An Evaluation of Condition Based Maintenance for a Military Vehicle

Master of Science Thesis in the Master Degree Programmes Automotive Engineering and Product Development

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Cover
The picture on the cover page illustrates the military vehicle, CV9035, which this thesis focuses on. The vehicle propulsion system and current maintenance situation is described in chapter 4. Technical Information CV9035

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Acknowledgements

This report presents a master thesis project carried out at BAE Systems Hägglunds in Örnsköldsvik during spring 2010 by two students from Automotive Engineering and Product Development at Chalmers University of Technology. The project was executed at the department of Subsystem Development, Propulsion System under supervision of the department manager, Göran Westman.

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Abstract

BAE Systems Hägglunds is a military vehicle producing company who is offering to be involved in helping their customers during the system's entire life cycle. The main issue is the lack of knowledge of the vehicle's current condition out in the field and the extensive costs associated with maintenance activities due to the availability demands.

The purpose of this thesis is to evaluate the possibility of implementing a condition based maintenance (CBM) system in the military vehicle CV9035. Early on a distinction is made between an extended condition based maintenance system and one of its constituent parts, trending, where the main focus of this thesis lies.

Through utilization of sensors and a computerized network the propulsion system condition can be trended to enable prediction of future maintenance needs. The main outcome of this thesis is a basic trending system design proposal including recommendations of initial components and measurements together with system functionality requirements and a general communicative layout. In addition, requirements for complete development of an extended condition based maintenance system are compiled.

The report is finalized with company specific recommendations for implementation of a trending system together with suggestions of future projects to undertake in order to enable a complete solution to the current maintenance issue for the company.

Keywords: military vehicle, trending, condition based maintenance, fault diagnostics, opportunistic maintenance, static measurement, dynamic measurement.

Sammanfattning

BAE Systems Hägglunds är ett militärfordonstillverkande företag som erbjuder sig att medverka och hjälpa sina kunder under systemets hela livstid. De största problemen är bristen på kunskap om fordonets aktuella skick under drift och de omfattande kostnaderna för underhåll som kan uppstå på grund av kundernas krav på fordonens tillgänglighet.

Syftet med detta projekt är att utvärdera möjligheten att implementera ett tillståndsbaserat underhållssystem i det militära fordonet CV9035. Tidigt i arbetet har en urskillnad gjorts mellan ett komplett intelligent tillståndsbaserat underhållssystem och en av dess beståndsdelar, trendning, vilket fokus i denna avhandling ligger på.

Genom användning av sensorer och ett datorbaserat system kan framdrivningens tillstånd trendas vilket möjliggör prognostisering av framtida underhållsbehov. Det viktigaste resultatet i denna avhandling är ett grundläggande designförslag tillsammans med rekommendationer av initiellt implementerade komponenter och mätningar samt funktionella systemkrav och en allmän kommunikativ layout. Dessutom ges förslag på kvarvarande insatser som krävs för fullständig utveckling av ett heltäckande och intelligent tillståndsbaserat underhållssystem.

Rapporten avslutas med företagsspecifika rekommendationer för genomförandet av ett trendningssystem tillsammans med förslag till framtida projekt att genomföra för att möjliggöra en fullständig lösning på de nuvarande underhållsproblemen för företaget.

Nyckelord: militärfordon, trendning, tillståndsbaserat underhåll, feldiagnostik, underhållsoptimering, statisk mätning, dynamisk mätning.

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1 Introduction

In the following chapter the underlying reasons for this thesis and a more detailed problem definition is presented. The delimitations taken for this project and the structure of the report is also displayed to give the reader a thorough assessment of the thesis content and organization.

1.1 Background

BAE Systems Hägglunds is a company developing and producing military vehicles. Their current lineup of produced vehicles consist of two types, a combat vehicle and an all terrain vehicle, which both can be customized to customer needs regarding its intended purpose and environment.

