inspection remarks and failures for S&Cs can be treated as iid (independent identically distributed), but in most cases this is not correct, so this hypothesis should be tested [5].

To have enough statistical data several S&Cs are grouped. The conditions for each S&C vary between different places. The most important factors are the type of S&C, traffic and the placing of an S&C [4]. The distribution of maintenance frequency will probably vary with these factors. For a set of S&C in one track section, the traffic conditions do not vary so much and it can be assumed that this set of S&Cs can be treated as a unity. It is expected that the failure rate and the maintenance rate for a group of S&Cs should be constant over time.

4.4   Dependency of time and place

Figure 2 shows the number of inspection remarks over time for 22 selected S&Cs on track section 512. These S&Cs are all at crossover stations. The number of inspection remarks per year decreased by approximately 40 % between 2004 and 2005 (from 9.3 to 6.1 times per year for UIC60R760). The reason for this could be a change in the maintenance strategy, as a new maintenance contract was introduced during this period. Thus it has been concluded that only data for 2005-2007 should be used for analysis as otherwise the set of data is not iid. In **Figure 3** the global time for failure rate is shown. The data for this diagram was taken from eight SJ50 and fourteen UIC60 individual

S&Cs. There is no time dependence of longer periods; but there is a variation during the year (winter/summer). Therefore, it is necessary to compare full years instead parts of years. For both the failure rate and the maintenance rate, it can be concluded that for a group of S&Cs the distribution can be treated as iid. The same conclusion cannot be drawn for individual assets while over longer time there is a general degradation [4]. The following observation has been made:

- Over a short time of period (3 – 4 years) maintenance rate and failure rate are constant for a group of S&Cs
- For individual S&Cs the maintenance rate and failure rate changes over a long time period (40 years) due to degradation of the system
- Sudden changes in maintenance rate will appear when maintenance strategy is changed
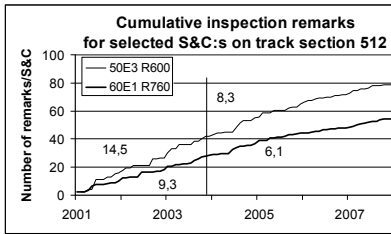
Figure 2: Accumulated number of inspection remarks as function of global time
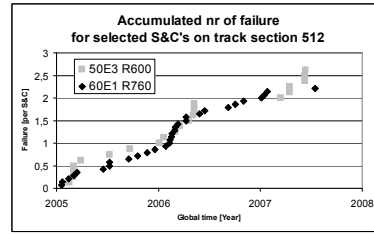
Figure 3: Acumulated number of failures as function of global time

5 Reliability model

A reliability model that can be used for inspection remarks and failures is a non-homogeneous Poisson process (NHPP) [6]. The non-homogeneous Poisson-process is used for repairable systems where the condition after repair is as bad as old, that is, the repair does not change the condition of the system. The probability of failure is the same as just before the repair. Together with covariates for traffic (γ_1) and place (γ_2) the number of inspection remarks can be treated by equation (1) and (2). The following assumed for this model:

- Minimal repair which leads to the power-law equation (1)
- Each track section will have an individual value for scale parameter, θ, reflecting the possibility of different maintenance strategy, age of the turnouts and so on. This is treated by the covariate (γ_2). Here is assumed that the form factor, β, is not changed.
- The load ($\gamma_1 t$) used in the equation has a linear relationship to the yearly tonnage

Equation (2) calculates the probability of a certain number of maintenance actions for a specific time period. Equation (3) shows that the failure rate is divided into many separate failure rates which can be the summary of the failure rate of several sub systems for each maintenance actions. This enables the model to predict the maintenance need on a subsystem level as well as type of maintenance action.

To build a reliability model more information about the conditions that influence the maintenance rate needs to be collected and analyzed to find values for β and γ. To build a cost-model the constant demand-rates can be sufficient while a high number of demand

processes will approach a Poisson process [7] and in that case only one value of λ is necessary.

$$\lambda(\gamma,\beta,\theta,t) = \gamma_2 \frac{\beta}{\theta}\left(\frac{\gamma_1 t}{\theta}\right)^{\beta-1} \quad (1)$$

$$\lambda = \sum_{i=1}^{k}\sum_{j=1}^{l}\lambda_{ij} \quad (3)$$

$$p(N(t)=n) = \frac{\lambda^n}{n!}e^{-\lambda} \quad (2)$$

$$\gamma_1 = T' \quad (4)$$

The number of inspection remarks for UIC60-760-1:15 have been modeled in **Figure 4** for the Western main route. The model is based on an increasing failure rate as the S&C gets older. In **Figure 4**, equation (1) is shown as the solid line and equation (2) is used to calculate 95 % probability to be within the dotted lines. The solid line is calculated by assuming some of the track sections to represent a normal behavior (in this case track section 418 and 611 was stated to be "normal"). About 70 % of the UIC60-760-1:15 have the number of inspection remarks within the predicted limits. To reach this level, some S&Cs are treated as outliers and considered not to belong to the normal population (grey dots). Reasons for this are, for instance, when the placing is in curves, close to bridges or the S&C is outside the normal main route.

The covariate γ_1 reflects the traffic load per year and is given by equation (4). The second covariate, γ_2, describes the type of track section and values. This is presented in table 5. The track section with $\gamma_2=1$ represents the "normal" track sections. For the remaining track sections values were calculated so that each track section could fit as well as possible for both types of S&C.
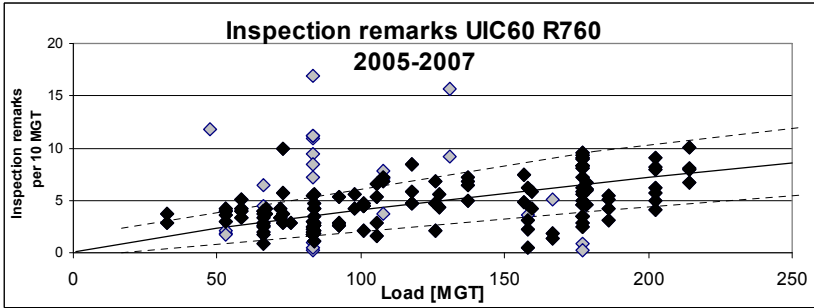
Figure 4: Number of inspection remarks for UIC60-760-1:15 on Western Main Route. Black dots show the S&C that is included in the model.

In **Figure 4**, the actual value of inspection remarks is divided by the covariates so it is possible to show the result in the same figure.

Table 5: Covariate for track section, γ_2

Track section	410	412	414	416	418	420	511	512	611	612
λ_2	2.5	2.1	2.2	3.3	1.0	3.0	1.7	1.5	1.0	0.8

6   Subsystem of S&Cs

Subsystems of an S&C have been chosen based on two different sources, the asset management register, BIS, and the headings used in the failure report system. In **Figure 5**, the subsystem, unit and component level is shown. The chosen headings are based on the subsystems, units or components that have at least 1% of the failures or inspection reports.
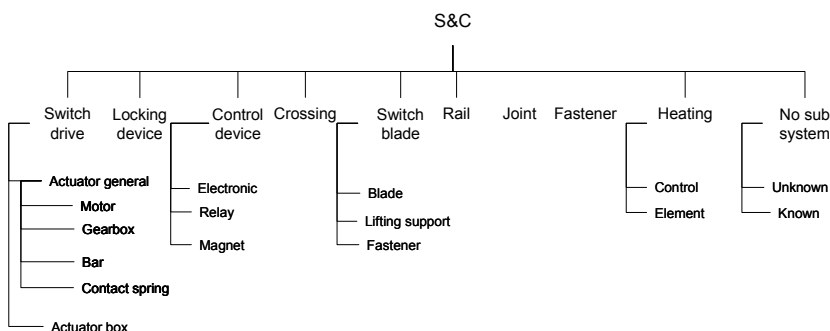
Figure 5: System breakdown of an S&C

7   Data analysis of maintenance actions

Maintenance actions are described in the two different maintenance systems. The failure rate and need for preventive maintenance can be expressed as number of maintenance actions/S&C. One problem in comparing different S&C types is that the number of subsystems as well as the design depends on the type, which might affect the maintenance needed for a specific subsystem (for instance, the switch drive motors vary between 1 and 4 in Swedish S&Cs).

Failure rate and preventive maintenance actions are presented first for different S&C-types and then for some selected S&C-types on subsystem/component level. For each subsystem, it is also possible to analyse the type of action taken. It should be noted that even if there have been over 5,000 failure records and 32,000 preventive maintenance reports analysed, when grouping the data so it is from a specific action for a certain subsystem on a specific switch type, only a few records remain.

The data analysis is done to establish;
- failure frequency
- preventive maintenance frequency
- mean time to repair (based on corrective maintenance)
- train delay time
- grinding
- tamping

In most of the calculations only mean values have been calculated. This is motivated by the fact that the frequency is so low that even three year data cannot support if the single value should be used or discard as nearly all single values are within predicted limits. For the number of inspection remarks the model described by equations (1) and (2) has been used.

7.1   Corrective maintenance

Corrective maintenance is defined as actions taken after a functional failure has occurred. Not all organizations define functional failures in the same way. In railway system, train stopping failures and failures that might lead to train stops are considered to be functional failures. For Banverket, events recorded in the failure report systems are treated as functional failures and short range planned actions after inspection reports are also treated as functional failures. In this report, only the former one has been used to calculate the failure rate.

Figure 6 show the failure rate for different types of S&C is shown. In cases where there are less than 20 S&Cs of a certain type, it is marked by diagonal stripes. There is a difference between main track and side track which depends on traffic volume and usage of S&C.

The failure rate for the S&Cs SJ50-12-1:15 and UIC60-760-1:15 are studied in **Figure 7**. The failure rate for these two types of S&C does not differ very much on main routes 1 and 2. On line 21, the number of S&C's is fewer (18 and 14) which adds some uncertainty to the figures. The failure rate not only depends on type of S&C, it is also a function of load conditions. Even within a main route, variation will be found if the traffic differs from one end to the other. Main factors that affect failure rate are axle weight, number of trains, speed, usage in diverting track and number of movements. Two subsystems dominate the number of failures and that is control device and switch device, which can be seen in **Figure 7**.
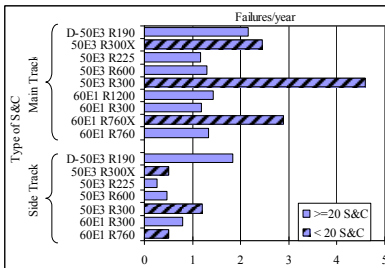
Figure 6: Failure rates for different types of S&Cs
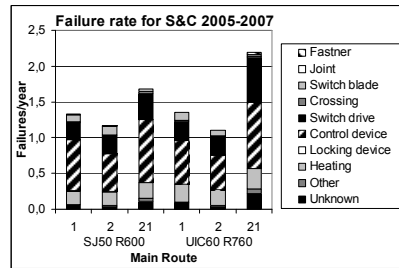
Figure 7: Failure rates for two types of S&Cs on three different main routes.

