Condition Based Maintenance on Rail Vehicles
– Possibilities for a more effective maintenance strategy

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Abstract
Today, the Swedish industry is budgeting billions in maintenance related costs on a yearly basis. The high costs come from productivity losses due to low availability. With condition based maintenance the maintenance intervals will be a lot more dynamic and no actions will be done unnecessarily. Sensor technology makes it possible to monitor an assets most important components. Different Artificial Intelligence techniques make it possible to analyze the measured data. With process knowledge of the monitored asset the analysis will show whether maintenance actions need to be performed or not. The condition based maintenance approach has been tried successfully on different engineering industries; now, the time has come to rail vehicles.

Keywords: Condition based maintenance; rail vehicle; standards

Introduction
There is a need for a change in maintenance execution. Today, most maintenance actions are carried out in either time- or distance based intervals or by the run-to-failure technique. The preventive maintenance, with its intervals, is often guided by sub-contractors or operation experience. With the technique one tries to prevent components, sub-systems or systems to degrade to the degree of breakdown. This is done by reparations, service or component exchange in preset intervals. With the run-to-failure technique one instead let the component, sub-system or system, run until breakdown or obvious fault occurs before maintenance action is taking into account.

On a yearly basis, the Swedish industry budgets up to 200 billions (SEK) in maintenance related costs and have of course a lot to gain by performing maintenance more effectively. There are a few concepts and techniques how to do this, this paper will present the condition based maintenance approach. With condition based maintenance (CBM) one measure an assets condition and estimate the needed maintenance by the results. By vibration measurement, oil analysis, measurements of harmful currents/voltages etc. one can, before an asset irrevocably have taken damage, stop the process and execute maintenance. This procedure will lead to a more dynamic maintenance interval. One will, with a large chance, be able to prolong the intervals and the breakdowns will, to some degree, be eliminated. With a well implemented condition based maintenance system a company can save as much as 20% in decreased stock in spare parts, decreased loss in production, decreased loss in quality flaws etc.

This paper is a literature overview within the CBM community. It will in short words explain the CBM technique; the tools and standards needed for a successful implementation. It will also present a concept and two case studies on how the technique can be implemented on rail vehicles. Sensors and other sophisticated sensing hardware, which are needed in the application, are beyond the scope of this paper.

Condition Monitoring
Condition monitoring has always, to some extent, been used. Years back, the monitoring of an asset was made by the operator. They often worked close to the same machine for a long time and they could very quickly with help from the five senses; sight, hearing, smell, taste and feeling, sense if something was going wrong with the process. With more complex machinery monitoring equipment has been built in and the process variables have been presented for the operator. Today, most workers

don't work close to the same machine years in and out, and the knowledge of the process of a machine is going lost. An automated condition monitoring system is needed; a system that in adequate time can alert incipient faults. An automated condition monitoring system also gives a better and faster result. This will result in a decreased life cycle cost (LCC), increased availability and decreased operations and maintenance cost (Grimmelius, 1999). According to Johansson (1993) an automated condition monitoring system must fulfill following demands.

- Real time applications
- High reliability
- At early stages alert where faults is impending
- Classifications of alerts
- The alerts must be easy to understand
- The system must be connected to a superior computer
- For humans and equipment dangerous fault, automated shut down process

To accomplish such a system Thurston & Lebold (2001) lists seven layers as a standardization proposal in CBM architecture (more to read under the standard section of this paper).

- Sensor module
- Signal processing
- Condition monitor
- Health assessment
- Prognostics
- Decision support
- Presentation (human interface)

When condition monitoring, the key variables that have relations to an assets condition are measured. These variables levels will give indications to the condition of an asset. Johansson (1993) gives a number of examples of measurable variables, the list could be made longer, with today's sensor technology, it is pretty much ones imagination that sets the limit.

Measurements of vibrations: Vibration alone is probably one of the most effective parameter to monitor. Portable monitoring system is widely used in the industry. There are several different techniques to measure vibration; shock pulse measurement (SPM), envelope technique, g-method, acoustic emission etc.