This master thesis takes place at the department of Subsystem Development, Propulsion System which is responsible for the military vehicles' propulsion system. The idea behind this master thesis is based on a need to make the maintenance more efficient and to increase the knowledge of their components condition. This originates from a desire to start selling vehicle availability instead of traditional spare part packages along with the vehicles. Currently, to ensure a high operational availability of the vehicles, BAE Systems Hägglunds sometimes exchanges somewhat healthy parts and fluids to make certain that the vehicles are fully operational. This results in unnecessary costs why a more efficient maintenance system is desired that can foresee the maintenance need and inform the company prior to the actual break down. Since vehicle availability is of high priority, grouping of maintenance activities is another desirable feature for a future maintenance system.

1.2 Purpose

The purpose of this master thesis is to evaluate the possibility of implementing a condition based maintenance (CBM) system in the military vehicle CV9035 produced at BAE Systems Hägglunds. The expected outcome is a basic design proposal together with suggestions of remaining efforts required for development of an intelligent condition based maintenance system.

1.3 Research Questions

To get a clear view of the problem that is to be solved the purpose is divided into three research questions. Solving these questions ensures a detailed and comprehensive solution of the main purpose of this thesis. The research questions are as follows;

1. **What** components shall be part of the monitoring system and **what** properties are to be measured?
2. **How** shall the system be designed in terms of functionality and communicative performance?
3. To ensure a comprehensive and intelligent system that meets all requirements, **what** work must further be accomplished?

1.4 Delimitations

The following chapter will address delimitations for this thesis. The subsequent issues displayed in Table 1 are not dealt with within the framework of this report.

Table 1. Delimitations

No.	Delimitation
1	The project will only consider the powertrain of the CV9035, currently produced by BAE Systems Hägglunds.
2	Components without a direct connection to maintenance tasks are not considered.
3	Diagnostic advantages for chosen components are used for justification purposes only and are not fully considered.
4	The project does not consider the financial aspect when proposing system specific components.
5	There are many possible techniques to utilize in order to gather a smooth data representation from sensors but these are not considered in this project.
6	An implementation of the system into the vehicles, for a compatibility evaluation, is not performed in this project.
7	The project is not considering the current data storage and bandwidth limitations of the CV9035.
8	When suggesting relevant components for the system, no consideration is taken to the performance of the sensor, i.e. whether or not it is the optimal choice of sensor.
9	The time limit for this project is set to 1600 man-hours.

1.5 Report Structure

This report structure follows a logical pattern with clear transitions in order to provide the reader a solid understanding of this thesis. First and foremost the methodology to the research is presented, i.e. the procedures taken in order to answer the research questions and fulfill the thesis purpose. Secondly a theoretical framework is presented aiming to offer the reader thorough understanding of the subject chosen and to show that the authors are well familiar with the theories. This chapter transcend in a complete description of the vehicle including maintenance situation, utilization and constituent elements relevant for this thesis. The following chapter then presents the core information gathered in the thesis including market research results, trending of chosen measures and a system requirement specification. The report is finalized with a discussion of the result which eventuates in conclusions and lastly recommendations to the company.

This report differs between the concepts of trending system or condition based maintenance system and an extended condition based maintenance system. This originates from Mobley (2001) who states that an extended condition based maintenance system involves more functions than trending e.g. fault diagnostics and self learning. In this report the concept of grouped maintenance tasks has also been added to the term extended condition based maintenance system.

2 Methodology

This chapter presents utilized methods in order to realize the research questions given and thereby also the main purpose of this thesis. The core work of the thesis is divided into three phases as presented in Figure 1.