The maintenance action depends on the subsystem that has failed. In **Figure 8** shows the type of actions for the SJ50-600-1:15 and UIC60-760-1:15 for the most frequent failed subsystems. Most of the actions are not replacement or repair. Cleaning, adjustment and checking are more common actions.
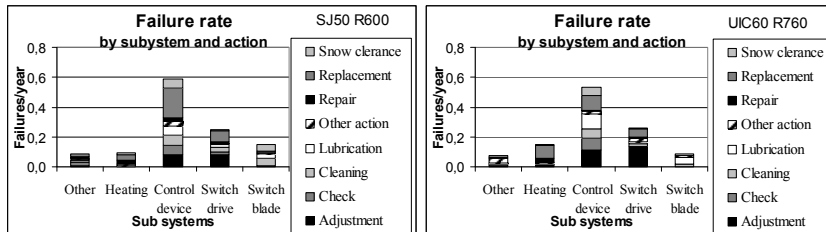
Figure 8: Corrective action taken for different subsystems for two types of S&C (main route 2)

To calculate the consequence or non-availability costs, it is of interest to know how often a failure also will stop a train. By definition by Banverket, delay time is only measured when it is larger than 5 minutes between two stations, so when a train passes an S&C at low speed there might not be any delay registered. On average 28% of the failures lead to delay time, which is shown in **Figure 9** for different sub systems. The delay time can be subdivided into short or long delay time. The author has defined long delay times to be more than 180 minutes. Even if long stops are few (about 6 % of the number of train stopping failures) they contribute with 54 % of the delay times. In **Figure 10**, it is shown how much each train stopping failure contributes to delay time depending on subsystem (in this figure delay time longer than 180 minutes has been excluded).
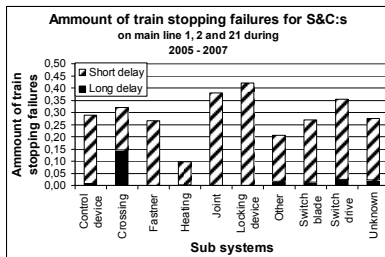
Figure 9: Amount of train stopping failures for different subsystems
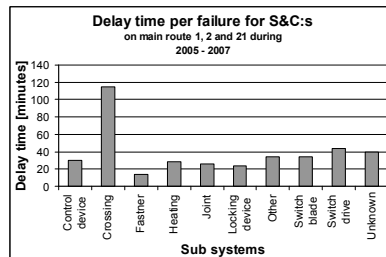
Figure 10: Delay time for train stopping failures for different sub systems

Maintainability is measured by MTTR (Mean Time To Restoration, IEV 191-13-08) or mean maintenance man-hours, IEV 191-13-04. Within the failure report system it is possible to present figures of time spend for maintenance. The maintainer reports at what time his work starts and ends. In most cases this is a reasonable figure, in a few cases the time is very long and therefore only maintenance man-hours less than 8 hours is used. If the maintenance action is not possible to do due to logistic delays it should not be counted. In fact only 4 % of the records state times longer than 8 hours. In **Figure 11** maintenance time for selected subunits and for two types of action is presented. Replacement takes two to four hours and adjustments less than one hour.
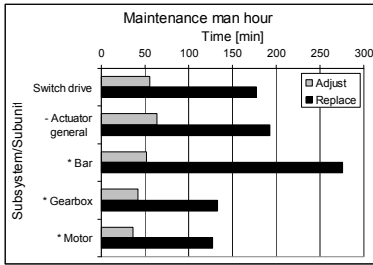
Figure 11: *Maintenance man time for two different actions of selected subunits (data based on all type of S&Cs)*
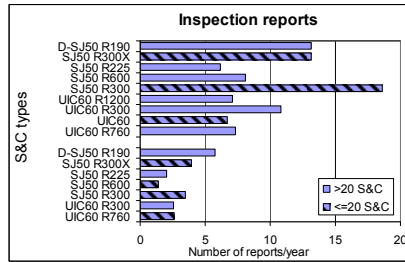
Figure 12: *Inspection remarks for different types of S&Cs*

7.2   Preventive maintenance

Preventive maintenance is defined as being actions taken before a functional failure has occurred. Within Banverket, preventive maintenance is mostly done after inspections. These inspection remarks are registered in an inspection report database called Bessy. Preventive actions undertaken on a scheduled basis or due to an undesired condition taken from the track measurement recording are not registered in this system. Examples of such actions are tamping and grinding, which are recorded in the asset register, BIS.

In **Figure 12,** the number of inspection remarks for different types of S&C's is shown. There is a difference between main track and side track. Other differences depend, for instance, on age of the S&C, load condition, maintenance activities and the type of S&C.

Inspections remarks have another rate than failures. There is no direct correlation between the two rates on a subsystem level. In **Figure 13,** inspection remarks for different subsystems of two types of S&C are shown. There are differences between the main routes that can be attributed to different loading conditions. The subsystems that have most of the remarks are control device, switch drive, crossing and switch blade.
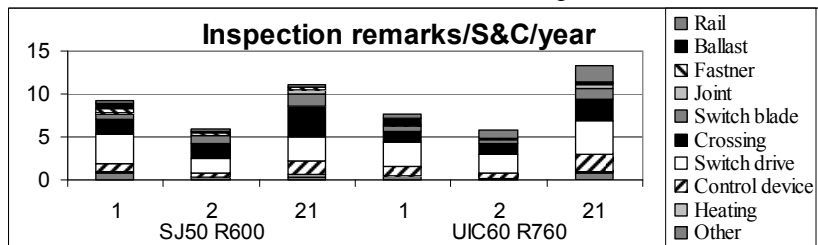
Figure 13: Inspection remarks for different subsystem for two types of S&C based on mean values of the total number of S&Cs in each main route

Figure 13 is based on mean values without taking traffic volume or age into consideration. To calculate a value θ (see equation 1) more work is needed. This has been done for the Western Main Route (Main Route 1). For each S&C and each subsystem the number of inspection remarks is counted and compared to a predicted value. The value of θ that results in a deviation between the model prediction and the actual number of

inspection remarks are calculated (LSM, least square mean). The result is shown in **Table 6**. In **Table 6** the maintenance frequency at total load 100 MGT, λ (100), is also calculated. The third column shows how many of the S&Cs can be fitted in the 95 % tolerance limits of the model.

Table 6: Constant θ for S&C's at the Western Main Route

	UIC60-760-1:15			SJ50-12-1:15		
	θ	λ(100)	S&Cs within prediction	θ	λ(100)	S&Cs within prediction
Ballast	21.0	0.30	83%	25.5	0.21	83%
Control device	14.8	0.56	85%	18.5	0.37	71%
Crossing	14.5	0.58	73%	13.9	0.63	66%
Fastener	52.0	0.06	89%	28.4	0.17	85%
Heating	67.5	0.04	96%	54.0	0.05	90%
Joint	148.8	0.01	84%	73.2	0.03	82%
Other	25.5	0.21	89%	20.8	0.30	80%
Rail	25.5	0.21	90%	43.4	0.08	84%
Switch blade	21.8	0.28	91%	26.3	0.20	87%
Switch drive	8.1	1.64	64%	7.8	1.78	51%
Total	5.0	3.89	70%	5.1	3.84	54%

In **Figure 14,** the action taken according to the inspection remarks is shown. A single action depends on the subsystem and is not always on the same level for different type of S&C's. The calculation is based on table 6, and for each subsystem the fraction of different maintenance actions is calculated for all chosen S&Cs without taking the age or traffic volume into account.

Figure 15 shows the tamping frequency. Here all S&Cs of the same type for any main route are shown in the same diagram. There are differences between the main routes with a lower frequency on main route 2 (0.23 times/S&C/year) and highest on main route 1 (0.38 times/S&C/year). It might be possible to study if there is any difference in how often an S&C is tamped depending on type of S&C. To do this, factors as traffic and use of deviating track must be known.
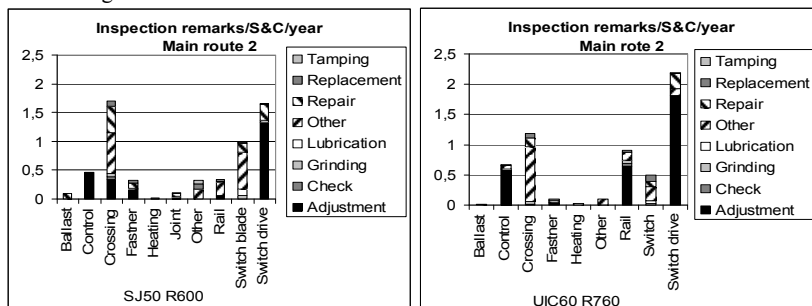
Figure 14: Preventive actions taken according to inspection remarks for subsystems of two types of S&C on Western Main Route

Figure 16 shows machine grinding frequency which is a dependent on which main route has been studied. A normal interval between grinding operation seems to be 6 years. This data is from 2002 – 2007 and the maintenance strategy is changing towards more grinding of S&C's. At main route 21, grinding is done about every 2nd – 3rd year since this grinding strategy was started before year 2000. More frequent grinding lowers the forces and wear according to the theory [8] so it should affect the other parameters if the grinding strategy is changed. It is beyond the scope of this study to give any estimation of the effect.
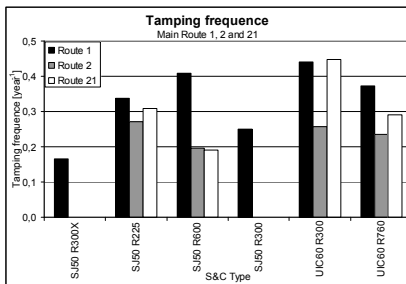
Figure 15: Tamping frequency for different types of S&Cs between 2002-2007
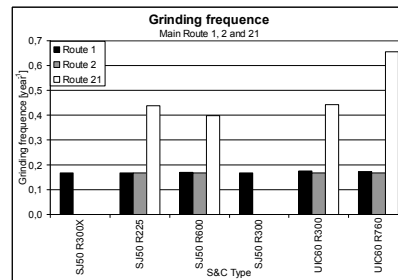
Figure 16: Grinding frequency for different type of S&Cs between 2002-2007

8   Discussion

In a model of LCC the life cycle can be subdivided into 6 phases [9]:

1. concept and definition
2. design and development
3. manufacturing
4. installation
5. operation and maintenance
6. disposal

The first 4 phases are for infrastructure owner buying of shelf products covered by the procurement price. During the operation and maintenance phase, failure rate, preventive maintenance rate and actions cost are used to calculate the LCC-value. In addition to these costs there are indirect costs, mostly caused by train delays.