Measurement of speed of rotation: A stroboscope or electrical counters could be used for this application. Fixed, to the machine shaft, mechanical sensors could be used for the same purpose.

Measurement of sound: With vibration there is acoustics. To measure the acoustic levels, with e.g. an electromagnetic microphone, can be an effective mean of detecting vibration.

Measurement of temperature: An increase in temperature in an asset will tell of an increased friction. This can be measured by thermistors or other temperature sensors. A relatively simple and cheap technique of measuring temperature is to paint some heat sensitive paint to an asset, if the temperature exceeds the normal level the color of the paint shifts.

Oil analysis: By measuring the compound in the lubrication in e.g. bearings and gears one can see if there exists too much wear or contamination.

Condition Based Maintenance

In the condition based maintenance (CBM) technique one take the condition monitoring results in account and plan the maintenance action by it. The purpose of CBM is to eliminate the breakdowns (see figure 1) and prolong the preventive maintenance intervals (see figure 2). With this an increase of availability of an asset will follow. With CBM technique one wants to analyze the condition monitoring data deep enough to be able to say whether the asset is running at a normal operation condition or not. If the preset limits for normal condition exceeds, one also wants to know the reasons behind it and how long before a fatal breakdown will occur. With this information it will be easier to plan the maintenance actions more effectively. Ahlmann (2002) mean that with a more effective maintenance execution and an increase of availability, Swedish industry can save up to as much as 20% in non-realized revenue, e.g. due to loss of productivity when non-effective maintenance is carried out.

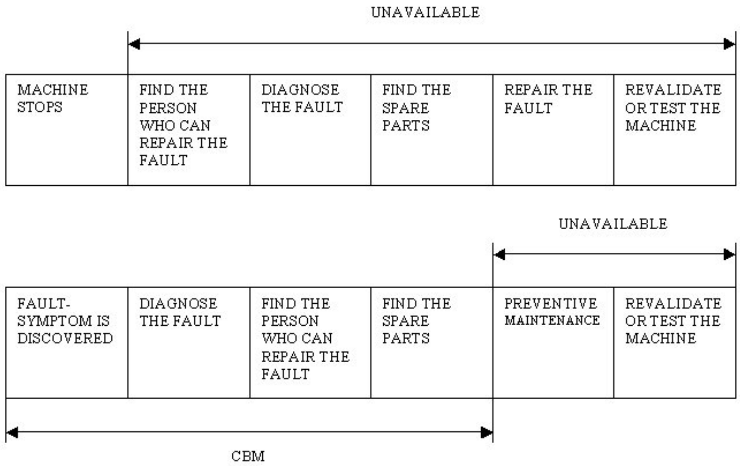

Figure 1: Differences in run-to-failure technique and CBM.

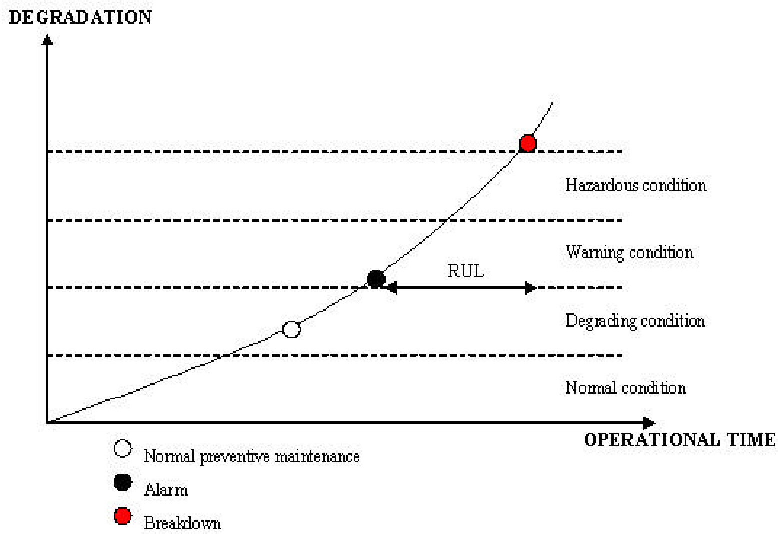

Figure 2: The normal preventive maintenance is often carried out before the component, sub-system or system is showing any signs of fault. With the CBM technique one often say "If it ain't broke, don't fix it". RUL is an abbreviation of Remaining Useful Life.