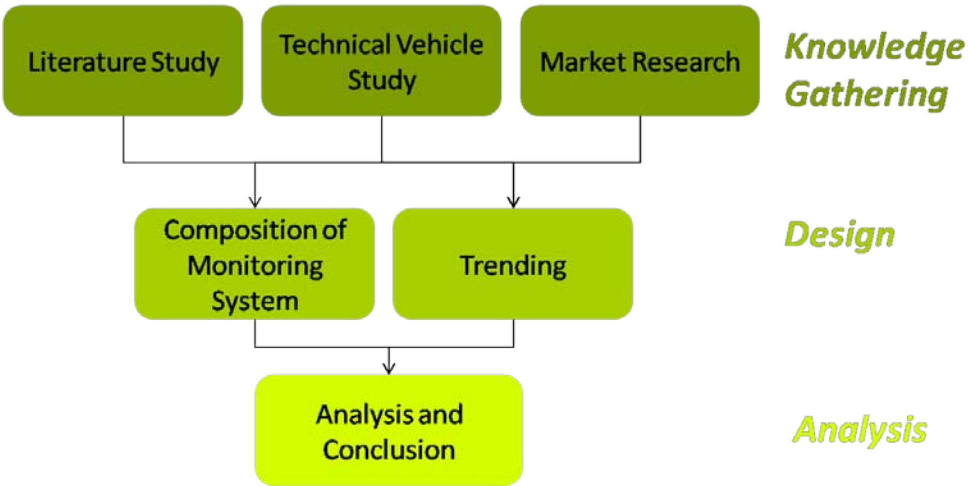


Figure 1. Thesis core work phases

2.1 Literature Study and Technical Vehicle Study

To be able to accomplish satisfying and comprehensive end results a lot of information needs to be taken into consideration. The knowledge gathering phase is executed by performing secondary research, both internal and external, accompanied by company visits based on recommendations from McQuarrie (2006). The secondary research is performed with an exploratory approach to gain as much knowledge as possible to be able to make proper decisions early on in the thesis.

The secondary research is performed in order to gain adequate knowledge of the research subject, condition based maintenance, and to discover the role of the vehicles technical systems. The internal secondary research is performed by meetings, database material reading and discussions with experts from different departments. The external research is executed by a literature study where articles, books and other interesting material are reviewed, processed and documented thoroughly. Since the company possesses the most information about their business a lot of effort is put into gathering colleague opinions but as McQuarrie (2006) explains:

"…the interviewers must always attain some degree of healthy skepticism."

2.2 Market Research Study

To further understand how CBM is realized in companies today a market research study is performed by company visits. These visits have an exploratory approach in the sense of "*What's new?*" and "*What are we missing?*" The research segment in our study is a market where theories are drawn from facts rather than feelings which are more suitable for this thesis objective since qualitative data rather than assumptions and estimates are required.

In preparation of the interview questions the suggested guidelines developed by Kvale (2008) are utilized. Below, presents nine different types of questions that are suitable to use when conducting this type of semi-structured interviews.

1. **Introductory questions**
   E.g. "When did you start working with cars?"
2. **Follow-up questions in order to make the interviewee elaborate on the answer.**
   E.g. "What do you mean with low cost articles?"
3. **Probing questions, following up with direct questions.**
4. **Specifying questions**
   E.g. "How do you place orders with the inventory management system?"
5. **Direct questions**
   E.g. "Do you believe that you have enough staff to work with?"
6. **Indirect questions**
   E.g. "How do you place orders on spare parts?"
7. **Structuring questions**
   E.g. "All right, how about talking a bit about the general agencies now?"
8. **Silence**
   Silence allows the interviewee to reflect which might lead to more correct answers.
9. **Interpreting questions**
   E.g. "So the organization found it appropriate to increase the inventory levels in order to increase the return on investment"

Using a predefined set of these types of questions at the study visits ensures profound qualitative data and diminishes the risk of leaving important questions unanswered.

The introductory questions that are to be presented during the interviews can be derived from the main purpose of the thesis along with the research questions presented. Besides a general description of the company the following questions are of interest for this thesis.

Introductory questions, follow-up questions and probing questions utilized in the interviews to discover the magnitude of CBM involvement for the company.