From the Banverket system it is possible to retrieve most of the information that is needed for an LCC-analysis. Additional information such as investment cost and cost for installation can be taken from the material delivery system or from different procurements. Pre-investment cost can be considered equal for different alternatives. In this article it has been shown that failure rates, delay time, inspection remarks, grinding and tamping are possible to calculate for subsystems of different types of S&Cs. These estimations are still coarse and must be followed by a discussion with a railway expert to validate the information.

An LCC-model for the maintenance of an S&C should be subdivided into a number of subsystems. For Banverket it would be sufficient with 13 subsystems/units, see **Figure 17**. For each subsystem, 10 types of action are sufficient to describe the maintenance work, see **Figure 18**. For each combination of subsystem and action the parameters of failure rate, preventive maintenance rate, cost for machines and maintenance time needs to be established. In the worst case that would lead to more than 530 values needed for the model. By finding cost drivers and not combining every type of action with every type of

subsystem it should be possible to describe the model with less than 100 values. This is schematically shown in **Figure 19**.
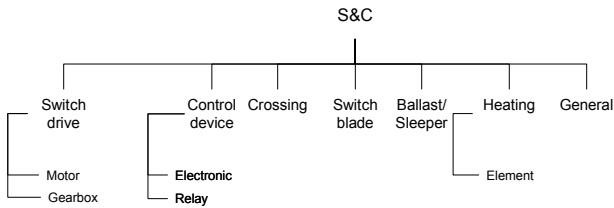
Figure 17: Important subsystem to be used in a Swedish LCC-model
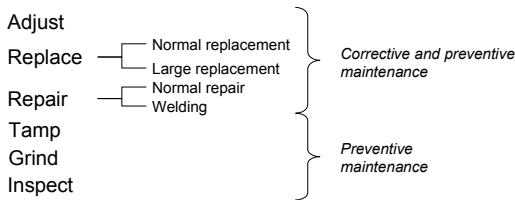
Figure 18: Important actions to be used in a Swedish LCC-model

Figure 19: Proposal of possible values that need to be established within an LCC-model for S&Cs

When making the LCC-model there will be a need for more information. One of the most difficult pieces of information to obtain is the cost per action (or time spent for each type of action). One way to do this is to discuss this for each subsystem with an entrepreneur.

Replacement and repair of larger components is not so frequent. There are four types of action in particular that have a low frequency but a high cost. It is therefore essential to have good estimation of the maintenance rate of to be able to take good decisions. These four types of actions are grinding, tamping, and replacement of crossings and switch blades.

The LCC-model should be combined with a risk-analysis while unexpected failures or malfunctions will lead to extra cost or safety problems [10]. This has not been done in this study.

9   Conclusions

This study has shown that Banverket is registering data that can be obtained by using available databases. The information can be used to build an LCC-model as it is possible to identify data for different types of S&Cs on a specific route. The most important data to be used in an LCC-model is:

- failure and preventive maintenance frequency
- mean time to repair (based on corrective maintenance)
- train delay time

There are variations in the data that can be seen as influenced by traffic condition or maintenance strategy. By using covariates some of these effects have been dealt with, but the author does not believe this is the final way that this data should be treated, instead it should show where there are differences and used by Banverket to find better maintenance strategies.

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11   References

[1] Banverket. *Årsredovisning 2007*. Annual report 2007,
      (http://www.banverket.se/pages/1493/BV-AR-2007-TG-x.pdf, 2009-10-27).
[2] SS-EN 50126. *Railway specifications – The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)*. European Committee for Standardization; 1999.
[3] Banverket. *BVF 800 Övergripande regler för Banverkets underhållsverksamhet (General rules for maintenance within Banverket)*. Banverket; 2007.
[4] Nissen, A. *Analys av statistik om spårväxlars underhållsbehov (Analysis of Maintenance Statistics of Railway Turnouts)*. Licentiate thesis, Luleå University of Technology; 2005, ISSN: 1402-1757; 2005:86.
[5] Bendell, A. and L. A. Walls. *Exploring reliability data*. Quality & Reliability Engineering International 1985; 1: 37-51.
[6] Rigdon, S. E. and A. P. Basu. *Statistical Methods for the Reliability of Repairable systems*. Wiley Interscience, New York; 2000, ISBN 0-471-34941-0.
[7] Alfredsson, P. and O. Wååk. *Constant versus non-Constant failure Rates: Some Misconceptions with Respect to Practical Applications*. 1998
      http://www.systecon.co.uk/techpapers/papers/constant.pdf (2009-10-27)
[8] Schoech, W. *Advanced application of rail grinding in switches*. Rail-Tech Europe, Switch Design & Maintenance; 2007.

[9]   IEC 60300-3-3, *Dependability management - Part 3-3: Application guide - Life cycle costing*, International Electrotechnical Commission, 2nd Ed., Geneva , Switzerland; 2004.

[10] Markeset, T. and U. Kumar. *Integration of RAM and risk analysis in product design and development work processes*. Journal of Quality in Maintenance 2003; 9(4): 393-410

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LCC-analysis for Switches and Crossings – a case study from the Swedish railway network

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ABSTRACT

Banverket (the Swedish Rail Administration) plans to achieve a lower operation and maintenance cost for infrastructure through a better understanding of the life cycle cost. It is easier to propose changes in the design and maintenance strategy for its assets through quantified values of cost instead of just failure rates and the number of inspection remarks. This paper makes an attempt to analyze the LCC-values of S&Cs (switches and crossings) on Swedish railway track. The scope of the paper is to explore the possibility of using LCC as a decision tool for an infrastructure manager.

The S&C cost data from Banverket were collected for the LCC-analysis as a part of the case study. A cost model based on the acquisition phase and the operation and maintenance phase has been developed and tested. In this model the LCC-values of three types of S&Cs are compared. The model can also be used to find cost drivers, as well as to perform sensitivity analysis to find parameters that have a large influence on the result. The model has been built with the assumption that a multiple type of maintenance action is undertaken for each subsystem. Within the model, there is a possibility of defining periodical maintenance intervals besides the annual maintenance cost. The LCC-value may be presented as an annuity cost, which enables a comparison between assets that have different technical lifetimes.

The cost drivers are the inspection cost and the periodical maintenance costs of subsystems, such as the costs for crossing and switch blade replacement, welding and tamping. The sensitivity analysis confirms that the most important parameter to have control of is the frequency of periodical preventive maintenance.

Keywords: Switches and crossings, LCC, railway

Mathematical symbols and abbreviations

$[\rightarrow]$ –   Conditional statement, if the statement is true, assign the value after the arrow

$|$ –   Used in conditional statement, interpreted as Boolean AND

λ_{ij} –   Failure intensity for action i and unit j [year^{-1}] (this is a function of time)

C_A –   Cost of acquiring an asset [€]

C_{Eij}	–	Maintenance equipment cost for action i and unit j [€/h]
C_{Delay}	–	Unavailability cost per hour [€/h]
C_I	–	Cost for investment in maintenance equipment [€]
C_{IN}	–	Cost for installation of asset [€]
C_L	–	Man hour cost for labour [€/h]
CO	–	Operational cost [€]
C_{Pij}	–	Spare parts cost for action i and unit j [€]
CP_{PM}	–	Periodical preventive maintenance cost (typical interval of 5 – 30 years) [€]
$CPPM_E$	–	Yearly cost for use of maintenance equipment for periodical preventive maintenance [€/year]
$CPPM_M$	–	Cost for man hours performing periodical preventive maintenance [€/h]
$CPPM_S$	–	Cost for spare parts used for periodical preventive maintenance [€]
C_Y	–	Yearly cost for maintenance [€/year]
CY_{CM}	–	Yearly cost for corrective maintenance [€/year]
$CYCM_E$	–	Yearly cost for use of maintenance equipment for corrective maintenance [€/year]
$CYCM_M$	–	Yearly cost for man hours performing corrective maintenance [€/year]
$CYCM_S$	–	Yearly cost for spare parts used for corrective maintenance [€/year]
CY_{PM}	–	Yearly cost for preventive maintenance [€/year]
$CYPM_E$	–	Yearly cost for use of maintenance equipment for preventive maintenance [€/year]
$CYPM_M$	–	Yearly cost for man hours performing preventive maintenance [€/year]
$CYPM_S$	–	Yearly cost for spare parts used for preventive maintenance [€/year]
f_{ij}	–	Maintenance frequency for action i and unit j [year^{-1}] (this is a function of time)
I	–	Index for maintenance actions
INT	–	Calculates the integer value of the function
j	–	Index for units/subsystems
LCC	–	Life cycle cost [€]
LCCA	–	Acquisition cost [€]
$LCCA_E$	–	Acquisition cost for equipment [€]
$LCCA_I$	–	Installation cost at the acquisition [€]
LCCO	–	Ownership cost [€]
LSC	–	Life support cost [€]
LUC	–	Unavailability cost [€]
LCT	–	Termination cost (disposal cost) [€]
m	–	Maintenance actions between 1 and m are treated as annual maintenance actions
m_1, m_2	–	Maintenance actions between m_1 and m_2 are treated as periodical preventive maintenance
MAT_{ij}	–	Mean action time for action i and unit j (preventive maintenance) [h]
MLT_{CM}	–	Mean logistic time for corrective maintenance [h]
MLT_{PM}	–	Mean logistic time for preventive maintenance [h]
MRT_{ij}	–	Mean repair time for action i and unit j (corrective maintenance) [h]
$MTDT_j$	–	Mean train delaying time for unit j [h]
n	–	Number of units/subsystems
n_L	–	Number of workers to perform the maintenance

NPVF   –   Net present value factor $(1+r)^{-t}$
p_{ij} –   Probability that a failure will lead to a train delay
r   –   Discount rate
S&Cs   –   Switches and crossings
t   –   Index for time [years]
t_1 –   Technical lifetime for S&Cs [years]
TLT   –   Technical lifetime for a subsystem [years]

1   INTRODUCTION

Banverket (the Swedish Rail Administration) manages an infrastructure consisting of 13,000 km of track with about 12,000 switches and crossings (S&Cs). The cost of maintenance and reinvestment is on average €26,000/km of track/year.