For a completely automated CBM system, with the ability to diagnose an abnormality and calculate the remaining useful life (RUL), new analysis techniques, with Artificial Intelligence (AI), will be a necessity. AI, such as Neural Networks, Case Based Reasoning and Fuzzy Logic etc. are excellent tools for quick analysis. AI techniques are also good at handling large amounts of data, pattern recognizing, complex non-linear data etc. Fenton (2001) presents an overall view of different AI techniques, Jain et.al. (1996) gives a tutorial in Neural Networks.

Prototypes and case studies

There are numerous papers written on system development in CBM technique, here will only follow a few examples. Rao et.al. (2000) presents two field trials with a CBM system called INTEMOR (INTElligent Multimedia system for On-line Real-time application). The system that was built on a combination of Neural Network and expert system techniques were successfully applied on a steam boiler and in a pulp and paper plant. Hu et.al. (2001) presents a system, built with similar software that also has worked successful in a field try. The system has monitored a process machine since 1997 and has so far worked unquestionably. Shukla & Chen (2001) gives a detailed explanation on how one can train an intelligent system, here, monitoring a FMS (Flexible Manufacturing System). In this case they train through simulated data and it proved to have a good effect. Hadden et.al. (2000) presents a monitoring system for naval ships that can integrate acoustic signals, vibration signals and oil analysis while taking account to historic data. The application of the system is to give feedback to operators on the conditions of the machines; it is called SHM (System Health Management) and is built on a combination of Fuzzy Logic and expert system. Yam et.al. (2001) presents a CBM system with a Recurrent Neural Network approach. The technique actually includes predictions on the condition one step into the future. Yam et.al. calls the system IPDSS (Intelligent Predictive Decision Support System).

Standardization of CBM systems

Below, a standard for smart transducer interface for sensors and actuators (IEEE 1451), a standardization proposal in CBM architecture (OSA-CBM) and a standardization proposal in communication between different CBM modules (MIMOSA) will be presented. With these standards the CBM community would achieve interchangeable hardware and software components, more technological choices for users, more rapid technology development, reduced prices and improved ease of upgrading of system components. When developers in CBM technique start to follow standard and standard proposals it will be easier to direct the development towards algorithms and new ways of predicting remaining useful life.

IEEE 1451

At the basic level of condition based maintenance there is sensors or other devices to pick up the data needed for analysing the health of an asset. This is often referred to as a distributed measurement and control system (DMC). Due to the customers problem of integrating different vendor products (transducer, sensors and actuators) when networking, a standard for the hardware interconnection level is needed. But there is also need for standards in the software module of the transducers to achieve network interoperability at the network-node level. The developing and using industries of DMC systems are moving away from proprietary standards in hardware and software towards de facto standardized open systems approaches (Lee & Schneeman, 2000).

Looking to develop a standardized interface to network smart sensors, the National Institute of Standards and Technology (NIST) started to work together with the Institute of Electrical and Electronics Engineers (IEEE) in the middle of the 1990's. To achieve easy installation and upgrading of sensors one should link them together like personal computers via a local area network (LAN). Through this connection one will be able to connect many sensors via a single cable or bus. This will mean that sensors can be detached without affecting other sensor nodes (Gilsinn & Lee, 2001).

The IEEE 1451 standards for smart transducer interface for sensors and actuators purpose is to achieve common interfaces for connecting transducers to microprocessor-based systems, instruments and field networks in a network-independent fashion. The IEEE 1451-standard is divided into four sub-standards. For more information of the standards IEEE 1451.1 and IEEE 1451.2 see Lee (2000). For the two proposed standards; IEEE P1451.3 see Baruah & Eccles (2001) and IEEE P1451.4 see Potter (2001).