- **How does your current maintenance program look like?**
  Do you have a corrective, preventive or predictive maintenance program?
  How was the program developed?
  What information did you use as a foundation for this program?
- **Is your company involved in any kind of CBM or predictive maintenance activities?**
  Are you currently or have you been involved in R&D projects or other possible activities to increase the company knowledge around CBM?

When the companies are involved in CBM a mix of the following questions were used.

- **Are any of the process or product parameters logged currently?**
  Are you in some way reading and storing data of interest for important parts in the machinery?
  How is that information handled?
- **How do you measure the condition of your components?**
  How do you ensure the assumed condition of your components?
  Do you have visual inspection or other condition monitoring activities in your maintenance plan?
- **How is the condition visualized to the right people**
  Are the data gathered visualized in real time or are they handled separately to discover possible trends?
  If real time display, when and how are you alerted of the conditions of your parts?
- **Are your maintenance activities grouped?**
  How is this done?
  What information has been used to realize this?

2.3 Design

The second phase involves the actual design of the system including measurement assessment, specification of requirements and a communicative system architecture. This is accomplished by performing calculations, estimations and expert discussions but also by the use of evaluating discussions. The basis of these actions is the knowledge gathered throughout the project together with knowledge gathered prior to this thesis. Many calculations as well as assumptions are supported by the study visit findings together with information gained by evaluating discussions with employees at BAE Systems Hägglunds.

2.4 Analysis

The empirical findings and the theoretical framework form the basis for the analysis. The processes utilized in order to achieve properly analyzed results are illustrated in Figure 2.

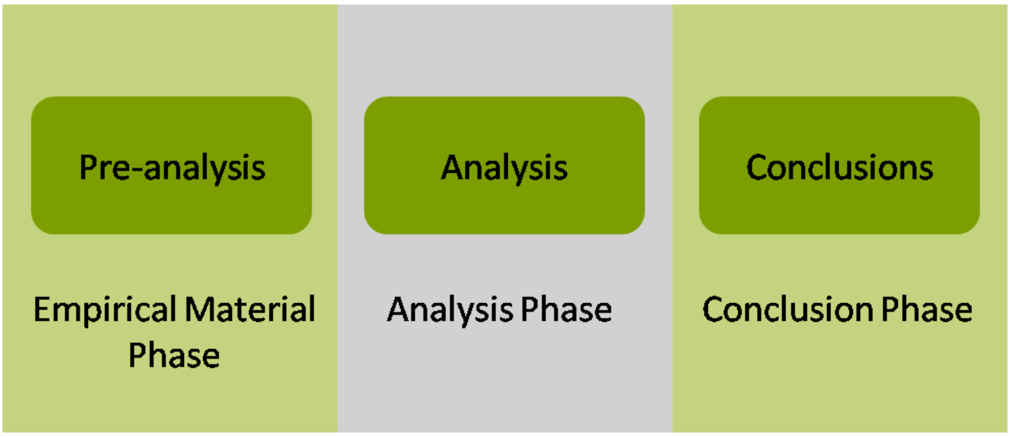


Figure 2. Schematic illustration of analysis process

First, a pre-analysis is made in the empirical work section. The pre-analysis consists of justifications for implementing the components of interest. Biased comments are not presented in this section but merely empirical objective findings relevant to each component. In the second phase the actual analysis is made where advantages and disadvantages are compared against one another managed by biased knowledge gained throughout the project. A properly conducted analysis results in solid and well supported conclusions and recommendations for the company.

2.5 Reliability and validity

Reliability is related with the question of whether the results of a study are repeatable and is primarily an issue related with quantitative research. This master thesis's nature as a case study based on qualitative data through a set of semi-structured, exploratory interviews naturally gives little room for repeatability which could question the reliability of the information presented.

Kirk & Miller (1986) describes the question of validity as follows:

"In the case of qualitative observations, the issue of validity is not a matter of methodological hair splitting about the fifth decimal point, but a question of whether the researcher sees what he or she thinks he or she sees."