Life cycle cost (LCC) analysis has been used since the late '60s and has its roots in the American defence industry [1] as a tool for decision making by assessing the total cost of acquisition, ownership and disposal of a product [2].

This study has been undertaken to analyze the LCC-values of S&Cs in the Swedish railway network. By presenting quantified values, one can gain a better understanding of the type of changes in the design and maintenance strategy that can be planned to lower the life cycle cost.

The scope of this article is to explore the possibility of using LCC as a decision tool for an infrastructure manager.

The article is based on data retrieved from maintenance databases in use for the Swedish rail network. The data may differ considerably from that for other railways. The equations for dependency on the traffic load have not been validated, but are general and therefore possible to adapt to other circumstances. The cost for operation has not been included in the model and it is considerable in the northern part of Sweden, especially concerning snow removal and heating.

Railway infrastructure and particularly track components are expensive assets with long life spans. This motivates the use of LCC, an engineering economics technique. LCC can, for instance, visualize the importance of good maintenance strategies [3].

There are a few examples of reports assessing the long-term cost for track components within Banverket. Strategies for managing rail cracks and rail breaks, lubrication and grinding of rail have been studied [4,5]. The life cycle cost for tunnels has also been discussed and analyzed by Banverket [6,7]. Rail life and grinding strategies have been modelled in economic terms [8]. The author is not aware of any more reports showing the use of LCC within Banverket.

S&Cs contribute to about 13% of the maintenance budget for Banverket [9]. The life length of S&Cs on the main track is in general 40 years and, therefore, in the reinvestment plan, it is necessary to calculate for more than 200 new S&Cs per year. A cost-benefit analysis based on life cycle costing could be a good tool for finding which S&Cs need to be replaced. Life cycle costing can also be used in the design stage or when choices between different types of S&Cs must be made. In the European project Innotrack, life cycle costing and RAM-analysis have been used as a foundation for making choices. Banverket is involved in this European project as one of 8 infrastructure managers. The Association of American Railroads has presented a report on LCC for railroad turnouts [10]. Any other research on the life cycle cost of S&Cs has not been found by the author.

2   LCC METHODOLOGY

The life cycle of an asset can be subdivided into 6 phases according to (IEC 60300-3-3) [2]:

    1. concept and definition

2. design and development
3. manufacturing
4. installation
5. operation and maintenance
6. disposal

The owner of an asset can consider 3 stages [11] for LCC-analysis:

1. development
2. operation
3. phase-out

These 3 stages have been used in this case study. Cost can be attributed to each stage by information available at Banverket. The life cycle costing model (LCC-model) is based on three S&C-types used in Sweden.

For the asset owner, the cost connected with the development stage is the acquisition and installation cost, while the development is carried out by the vendor. These costs are normally fixed. The S&Cs can be described by different levels. Level I is the superstructure carrying the load, and level II is the superstructure and the mechanical parts with the driving and locking devices. Level III is the total system with the signalling and interlocking system, see Figure 1. Only level II is used in the operation phase of the LCC-model. In Figure 2 the S&Cs are decomposed into subsystems and units.
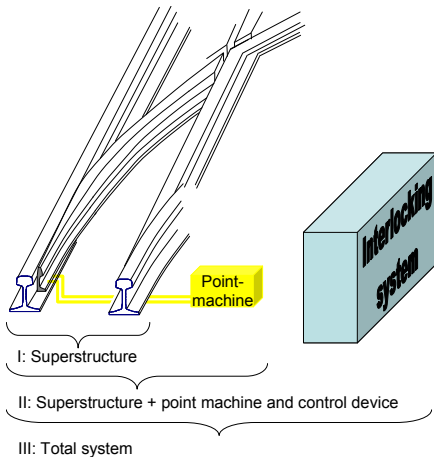
Figure 1 Decomposition of an S&C into different levels

For each subsystem different maintenance activities are possible. A maintenance activity is described by the frequency and the unit cost. For a few subsystems, the operation cost (such as the cost for heating and snow and leaf removal) can be added. In the phase-out stage the disposal cost and the cost for possible restoration and further use in a low traffic area can be considered.
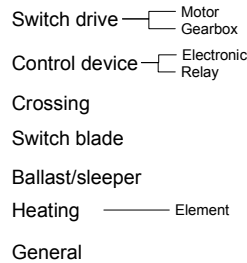
Figure 2 Decomposition of an S&C into subsystems and units

2.1 Product breakdown structure (PBS)

The product breakdown structure is used to allocate the cost, maintenance rate, repair time, etc. at a level where parameters for repair and replacement can be identified.

2.2 Cost breakdown structure

The cost breakdown structure enables the analyst to find the cost driving elements and also simplifies the work involved in setting up correct equations. The breakdown shown in Figure 3 is an adaption of that used in IEC 60300-3-3 [2] and Wååk [12]. The equations used in the cost breakdown structure are summarized in equation (1) – (5). The operational cost, C_O, and the termination cost have been set to zero in the model. Three features not normally used in LCC-calculation have been introduced.

- Several maintenance rates can independently be attributed to each subsystem.
- The preventive maintenance has been separated into annual preventive maintenance and periodical preventive maintenance.

4

- The yearly costs are not constant, but functions of time. An application factor that normally is used has been substituted by $\Sigma(NPVF*CY)$.

The reason for doing this is explained in the discussion.
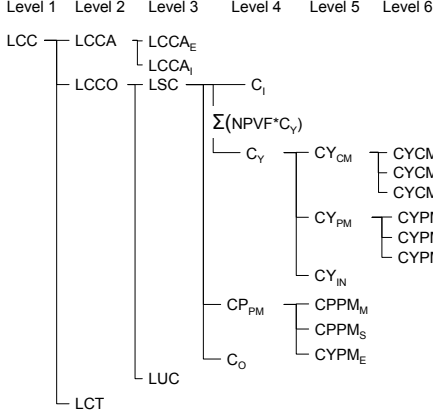
Figure 3 Cost breakdown structure adapted of that used in EN IEC 60 300-3-3 [2]

Acquisition cost $LCC_A = C_A + C_{IN}$ (1)

Annual cost for corrective maintenance

$$CY_{CM} = \sum_{i=1}^{m}\sum_{j}^{n} \lambda_{ij} * \left(C_L * n_L * (MRT_{ij} + MLT_{CM}) + C_{Pij} + C_{Eij}\right) \text{ (2)}$$

Annual cost for preventive maintenance

$$CY_{PM} = \sum_{i=1}^{m}\sum_{j}^{n} f_{ij} * \left(C_L * n_L * (MAT_{ij} + MLT_{PM}) + C_{Pij} + C_{Eij}\right) \text{ (3)}$$

Periodical preventive maintenance cost $CP_{PM}=$

$$\sum_{t=0}^{t1-1}\sum_{i=m1}^{m2}\sum_{j=1}^{n}\begin{bmatrix} t < t_1 - t_{ep} | INT((t+1)*f_{ij}) > INT(t*f_{ij}) \rightarrow \\ \rightarrow NPVF * C_L * n_L * (MAT_{ij} + MLT_{PM}) + C_{Pij} + C_{Eij} \\ t >= t_1 - t_{ep} \rightarrow 0 \\ INT((t+1)*f_{ij}) = INT(t*f_{ij}) \rightarrow 0 \end{bmatrix} \text{(4)}$$

Consequential cost

$$LUC = \sum_{t=0}^{t1-1}\sum_{i=1}^{m}\sum_{j}^{n} NPVF * \lambda_{ij} * p_{ij} * C_{Delay} * MTDT_j \text{ (5)}$$

2.3 Maintenance breakdown structure

The maintenance of a subsystem can be conducted in several ways and the cost associated with a subsystem depends heavily on the type of maintenance action. Banverket's maintenance actions are registered in two databases (Bessy and 0felia). Table 1 lists typical maintenance actions used by Banverket. The model developed in this paper uses the activities written with bold letters.

2.4 Parameters

Each stage is described with a certain number of parameters.

Development

The pre-investment has so far been considered to be equal for all the cases and has therefore been set to 0. It is possible that an S&C with a new design would need a test period and this could be treated as a pre-investment cost.

The cost for investment was assumed to be the price for a new system given by Banverket, Spare Part Support (Materialservice). The cost for installation was requested from the entrepreneur or vendor.

2.4.1 Operation

The most important operation cost for S&Cs in Sweden is the heating and snow removal cost. This cost is treated as equal for different S&Cs and therefore normally set to zero. In certain cases where improvement of the heating system is considered, this is an essential cost.

Table 1 Maintenance action for S&Cs in use by Banverket. Activities in bold letters are headings used in the model.

Action	Corrective Maintenance	Preventive Maintenance
Replacement	**28.0%**	**9.4%**
Adjustment	**14.8%**	**45.8%**
Checking	12.2%	
Lubrication	10.2%	
Snow clearance	7.4%	
Repair	**7.2%**	**0.4%**
Rinsing	7.1%	
Cleaning	5.0%	0.4%

Restart	3.1%	
Minimal repair	2.2%	
No action	1.5%	
Not specified	0.4%	0.1%
Removal	0.3%	0.0%
Restart	0.3%	
Advice	0.2%	
Speed restriction	0.1%	
According to notes		9.8%
Tightening		8.7%
Grinding		**7.9%**
Building up weld		**7.3%**
Complement		4.0%
Bolt replacement		3.3%
Tamping		**1.7%**
Lubrication		0.4%
Visual inspection		0.3%
Lifting		0.2%
Lock		0.1%
Plan for action		0.1%
Action needed		0.0%
Alignment		0.0%
Removal of vegetation		0.0%

The maintenance training cost and the cost for investing in maintenance equipment, C_I, have been set to zero.

The data used to describe the maintenance can be grouped into some general parameters and 8 sheets with values. Table 2 describes which type of data should be gathered, and one sheet with values for the LCC-model is shown in Figure 4, which contains data on the preventive maintenance rate (times per year). Each sheet is based on 12 subsystems/units and 9 possible actions. A primary assessment has been carried out using data taken from Banverket's maintenance systems [13]. A second assessment has been performed by interviewing people involved in maintenance activities. It is important in this stage that the case has been described and that the traffic volume and type of track have been specified. The values that are the most critical are discussed in the section "*Sensitivity analysis*" and written in bold print in Figure 4.

2.4.2 Phase-out

There are three possible outcomes concerning how the asset is treated after the operation and maintenance phase.

- The technical life length is sufficient to keep the system in use for a certain period.
- The asset is reconditioned and moved to a low frequency track.
- The asset is taken out and disposed of.