OSA-CBM

OSA-CBM is an abbreviation for Open System Architecture for Condition Based Maintenance and is a proposal for a de facto non-proprietary standard. In the mission statement from the OSA-CBM organization (www.osacbm.org) it is declared that the standard proposal shall cover the whole range of functions of a CBM system, for both hardware and software components. The benefits of such a standard would according to the organization be:

- Improved ease of upgrading for system components
- A broader supplier community
- More rapid technology development
- Reduced prices

The OSA-CBM proposed standard divides a CBM system into seven different layers (Thurston & Lebold, 2001), all interconnected (see figure 3).

Layer 1 Sensor Module: The sensor module provides the CBM system with digitized sensor or transducer data. The signal module could be built on the IEEE 1451 standard.

Layer 2 Signal Processing: The signal processing module receives signals and data from the sensor module or other signal processing modules. The output from the signal processing module includes digitally filtered sensor data, frequency spectra, virtual sensor signals and other CBM features. The signal processing module could consist of AI-ESTATE (Artificial Intelligence and Expert System Tie to Automatic Test Equipment), the IEEE 1232 standard, for more information see Ghoshal & Deb, (2001).

Layer 3 Condition Monitor: The condition monitor receives data from the sensor modules, the signal processing modules and other condition monitors. Its primary focus is to compare data with expected values (e.g. normal vibration, high vibration, hazardous vibration). The condition monitor should also be able to generate alerts based on preset operational limits. This can be a very useful function for fast fault developments.

Layer 4 Health Assessment: The health assessment module receives data from different condition monitors or from other health assessment modules. The primary focus of the health assessment module is to prescribe if the health in the monitored component, sub-system or system has degraded. The health assessment module should be able to generate diagnostic records and propose fault possibilities. The diagnosing should be based upon trends in the health history, operational status and loading and maintenance history.

Layer 5 Prognostics: The prognostic module should have the possibility to take account into data from all the prior layers. The primary focus of the prognostic module is to calculate the future health of an asset, with account taken to the future usage profiles. The module should report the future health status of a specified time or the remaining useful life (RUL).

Layer 6 Decision Support: The decision support module receives data from the health assessment module and the prognostic module. Its primary focus is to generate recommended actions and alternatives. The actions can be of the maintenance sort but also how to run the asset until the current mission is completed without occurrence of breakdown.

Layer 7 Presentation: The presentation module should present data from all previous modules. The most important layers to present would of course be the data from the health assessment, prognostic and decision support modules as well as alerts generated from the condition monitors. But the ability to lock even further down in the layer should be a possibility. The presentation module could be built in into a regular machine interface.

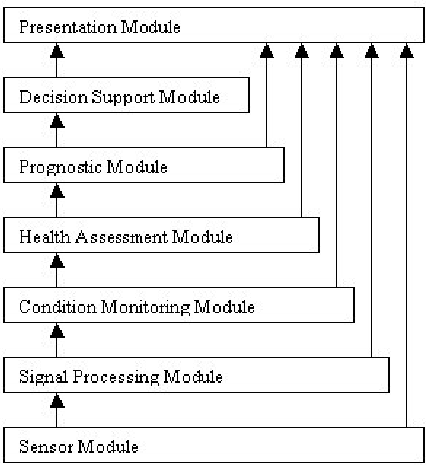

Figure 3: The seven layers in OSA-CBM standard proposal.