Table 2 Type of input data needed for the model (X – single values, XXX – sheet with values)

Parameter	Correct-ive main-tenance	Prevent-ive main-tenance	General
Frequency of maintenance activities	XXX	XXX	
Man hour time per action	XXX	XXX	
Logistic delay time	X	X	
Equipment cost per action			XXX
Spare part cost per action			XXX
Man hour cost			X
Train delay time per action	XXX		
Cost for train delay time	X		
Frequency of train stopping failure	XXX		

In each case it is possible to give a value for the asset. In the first case a value proportional to the investment cost and the life length used can be

calculated. In the other two cases a fixed cost can be used.

Subsystem \ Action	Adjustment	Replacement normal	Replacement large	Repair	Repair, welding	Other
Switch drive	**1.933**	0.013	**0.033**	0.246		0.117
- motor		0.000				
- gearbox		0.000				
Control device	**0.663**			0.000		0.063
- electronic		0.002				
- mechanical		0.004				
Crossing	**0.917**		**0.071**	0.154	**0.710**	**0.896**
Switch blade	0.283		**0.108**	0.088		0.233
Ballast/Sleeper				0.021		
Heating	0.033					0.033
- element		0.000				
General	0.15	0.025		0.029		0.100

Figure 4 A sheet for values of frequency of predetermined maintenance for the S&C UIC60-760-1:15 based on figures in Banverket's database (for a mixed traffic line with 10 MGT/year). The values in bold print are the most critical (discussed in the section "Sensitivity analysis").

2.4.3 General parameters

The general parameters include the discount rate, the calculation period and boundary conditions such as the maintenance strategy for tamping and grinding. In Table 3 some general parameters are shown.

2.5 Reference solution

The reference solution is the solution that is assumed to be the normal choice.

Banverket prefers to use the EV-UIC60-760-1:15 or a larger S&C when replacing cross-over S&Cs on most main tracks. The location is assumed to be at a meeting station on a double track line with 4 S&Cs and the station is used for cross-over traffic (with 1-2% usage), see Figure 5. The station is situated 100 km from the nearest maintenance service team. The technical lifetime is set to 40 years.
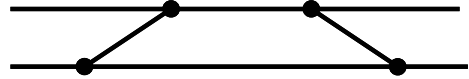
Figure 5 A cross-over station with 4 S&Cs

Table 3 General parameters used in the study

Parameter	Value
Discount rate	4%
Calculation period	35,40 and 45 years
Traffic	Mixed traffic line 10 MGT/year
Track	Double
Grinding frequency	40 MGT
Use of deviating track	2%
End period when no periodical maintenance is performed	20% of maintenance interval
Logistic delay time for corrective maintenance	3 h
Logistic delay time for preventive maintenance	1 h
Cost of train delay	€53/minute

2.6 Alternative solutions

Two different alternative solutions are discussed.

A) EV-BV50-600-1:15 with a technical lifetime of 35 years
B) EVR-UIC60-760-1:15 with a movable frog and a technical lifetime of 45 years

The EV-BV50-600-1:15 is an S&C with lighter rail (50 kg/m instead of 60 kg/m) and a smaller radius for deviating track (600 m instead of 760 m). This should normally lead to a lower investment cost, faster deterioration and a shorter lifetime than for the EV-UIC60-760-1:15 S&C. The EVR-UIC60-760-1:15 has the same dimension as the reference solution and has a movable frog. This S&C has a higher investment cost, but a lower cost for maintaining the crossing.

2.7 Input value with distribution

In many cases there is an uncertainty in the input value of the LCC-model. This uncertainty can be handled by using distributions instead of single values. Some of the possible distributions used for LCC are the triangle, square, half-circle and normal distributions, shown in Figure 6 [14].
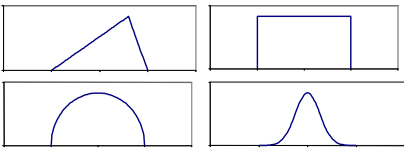
Figure 6 Distributions used in Monte Carlo simulations. A) Triangle, B) Rectangle, C) Half-Circle, D) Normal distributions

3 RESULTS

In this section the cost drivers for the reference solution are discussed, and a sensitivity analysis for the reference solution is presented. The alternative solution is compared to the reference solution.

3.1 Reference solution

In a previous study it was concluded that the cost for maintaining an S&C is about €900/MGT [15]. That would give a life support cost (LSC) in the order of €185 k. The reference solution has an LSC of €191 k. Figure 7 shows the LCC subdivided into cost elements (with the cost elements CYCM, CYPM and CYIN summed up for the total lifetime of the S&C). The cost for preventive maintenance dominates over that for

corrective maintenance, and in Figure 8 more details from the preventive maintenance actions (CPPM, CYPM and CYIN) are shown. The dominant activities are periodical preventive maintenance, adjustment and inspections. The subsystems that cause most of the preventive maintenance cost are the crossing, switch blade, rail, switch device and ballast (need of tamping) subsystems, see Figure 9.
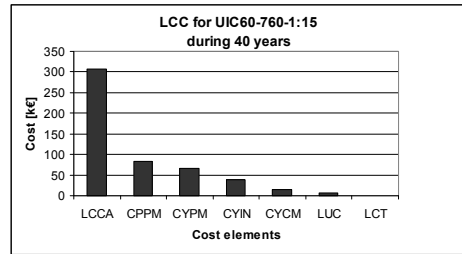
Figure 7 Cost elements of reference solution
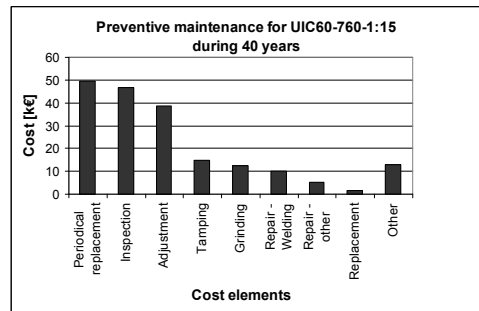
Figure 8 Maintenance activities within the preventive maintenance
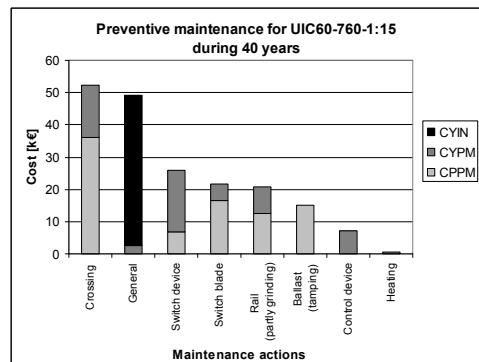
Figure 9 The cost of preventive maintenance divided up into subsystem costs

3.2 Sensitivity analysis

In the sensitivity analysis the parameters are varied to see how great an effect they have on the LCC-value.

In Figure 10 about eight parameters affect the LCC-value to a great extent. For the other parameters even a variation of +100% or -50% will not change the LCC-value by more than 10%. The need for precision of the input parameter is shown in Figure 11. For most of these parameters it is possible to have a good data quality, and it may be difficult to establish sufficiently good data quality for only a few of them. For instance, it is important to have knowledge of the preventive maintenance and the technical life length of subsystems such as the crossing and the switch blade.

As shown in Figure 4, some values can be considered to be more critical concerning the preventive maintenance rate. It is also important to perform a quality check on all the other parameters that are combined with the preventive maintenance rate, for instance the man hour time required to install a new crossing.
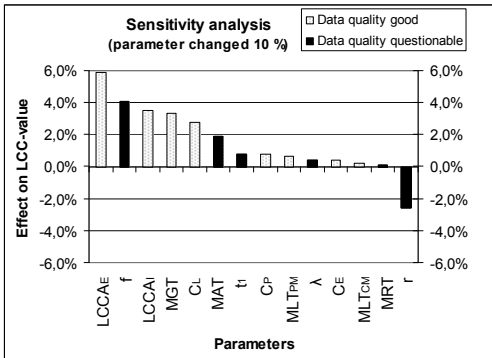
Figure 10 Sensitivity analysis showing the most important parameters

3.3 Alternative solution

A comparison between the UIC60-760-1:15 and the BV50-600-1:15 has been made based on historical data for the UIC60 S&C on Main Line 2 in Sweden (Järna-Arlöv) and the assumption of a 15% higher maintenance cost for the BV-50-

design. The BV50 is a Swedish development of the UIC60-design involving the use of a 50 kg/m rail where the traffic volume is lower than 8 MGT/year. The lack of historical data is due to the fact that very few BV50 S&Cs are installed on Main Line 2. The values have so far not been validated by discussions with a Swedish S&C expert, but the total cost level is in accordance with the cost figures taken from the accounting system [15].
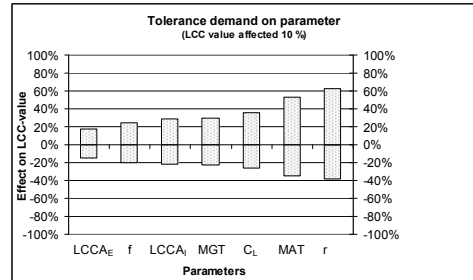
Figure 11 Tolerance demand on input parameter so that the effect will be less than 10% on the LCC-value

A comparison between the EV-UIC60-760-1:15 and the EVR-UIC60-760-1:15 (the new S&C with a movable crossing nose) has been made based on historical data for the EV-UIC60-760-1:15 on Main Line 2 in Sweden (Järna-Arlöv) and the assumption of a lower maintenance cost for the EVR-UIC60-760-1:15. The lack of historical data for the EVR-UIC60-760-1:15 is due to the fact that until 2007 only 11 had been in use (none of them on Main Line 2). Another 39 S&Cs have been installed on a new line, but this line has not been in use.

To be able to compare assets with a different technical life length, the LCC-value is divided by the sum of all the NPVFs and is presented as an annuity cost.

Annuity factor =

$$\sum_{t=0}^{t1-1}(1+r)^{-t} = \frac{(1+r)-(1+r)^{-(t1-1)}}{r} \quad (7)$$

9

In Figure 12 the LCC-values for the EV-UIC60-760-1:15, EV-BV50-600-1:15 and EVR-UIC60-760-1:15 are compared. The investment cost for the EV-BV50-600-1:15 is 8% lower and the maintenance cost is higher. The shorter lifetime also affects the annuity value of LCC, so it is 11% higher for the EV-BV50-600-1:15.

The investment cost is 43% higher for the S&C with a movable crossing nose (the EVR-UIC60-760-1:15). In this case the maintenance cost is considerably lower and the technical lifetime longer. The conclusion from this evaluation is that the investment cost is too high to be offset by the lower maintenance cost.
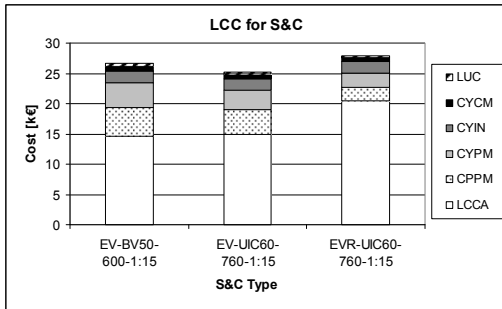
Figure 12 Life cycle cost (annuity cost) for 3 types of S&Cs

3.4 Dependency on traffic volume

The choice of S&C should be the EV-UIC60-760-1:15 according to the example of Figure 12. However, if the boundary condition is dramatically changed, this conclusion may not be correct. For instance, the traffic volume can be higher close to large cities and on heavy haul lines with mostly freight traffic. In Figure 13 the dependency on the traffic volume is shown. For a lower traffic volume it is still best to use the EV-UIC60-760-1:15 S&C, and the EVR-UIC60-760-1:15 should be used when the traffic volume is very high (more than 20 MGT/year).

3.5 Monte Carlo simulation

A Monte Carlo simulation has been performed by building the model in Excel and generating 10,000 individual calculations with a macro. The result has been summarised in histograms. Even

in Excel it is possible to trace the probabilistic cost for individual subsystems, but the need for such a detailed understanding is small.
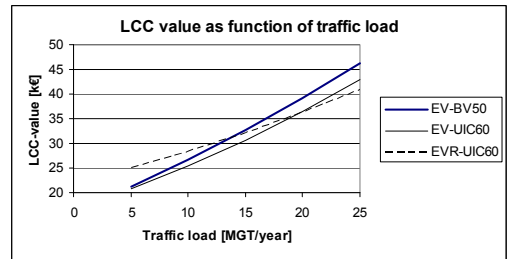
Figure 13 LCC-value as a function of the traffic volume

Figure 14 shows the probabilistic result for the maintenance cost (the annual and periodical preventive and corrective maintenance cost), based on the same model as that used for Figure 12. The solid line represents the result when the base model is used and the dashed line represents the result when the TLT for crossings is changed from 14.1 years to 16.4 years and the total lifetime of the S&C is changed from 35 to 40 years. As the uncertainty for the development of a new crossing material is greater than that for an existing material, the dashed line is based on a two times higher standard deviation in the input data (10% instead of 5%). The result shows that there is no clear benefit for the new material until this uncertainty is clarified.
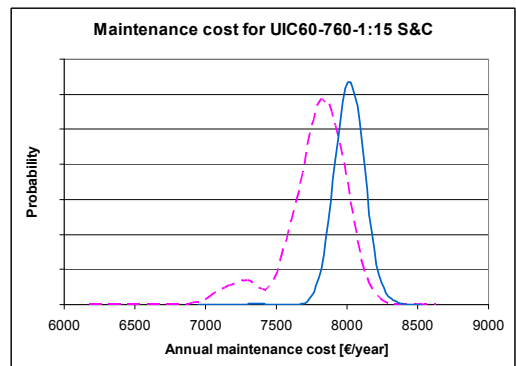
Figure 14 Probabilistic cost for two different designs of a crossing (the TLT is 14.1 years, the solid line, or 16.4 years, the dashed line)

4 DISCUSSION

The LCC-calculation presented in this article is based on the standard IEC 60300-3-3 and has been developed in three fundamental ways.

- The product breakdown structure has been complemented with several types of maintenance actions.
- The preventive maintenance cost is treated either as an annual cost or as a cost recurring at certain intervals.
- The yearly costs are functions of time.

4.1 Maintenance action

The frequency of maintenance needs can be presented as a mean value of all types of actions, equation (7), and the mean man hours can also be calculated, equation (8). Therefore, it is not necessary to have detailed data in the LCC-model. The reason for keeping the details within the model is to enhance the analytical part, both to find the cost drivers and to ensure that the sensitivity analysis can pinpoint the most critical parameters.

$$f_i = \sum_{j=1}^{n} f_{ij} \quad (7)$$

$$MRT_i = \frac{\sum_{j=1}^{n} \langle f_{ij} * MRT_{ij} \rangle}{f_i} \quad (8)$$

4.1.1 Periodical preventive maintenance

Grinding, tamping, welding and renewals of switch blades and crossings are not annual costs, especially if the frequency is low during the first 10 years. Consequently, these costs should be treated when they occur and not as an annual cost. At the end of the technical lifetime, larger replacements are normally not carried out, so in Figure 15 and 16 the parameter of the end period, t_{EP}, is used. This parameter makes the model omit a partial renewal late in the asset's technical lifetime. For this article, t_{EP} has been set to 20% of the TLT of the component.
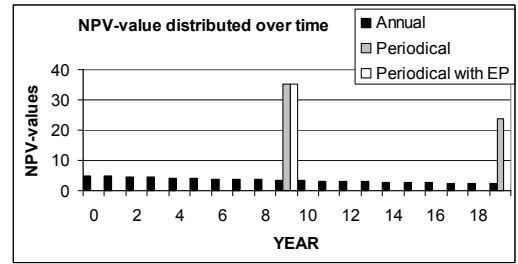
Figure 15 NPV-values of a reinvestment of €50 k calculated in three different ways
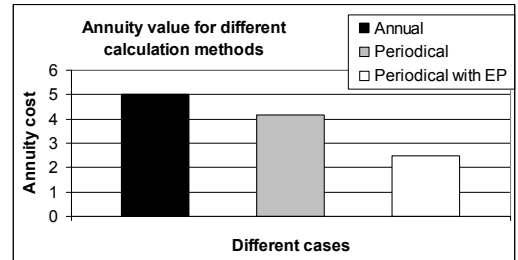
Figure 16 Annuity value for the calculated NPVs in Figure 15

4.2 Validation

The model has so far not been validated by an expert judgement. Instead the model has been compared with cost data from the accounting system Agresso (Nissen 2009B). The model has a reasonable similarity to the cost data for track section 512 and 611, see Figure 17. One input parameter that can be used to adjust short-range planned preventive maintenance and corrective maintenance is the logistic delay time. The number for tamping and grinding is adjusted more to the mean value than to a specific track section.
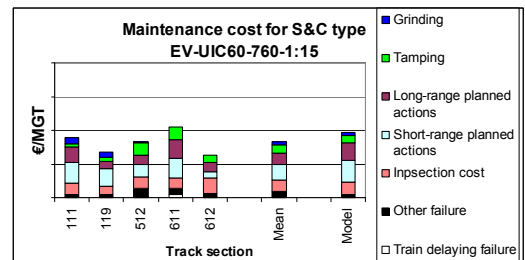

Figure 17 Comparison between cost estimations based on accounting data and the model

4.3 Risk assessment

It is desirable that risk analysis should be undertaken at the same time as the LCC-calculation is made. A solution that is chosen only because it has the best LCC-value cannot be trusted [14]. For the present research, no risk analysis has been performed, as the chosen examples are known S&Cs that are already in use. One example of a known hazard in Sweden is that of a train trying to run over a closed movable crossing nose although it is not trailable, which leads to derailment and high consequential cost.

5 CONCLUSIONS

LCC has proven to be a useful tool both for finding the cost-drivers and for comparing different types of S&Cs. In the analysis, cost-drivers can be found and give an understanding of the parameters that influence the calculation to a great extent. An even better understanding of the costing can be reached by using Monte Carlo simulations.

6 FUTURE WORK

Further studies are needed to investigate whether LCC can be a tool for taking decisions on maintenance strategy and for finding the most important S&Cs to be replaced.

The output and input parameters must be discussed with experts within Banverket to validate the information.

Risk assessment needs to be incorporated with the work of LCC-analysis.

7 ACKNOWLEDGEMENTS

8 REFERENCES

1. Kawauchi, Y.; Rausand, M. (1999). Life Cycle Cost (LCC) Analysis in Oil and Chemical Process Industries, Department of Production and Quality Engineering, Norwegian University of Science and Technology, Trondheim.

2. IEC 60300-3-3 (2004). Dependability Management - Part 3-3: Application Guide - Life Cycle Costing, International Electrotechnical Commission, Geneva.

3. Patra, A.P. (2007). RAMS and LCC in Rail Track Maintenance, Licentiate Thesis, Luleå University and Technology, Luleå

4. Chattopadhyay, Gopy; Kumar, Saurabh (2006). Parameter Estimation for Rail Degradation Model. Proceedings of Condition Monitoring and Diagnostic Engineering Management: COMADEM 2006. Published by COMADEM International, Birmingham, UK

5. Reddy, Venktarami; Chattopadhyay, Gopinath; Larsson-Kråik, Per-Olof; Hargreaves, Doug J. (2007). Modelling and Analysis of Rail Maintenance Cost, Int. J. Production Economics, Vol. 105. Issue 2 pp 475–482

6. Lindqvist, P.-A.; Malmtorp, J.; Stille, H.; Wååk, O. (1999). LCC-analys för Järnvägstunnlar – en Förstudie (LCC-analysis for Railway Tunnels), MC0281, Banverket, Borlänge

7. Boverket (2005). Personsäkerhet i Tunnlar (Safety for Personell in Tunnels), Boverket, Karlskrona

8. Chattopadhyay, G.; Reddy, V.; Larsson, P-O., (2003) Mathematical modelling for optimal rail grinding decisions in maintenance of rails, COMADEM 2003, Porc. 16th International congress, pp. 565-572, Växjö, Sweden, 27-29 August, ISBN 91-7636-376-7, 2003

9. Nissen A. (2005). Analys av Statistik om Spårväxlars Underhållsbehov (Analysis of Maintenance Statistics of Railway Turnouts), Licentiate Thesis 2005:86, Luleå University of Technology, Luleå

10. AAR (1993). Development of a Comprehensive Life-cycle Costing Model for Railroad Turnouts, R-854, Association of American Railroads, Washington

11. BVH 800 (2007), Vägledning till Banverkets underhållsstrategi (Guidance for the maintenance strategy of Banverket), Handbook, Banverket, Borlänge

12. Wååk, O. (1992). LCC, ett Beslutsverktyg som Ger Effektivare Tekniska Utrustningar med Lägre Totalkostnad (LCC, a Decision Tool that Leads to More Effective Technical Assets and Lower Total Cost), Luleå University of Technology. Luleå

13. Nissen, A. (2009). RAM-analysis of Switches and Crossings for the Swedish Railway – a Case Study, sent to IJPE for publication

14. Emblemsvåg, J. (2003). Life-cycle Costing Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks, John Wiley & Sons, Hoboken, New Jersey

15. Nissen, A. (2009). Classification and Costing of Switches and Crossings for the Swedish Railway – a Case Study, sent to JQME, special issue on condition monitoring and IC-application, for publication

Journal Paper 4

Condition Monitoring of Railway Switches and Crossing by using Data from Track Recording Cars

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ABSTRACT

Switches and crossings are vital components within the railway system and contribute to many of the maintenance activities needed to keep the track section available for traffic. Banverket administers about 12 000 switches. Switches and Crossings (S&Cs) contribute to about 13 % of the maintenance budget for Banverket. The age of the S&Cs in main track is on average more than 20 years and therefore in the reinvestment plan, it is necessary to calculate for more than 200 new S&Cs per year. Today, it is not possible to make a decision based on track recording data. The track recording car is measuring the level, alignment, cant, curvature and gauge. For level and alignment, the signal is recorded in three different wavelengths. Banverket has started to use this information in digital form and today it is possible to make more detailed study and investigation. In this study, all analysis has been made by Excel, This work has been a first step to integrate condition monitoring of S&Cs into the data management system for track recording data in Sweden. The program was introduced during 2009 for identifying S&Cs. The track recording car should be able to provide the alignment signal through the S&C for its health condition, so that appropriate repair/replacement decision can be made..