MIMOSA
The Machinery Information Management Open System Alliance, MIMOSA, was founded in 1994 and introduced in the September issue 1995 of Sound and Vibration. In December 1996 the non-for-profit organization was incorporated. MIMOSA's purpose and goal is to develop open conventions for information exchange between plant and machinery maintenance information systems. The development of MIMOSA CRIS (Common Relational Information Schema) has been openly published at their website (www.mimosa.org). The CRIS provides coverage of the information (data) that will be managed within a CBM system; this is done by a relational database schema for machinery maintenance information. Thurston & Lebold (2001) lists the typical information that will need to be handled:

- A description of the configuration of the system being monitored
- A list of specific assets being tracked
- A description of a systems functions, failure modes and failure mode effects
- A record of logged operational events
- A description of the monitoring system and characteristics of the monitoring components
- A record of sensor data
- Resources of describing signal processing algorithms and resulting output data
- A record of alarm limits and triggered alarms
- Resources of describing degradation in a system as well as prognostics of system health trends
- A record of recommended actions
- A record of work request, from start to finish

Integration of the above standards and standard proposals
In order to achieve all benefits from the above standard and standard proposals Lee et.al. (2001) carefully examined the three standards, looking for entry points or hooks that could provide a link. After analysis it was concluded that it would be feasible to establish such a link and let the standards work together.

CBM on rail vehicles
A certain amount of difficulties must be circumvented when applying the condition based maintenance technique on a moving system, such as a rail vehicle. Compared to an ordinary engineering industry, the degradation and maintenance will be connected to the geographical location. In an engineering industry, the analysis and diagnosing can take place in a stationary system, using real time data from the machinery. In the rail industry this data must be sent to a maintenance centre (see figure 4). There exist a few alternatives how to do this. One alternative is to look at the rail vehicle as a machine, and let the analysis and diagnosing take place on board, were only refined information of the condition leaves the vehicle. Another is to collect real time data at the vehicle and let the analysis and diagnosing take place at a maintenance centre, this means that a large amount of data must be transmitted to a central database. This transmit could either use GSM technique or wirelessly at train stations (Bluetooth, infrared etc.).

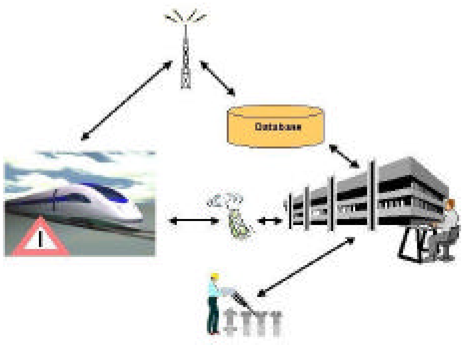

Figure 4: The communications between the rail vehicle, maintenance centre and service centre.

Main layers in the on rail vehicle CBM system
For an easy explanation how a whole CBM system, from the sensors that measures data to the maintenance centre who writes work orders, could work, one can divide it into different layers.

Sensor Module: To monitor the condition of a rail vehicle the use of sensors will be inevitable, but we can also see the immense value of monitoring the control and communication system, as well as using a global positioning system (GPS). The sensors will collect data from chosen components, sub-systems and systems, which most likely will be monitored by trend. The control and communication system, which is the "backbone" of the vehicle, will be monitored in the same purpose. The GPS will always tell the exact position of the vehicle, which renders the possibility to tie a fault to a geographical location. This enables identification of fault symptoms that are related to outer circumstances.

Today, micro system has made it possible to transfer digitally filtered signals directly from the sensors. The research and development within the sensor industry is strong and only time will tell how intelligent the sensors can get. Development in the technology shows that it will be possible to even put trend monitoring equipment in the sensors. This would of course decrease the communications between the different layers.

The communication between the sensors and data collectors should for practical and financial reasons be wireless, the cabling cost can average from $60 to $6000 per meter (Brooks, 2001). It can also, if necessary, be out of two-way communication, for calibration and gradation purposes.

Intelligent system: No matter where one chooses to perform analysis of the measured data, there will be a large need for knew advanced technique. To process all the information coming from the monitored components, sub-systems or systems there needs to be software capable of handling complex (non-linear) relations and from normal operation deviating trends. The technique that makes this a possibility is Artificial Intelligence (AI), a technique that has been developed during a number of decades. Neural Networks, Fuzzy Logics, Case Based Reasoning and Expert Systems, just to mention a few, are today existing methods that could work for this type of application (for more information see Fenton, 2001). Which method to use for diagnosing the condition and predict the remaining useful life depends on what's being monitored and how the monitoring is done. For the prediction of remaining useful life; algorithms, historic data, historic condition, mission history, failure history, maintenance history, model information and spare assets must be taken into account (for more information see Lebold & Thurston, 2001). The intelligent system should be programmed and have the functions to answer the following questions:

- Where does fault symptom exist (what component, sub-system or system)
- The cause of the failure symptom
- How long before breakdown or irreversible fault
- The consequent of component, sub-system or system failure
- Recommended maintenance action

To process all data that can be measured from a rail vehicle will demand powerful software, but it would be a mistake to completely remove the human as a factor in maintenance planning. A large amount of information of a vehicles condition can and will always be found within the service personnel and operators that have a day-to-day contact with the asset.

Human interface on rail vehicle: On the rail vehicle all information that is necessary for safety reasons should be presented to the operator. To some extent, this means that the operator can change hers or his driving routines, e.g. prolong breaking distance, to mitigate incipient faults diagnosed by the intelligent system.

Maintenance centre: In charge of maintenance planning of the vehicles the maintenance centre will probably work with some sort of planning software (e.g. Maximo). The centre should have access to all the measured data and of course all the refined information. With the information from the intelligent system as well as service and operators fault reports the maintenance planner will work out the best possible preventive maintenance schedule and work orders for a whole fleet of vehicles. After any maintenance actions have been executed a feedback-loop to the intelligent system should be made for evaluation purposes.

On board – off board

Compared to an engineering industry, a rail vehicle must have a system divided into one on board and one off board location. On the vehicles there will be placed sensors and other measuring equipment, one or more temporary databases and in some cases condition monitors (comparing the real time data with historic for faults with fast development). The analysis and prediction functions will most likely be place off board in the maintenance centre. The technique of transferring large amount of real time data is today not longer an immoderate problem and with this concept the cost of computer power on the rail vehicle can be kept lower.

Possibilities with a CBM system on rail vehicles

Rail vehicles are such large and complex system so it would be impossible to monitor every component. This means that one have to focus its attentions on what to measure. Safety critical functions (for both operation and human) are already today a lot of the times monitored and should of course always be. But the large incentives of implementation of CBM technique is the savings in increased process availability and more effectively preventive maintenance execution. When deciding what to monitor one should look on process critical functions and maintenance actions that is carried out non-effectively. The list of possible functions and components to monitor could be made long, here follows a few:

- Harmful currents/voltages
- Flat wheel detection
- Brakes
- Door systems
- Wheel bearings
- Filters
- Water and air pressure
- Rotating parts
- Derailment

Implementation of a CBM system

The key word for a successful implementation of a CBM system on rail vehicles is probably long term planning. Long before making reality of the monitoring and analysis of the process one has to be very clear of what is being monitored and how this is being done. To really start making money of the new way of planning the maintenance actions one also has to look over the way maintenance is planned today. All that is not working according to the original plan needs to be fixed before any major changes is being done.

On a rail vehicle or other large systems another keyword is probably small scale. To believe that every failure possibility can be monitored right away is a dangerous thought. There is no meaning of rushing into a situation one is not familiar with in order to save a few more dollars. Narrow down the failure possibilities to monitor to just a few. Chose them after failure rates, safety critical reasons (operational and human) and maintenance budget related actions (the faults that cost a lot of money to maintain). From these three categories one should start with faults that are well documented.

Difficulties of CBM system on rail vehicles

The differences of implementing a CBM system in an engineering industry and on a rail vehicle are quite large. A stationary process machine is always bolted to a heavy foundation, whilst a rail vehicle always is on the move with only the rail track as a foundation. A rail vehicle is also exposed for large differences in operating conditions during the year's seasons.

False alarms: That the CBM system doesn't cause false alarms is probably the most decisive parameter that the new technique will be accepted by the end-users. False alarm will most likely raise the maintenance budget instead of lowering it. The whole concept of CBM systems is that it is based on a high reliability. To avoid false alarms a good implementation plan is needed (see above).