Keywords: Switches and crossings, Track Recording Car, Condition Monitoring, Railway

Glossary: S&Cs - Switches and crossings

1   INTRODUCTION

Banverket is the Swedish administrator of the Swedish railway network. Sweden has 12 000 km of track and about 12 000 switches and crossings. Track condition monitoring is performed 4-6 times a year. Switches and Crossings (S&Cs) contribute to about 13 % [1] of the maintenance budget for Banverket. The age of the S&Cs in main track is on average more than 20 years and therefore in the reinvestment plan, it is necessary to calculate for more than 200 new S&C's per year. The information form track recording cars for S&Cs is barely used, while the only available information has been in paper sheet format so far. A new program introduced in 2009 makes it possible to treat the data in digital format. In general track recording car information can be used for decisions about tamping and ballast cleaning [2].

2   SWITCHES AND CROSSINGS

Switches and Crossings (S&Cs) are a vital subsystem in the railway system that allows traffic to change track. An S&C consists of three major parts: switch panel, closure panel and crossing panel. The switch panel is the movable part, consisting of switch blade, bars, switch device and control device. In this area there is a transition from stock rail to the switch blade. The closure panel connects the switch blade with the crossing. The crossing panel has a crossing nose, wing rails and check rails, all of which should be able to withstand the high forces that occur when the wheel is transferring from one rail to the next at the crossing nose.

2.1   Condition monitoring of switches and crossings

Normally, condition monitoring is a term, used for a support system that can measure special features of a system such as temperature, vibration, current and then give a an alarm when a predetermined limit is reached. Condition monitoring is applicable for a system that has a gradual deterioration with time [3]. In railway, there are three distinct types of systems [4]:

- Event loggers
- Condition monitoring systems
- Fault detection and diagnosis systems

Besides this, visual inspection is used for condition monitoring. For S&Cs scientific papers has been written on condition monitoring of the driving and locking devices [4,5] and not much research work has been done to study the data from the track recording cars for S&Cs.

3   PROBLEM

S&Cs contribute to about 13 % of the maintenance budget for Banverket [1]. The age of the S&Cs in main track is on average more than 20 years, and therefore in the reinvestment plan, it is necessary to calculate for more than 200 new S&Cs per year. The decision to replace an S&C is based on experience and judgment of information from past inspections, or because there is a need for renewal of a station area [6]. Today it is not possible to make a correct decision based on track recording data. This article is exploring the use of this type of data.

4   STUDIES ON SHORT WAVES IRREGULARITIES

Recordings from track recording cars or axle box accelerometers have been studied to find short wave irregularities by several authors. Bona [7] has tested to find weld irregularities by using data from track recording cars and found that track irregularities only sometimes were corresponding to misaligned welds. Li [8] has discussed a new index for standard deviation to evaluate the track geometry before and after maintenance work. Li [9] proposed the use of accelerometers mounted on axle boxes to find irregularities such as poor welds, squats and bad levelled insulated rail joints. Liu [10] have used a wavelet and empirical mode decomposition method and filtered the signal down to 1 m to find short wave irregularities. Esveld [11] has written about the examination of different wavebands to find specific phenomena. He recommended the use axle box acceleration measurements to find phenomena shorter than 2 meters. He also showed the usage of cumulative distribution of the change of standard deviation over time used by the Netherlands Railway. Berggren [12] analysed longitudinal level by filtering out only short-waved irregularities from track recording cars data. He wrote it is possible to indicate problems with hanging sleepers, variable sleeper support and other short-waved irregularities.

5   DATA COLLECTION

5.1   Selected data

Track recording data has been analysed for three selected main routes. The number of S&Cs on these routes is shown in Table 1. The track recording car measures level, alignment, cant, curvature and gauge. (Banverket BVS) For level and alignment, the signal is recorded in three different wavelengths. Banverket has started to use this information in digital form, and therefore it is possible to obtain more detailed information. In this study all analysis has been made by Excel, but the intention is to implement

the result in the analytic tool that Banverket has started to use.

For each S&C on the main route, track recording for a length of 400 m has been saved. In total 4-5 measurements/year has been used during 3½ years. That gives the possibility to compare 14-18 recordings. A recording of the level signal is shown in Figure 2. To be able to identify where the S&C starts and ends in the recording it is necessary to filter the signal, this is not done in Figure 2.

Only the level and alignment signal has been analysed and some of the other information has been used. The following data has been stored:
- Level (wavelength 1-25 m)
- Alignment (wavelength 1-25 m)
- Curvature (k/Radius), k being a constant

- Speed
- Track type (Single track, Up or Down track on double track)

5.2 Filtering

To be able to compare two recordings it is essential to identify the position of the S&C within 0.5 m. This is possible by finding the crossing in a filtered signal. A Butterworth 4-pole filter, which is a high pass filter, based on equation (1) and (2) has been used. This type of filtering has been used to find failures in the track structure such as bad joints and dancing sleepers [12]. The signal is filtered both upstream and downstream. This was necessary to keep the lateral position of the crossing; otherwise the lateral deviation will depend on wave form close to the crossing. Figure 3 shows the result after filtering.

$$u_i = \sum_{j=0}^{4} b_j * x_{i-j} \qquad (1)$$

$$v_i = u_i - \sum_{j=1}^{4} a_j * v_{i-j} \qquad (2)$$

where
u_i – miscellaneous vector
a_j, b_j – Coefficients depending on filter wavelength

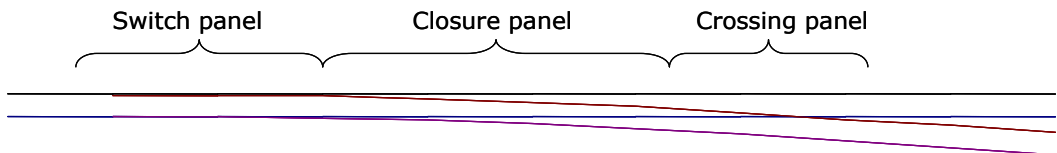x_{i-j} – input vector
v_i – Output vector

Figure 1: An S&C divided into 3 panels

Table 1: Number of different types of S&Cs on the main track lines

EV= Single S&C, DKV=Double crossing S&C

S&C Type	Abbreviation Used in figures	Main track Route number			
		1	2	7	Sum
DKV-SJ50-7,641/9,375-1:9	D-SJ50 R190	8	15		23
EV-BV50-300-1:9	SJ50 R300X	5	1		6
EV-SJ50-11-1:9	SJ50 R225	46	89	8	143
EV-SJ50-12-1:15	SJ50 R600	105	85	6	196
EV-SJ50-300-1:9	SJ50 R300	12	1		13
EV-UIC60-1200-1:18,5	UIC60 R1200	25	25		50

EV-UIC60-1200-1:18,5 BL33	UIC60 R1200X	13	82		95
EV-UIC60-300-1:9	UIC60 R300	74	34	17	125
EV-UIC60-760-1:14	UIC60 R760X	9	6	3	18
EV-UIC60-760-1:15	UIC60 R760	157	73	6	236
Other types		39	60	3	102
Sum		493	471	43	1 007

In **Figure 3** the position of the S&C is identified automatically. The position of the beginning of the switch blade, crossing and end of crossing joint is shown as dotted lines. The crossing is found as the lowest point in the graph
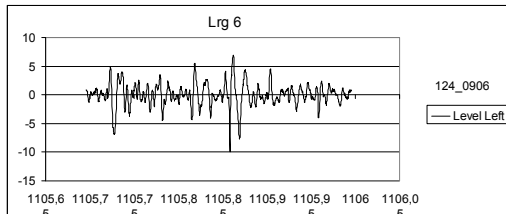
Figure 2: Level signal for S&C Lrg 6 (Laduberg number 6) on track section 124. Left wheel is passing the crossing. Measurement August 2009.

To establish a condition, standard deviation is calculated for the switch panel, crossing and after the crossing. So far, it is a length of 32.5m for switch panel after the crossing (long sleepers) and 5.0 m for the crossing has been used. Solid horizontal lines in **Figure 3** show these values. The information can be shown in a time graph,
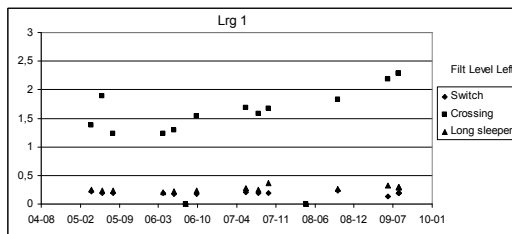
Figure 4: Filtered level signal for S&C Lrg 1 (Laduberg number 1) on track section 124. Standard deviation for level signal (left wheel) in three different parts of the S&C during 2005 – 2009.

6   RESULT

In total, over 500 S&Cs have been scanned by this method. About 150 S&Cs have been analysed so far, and although some patterns have

and the distance to the expected position is calculated. If the crossing is outside a range of 25 m from the expected position the program cannot identify the correct position, so manual identification is needed.
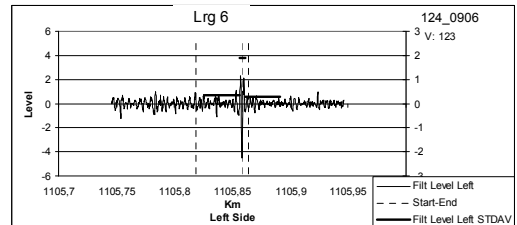

Figure 3: Filtered level signal for S&C Lrg 6 (Laduberg number 6) on track section 124. Only left wheel passing the crossing is shown. Measurement made in August 2009. Dotted line marks the start, crossing and end of the S&C

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as seen in **Figure 4**. In total 4 graphs is made for both rails and for the alignment and level signal.

One standard deviation for level and one standard deviation for the alignment is calculated for each wheel and presented in **Figure 5**. This characterises the S&C and can be used in comparison with other S&Cs.
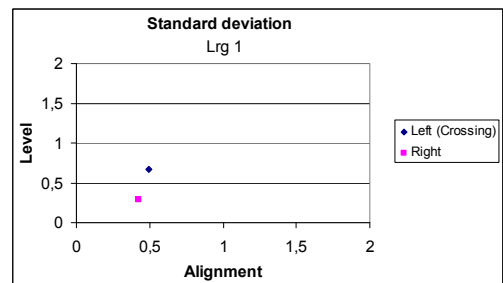

Figure 5: Condition measurement of left and right wheel for LRG 1. Diamond symbol is used for the wheel passing the crossing. Box symbol is used for the other wheel.

been identified, more research is needed before a standardised method can be established. The signal of the crossing has been clear in nearly all cases studied.

Normally, the level signal is very stable over time, as shown in figure 6. The alignment signal on many measurements is disturbed because of the transitions in the lateral direction. The lateral position is measured by a laser beam in combination with the accelerometer and even one missing measurement gives an unpredictable

result. The system automatically erases about 25 m of the recording when this happens. Whether it is possible to use an incomplete signal or not has to be decided. The idea is to compare part of the recording, where the signal normally is not erased
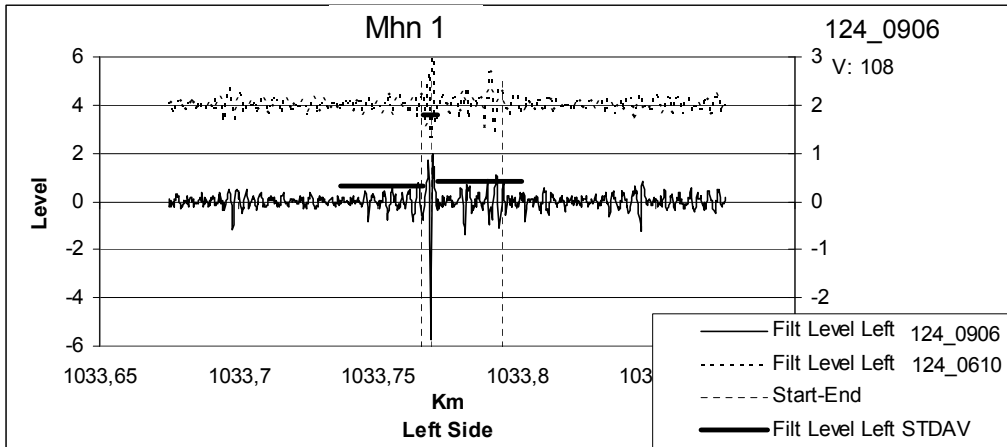
Figure 6: Filtered level signal for S&C Mhn 1 (Myrheden number 1) on track section 124. Only left wheel passing the crossing is shown. Measurements made in April 2005 and August 2009. Dotted line marks the start, crossing and end of the S&C. Close to the switch blade there is a change in the recording comparing 2006 with 2009. The other part seems to be in the same order in 2009 as 2006.

To compare S&Cs in an area, the average value for level and alignment can be calculated. For the alignment signal the erased portion is not used, and therefore, the calculation may not be perfect. In **Figure 7** and **Figure 8** alignment is compared between two types of S&C. For the

stock rail in particular, the alignment in the UIC60-300-1:9 type of S&C seems to be not as good as the alignment in the UIC60-760-1:15 S&C. This result is not final, but the same trend has been seen in several track sections.
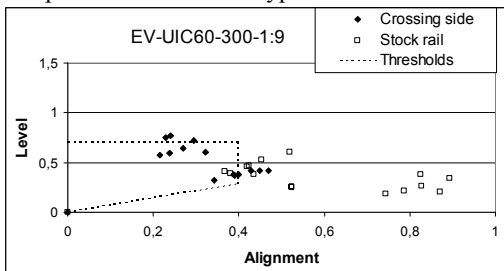

Figure 7: Average of level and alignment for all UIC60-300-1:9 S&Cs on track section 124
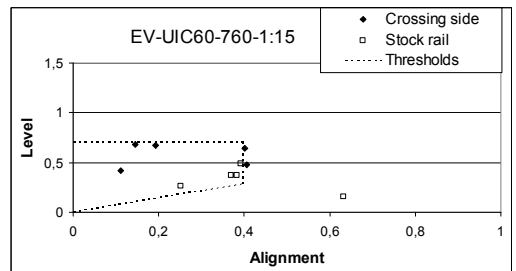

Figure 8: Average of level and alignment for all UIC60-760-1:15 S&Cs on track section 124

6.1 Cumulative distribution of the signal

Normally, standard deviation is measured for a distance of 200m. For S&Cs which are in the order of 30-50m in length, the normal way of calculating the standard deviation cannot be used. To use just one standard deviation value for the whole length of the S&C is not to be recommended, as only a few large values will give a high standard deviation, even if most of the S&Cs have a smooth signal. A way to manage these problems has been to use many standard deviation values calculated by only 10 measurements each (2.5 m). Then these values are plotted as cumulative diagram. In Figure 9 the plot shows two different measurements where the difference can be measured by calculating the cumulative index for a certain standard deviation (3 mm). This value can be trended over time as a quality index, see **Figure 10**.

Tamping or renewal can be correlated with shift in the curve, which confirms this can be a way of following the trends over time. More work is needed to establish the method.
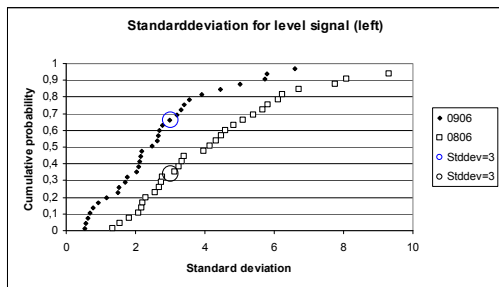
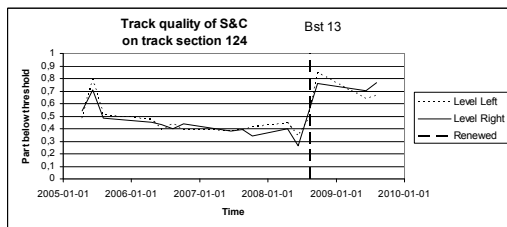**Figure 9** Cumulative plot standard deviation of the level signal

Figure 10 Track quality index over time showing correlation with renewal or performed tamping

7 CONCLUSIONS

This work has been carried out on the data from the track measurement car in Sweden. The data has proved that it is possible to identify the position of a single turnout automatically. Filtering of the level signal to 0.5 – 5 m is necessary to find the crossing of the S&C. The filtered signal is used to compare an S&C with other S&Cs in the same track section. There seems to be a difference between types of S&Cs. A non-filtered signal has been used to calculate a quality index. For example, this index can be used to make decisions regarding tamping intervals.

8 FUTURE WORK

This work has been a first step towards integrating condition monitoring of S&Cs into the data management system for track recording data in Sweden. The programme was introduced in 2009, and development for identifying S&Cs and following their trends is planned to be done in 2010.

The track recording car should be able to give an alignment signal through the whole S&C. This is not the case now and will need modification in how the signal is treated.

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9 REFERENCES

1. Veit, P. (2007), Track Quality – Luxury or Necessity?**,** *RTR Special 2007*, ISBN 978-3-7771-0367-9, Eurailpress, Hamburg, Germany

2. Nissen, A. (2005), *Analys av Statistik om Spårväxlars Underhållsbehov* (*Reliability Analysis of Maintenance Statistics of Railway Turnouts*)*,* Licentiate Thesis, Luleå

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University of Technology, ISSN:1402-1757; 2005:86, Luleå University of Technology, Luleå.

3. Parida, A. (2008), Relevant Health Monitoring based Maintenance for an Effective Strategic Engineering Asset Management, *Comadem 2008*, 21th International Congress, Prague, ISBN: 978-80-254-2276-2, pp 377-384

4. Roberts C. and J. Chen (2006), Railway Condition Monitoring, *Comadem 2006*,19th International Congress, Luleå, ISBN: 978-91-631-8806

5. Márquez, F.P.G., Schmid F., Collado J.C. (2003), "A reliability centred approach to remote condition monitoring: A railway points case study**,** *Reliability Engineering and System Safety*, **80** (1), pp. 33-40

6. Hedström, R. (2001), *Kriterier för byte alternativt fortsatt underhåll av spårväxlar*, (*Decision criteria for replacement or continued maintenance of switches and crossings*), VTI notat-20-2001, Väg och transportforskningsinstitutet, Linköping, Sweden

7. Bona, M. E. (2005) *The effect of straightening and grinding of welds on track roughness,* Doctoral Thesis 16180, Queensland University of Technology, 2005, Brisbane

8. Li, H., Xu, Y., Wang, J. (2009), Track geometry equality index and its application*, Tongji Daxue Xuebao/Journal of Tongji University,* **37** (4), pp. 495-499

9. Li, Z., Moldova, M. and Dollevoet, R. (2009). Detectability of isolated short wave rail surface defects by way of axle box acceleration, *21st International Symposium on Dynamics of Vehicles on Roads and Tracks*, 2009, 17-21 August, KTH, Stockholm, Sweden

10. Liu, X.-B. (2006), Method for picking up rail wavy irregularities based on empirical mode decomposition method, *Zhongguo Tiedao Kexue/China Railway Science*, 2006 **27** (2), pp. 26-30

11. Esveld, C. (2001). *Modern Railway Track*, ISBN 90-800324-3-3, MRT Production, Zaltbommel, The Netherlands

12. Berggren, E. (2006), Measurements of Track Stiffness and Track Irregularities to Detect Short Waved Support Conditions**,** *Proceedings of International Conference on Railway Track Foundations*, Birmingham, 11-13 September, 2006