Running-in: When which components, sub-systems or systems have been decided to monitor one need to establish what is normal operation and what is not. Measurements and readings must be collected if they do not already exist. This might take some time and it is important to let it. If rushing into trust for a CBM system all too soon, one will probably experience unnecessary false alarms.

The human factor: As always with new technique the human factor might be a problem, there will always be reactionary persons that think “the way we are doing it is working just fine”. The technique, profits, possibilities, incentives etc. must be presented before starting a new maintenance approach.

Maintenance planning: When moving away from the time based or operational based maintenance planning toward the condition based planning a lot of problems will most likely occur. The planning will move from static (intervals) to dynamic (intervals). Today, the intervals time length can almost be decided when constructing a new rail vehicle. With CBM, the intervals length and frequencies will change from time to time. Maintenance planners will have to put more trust in the computerized maintenance management systems (CMMS) that automatically will take traffic plans, spare parts, maintenance schedules, work orders etc. into account.

Case study

The case study presented here was performed for Bombardier Transportation, Sweden, in the spring of 2002 (for more information see Allström & Bengtsson, 2002). The case members were presented to a sub-system and were given the task to brainstorm different ideas how to monitor its condition and by that be able to use the CBM technique.

Method

After discussions with many Bombardier Transportation employees (Västerås site) the case study’s delimitations where set to the C20 Metro and its door systems. To understand the function and construction of the door system, internal description of the system were studied. Open interviews (as explained in Lantz, 1993) followed with employees from Bombardier Transportation (from both the Västerås and Kalmar site) and Tågia AB (the company that have maintenance contract on the C20). The interviews that consisted of thoughts around the construction, problems on the construction, maintenance related issues, how the maintenance could be done in a more effective manner etc. where held over a few weeks of time. The newly acquired knowledge was used in a series of brainstorming sessions on how to use the CBM technique for a more effective maintenance. The final result were presented to Bombardier Transportation’s site in Västerås.

C20 Metro

In 1995, AB Storstockholms Lokaltrafik (SL) ordered a new metro cart from Adtranz, Sweden. The first carts were delivered in 1997 and when Bombardier Transportation acquired Adrantz in 2001 they took over the contract. Each cart is divided into three different sections, A, M and B, all rests upon four bogies. Section A and B is connected to section M (middle section) in a semi-trailer configuration, which allows passenger to move freely through the sections. A metro can consist of up to three carts, connected by automatic couplers. A cart is 46.5 meter long and 2.9 meters wide, it has room for 128 sitting and 286 standing passengers, top-speed is around 90 km/h.

Door system

Below, a short introduction to the passenger door system follows.

Purpose: The purposes of the passenger doors are to prevent passengers to leave the metro when not allowed and to let passenger leave when allowed. The purpose is also to give adequate comfort and protection towards the outer environment, e.g. noise and weather.

Design: Every cart is equipped with seven passenger doors on each side of the metro, two doors in the A and B section and three doors in the M section. The passenger doors consist of:

- Door mechanism
- Lower guiding arms
- Door leaf
- Door control unit (DCU)
- Emergency handle

- Unlocking cable
- Internal push button

Every component is mounted to the cart. The door leafs are connected to the machinery and the lower guiding arms. The machinery and the lower guiding arms are mounted to the cart. The DCU is connected both physically and electronically to the machinery. The DCU is also connected to the train computer through a communication bus. The emergency handles and unlocking cables are mounted close to the doors and the internal push button is mounted to the right door post and connected to the DCU.

The DCU consists of a circuit board mounted on a back board, both protected by a cover. There are three switches connected to the DCU, emergency handle switch, door locked switch and door closed switch. These functions as safety switches and when activated lets the DCU send signals to the train computer so that the operator knows if all doors are locked/open or if the emergency handles have been activated.

Function: The doors opening and closing sequences are powered by the electric motor. The DCU gives signals to the motor for both opening and closing movement. The motor unlocks the doors and by the lower guiding arms guides the doors out, away from the cart. The motor then generates power to cog poles that guides the doors in a sliding motion alongside the cart. The motion of the doors is at the top guided by the cog poles and at the bottom by bearings (fitted at the outer part of the lower guiding arms) sliding in steering rails. Opening and closing sequences can be maneuvered by the operator and the passengers.

Maintenance on door system

The maintenance that is performed on the door system is scheduled preventive maintenance. But it is of course inevitable that sometimes corrective maintenance actions have to be made. The preventive maintenance is governed by operational kilometers. A C20 metro is yearly in operations about 120 000 kilometers. In the scheduled preventive maintenance there is four major kilometer based maintenance intervals:

- 20 000 kilometers, complete control of the door system functionality
- 40 000 kilometers, complete inspection of the door system
- 250 000 kilometers, complete wash and lubrication of the door system
- 835 000 kilometers, complete renovation of the door system

Possible condition monitoring

After not to long time into the case study it was learnt that the door system consisted of several, in itself, relatively simple and cheap components. To condition monitor on component level would probably imply a pretty high investment cost and the solution would be complex with lots of sensors. To find the critical components, FME(C)A and fault tree analysis, should have been helpful tools, but the idea was left pretty fast. The solution came to be condition monitoring on a sub-system level. The signals and data (to monitor) that were discussed with employees of Bombardier Transportation were:

- The time consumption per cycle of door opening respectively closing
- The current through the motor
- Number of cycles the doors open and close

To monitor trends in the time consumption of the doors opening and closing cycles would mean that one quickly can react to if something is going wrong. When enough measurements have been done one could probably even tie the extra time to open or close the doors to a specific fault. When measuring and monitoring the current through the motor one could if it is higher than normal expect that e.g. the cog poles are in need of lubrication and if rapid loss of current outage occurs that it e.g. might be damages of cogs at the cog pole. Tågia already have a pretty good idea how many cycles the doors open and close per kilometer, but a counter would not be a very costly application to invest in.

All monitored data could probably be analyzed in some Artificial Intelligence software, such as Neural Networks or Case Based Reasoning to find trends and connections.

Another case study
Approximately at the same time as this case study was presented to Bombardier Transportation, Sweden, and Mälardalen University, another case study result was released. Smith et.al (2002) presents a case study on the door system of an airport ground transportation vehicle. The vehicle, constructed by Bombardier Transportation, USA, had a door system constructed in a similar manner as the door system on the C20. The goal of the case study were to find measurable signals to determine if normal or abnormal condition exists, how to analyze those signals and to construct a working prototype.

The available signals from the door system were time, current and voltages of the door leafs as they pass through five different switches. To collect signals for analysis a test rig was set up at Bombardiers test track. The collected signals consisted of current through the motor, the voltage across the motor, the time interval of the open and closing cycle and the timing of the micro-switches. To simulate degradation of the door system a set of four different loadings (2, 4, 6 and 8 lbs) were applied to different locations as the doors moved in the cycle. To receive data between the different loadings, they simulated values with the use of statistical calculations. The data was analyzed using Neural Networks.

The data collection and analysis led to a prototype that was installed at a real vehicle. The data was collected in a laptop and removed every other day when the vehicle came in for routine maintenance. The data was then sent to Bombardier Transportation and Auburn University for analysis and monitoring. After testing of the prototype a lot of conclusions could be made. The most important one might be that it was possible to design, built and implement a predictive maintenance system on the door system without major design changes and without significant investment.

Conclusions
When scanning through the existing literature within the CBM community it shows that there is a lot written about it. This paper is not an attempt to be a summary of all, but merely a try to explain the maintenance technique in a short and easy approach. The mere amount of literature shows that there is an obvious interest to renew yesteryears maintenance technique and move into tomorrows. All the prototypes and case studies presented in the paper also indicate that there is a lot of research happening in the world. In most cases though, these prototypes are constructed for single applications. To lead the development process towards a more general CBM system it is important to come together and move towards general solutions. The standards and standardization proposals presented in this paper can be one way to accomplish this. The two case studies presented at the end of the paper shows that it is possible to use the same technical approach of CBM on rail vehicles as it is in an engineering industry.

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