The question of whether or not the material presented in this report is valid is uncertain since the empirical findings in some cases are based on the authors biased knowledge. Some of this knowledge is gathered throughout the project based on subjective perceptions of the information provided at study visits. However, validity is also a matter of deviation from project purpose which in this case is nonexistent due to a properly defined framework which leaves little or no room to wander off the path presented. Finally, validity of the knowledge gathered can be measured in terms of internal information validity, gained within the company, and external information validity, gained from external actors. The information gathered internally is probably of higher validity than external information due to the self gaining purposes of aiding this project that goes for employees within the company.

3 Theoretical Framework

In today's vehicle industry, product and production efficiency and low costs are getting increased attention. This philosophy has also impacted the utilization of maintenance for vehicles on the aftermarket. To increase efficiency and to lower costs a balance between prevention and repair needs to be established. According to DiLeo et al. (1999) there are currently three ways to assess maintenance as illustrated in Figure 3.

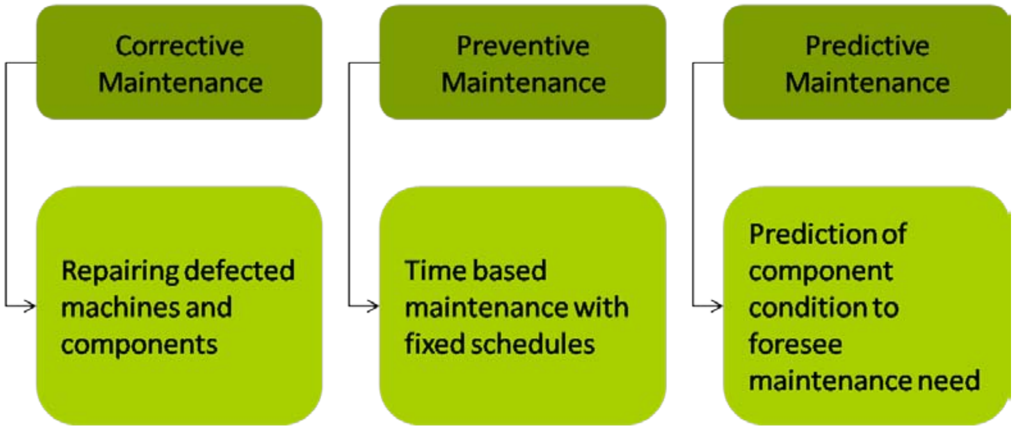


Figure 3. Three maintenance approaches

When it comes to corrective maintenance, also called breakdown maintenance, actions are taken only when urgently and immediately required (DiLeo et al, 1999). This approach is cost efficient as long as no catastrophic failures occur but unfortunately the likelihood of them occurring is dangerously high since no precautions are taken to prevent them.

Currently BAE System Hägglunds utilizes the preventive maintenance technique (see 4.1 Current Vehicle Maintenance) to assess their need for maintenance. According to DiLeo et al. (1999) preventive maintenance is the most widely accepted technique and it is a calendar based maintenance program which also involves unnecessary costs due to non optimized maintenance intervals.

According to DiLeo et al. (1999) predictive maintenance systems takes advantage of the proven cause-symptom-effect relationship to forecast the need for maintenance. This technique is generally an equipment specific approach rather than a complete system strategy. Some authors call predictive maintenance condition based maintenance but a distinction is made by DiLeo et al. (1999) based on the fact that CBM is rather more comprehensive since it involves both online and offline data.

The following chapter describes condition based maintenance systems and its possible constituent elements. Moreover it explains how to develop a successful condition based maintenance program including measurement trending and maintenance task grouping.

3.1 Condition Based Maintenance

According to Rabeno and Bounds (2008) condition based maintenance is a maintenance arrangement based on actual condition of the system. DiLeo et al. (1999) states that CBM offers the promise of enhancing the effectiveness of maintenance programs in a way no other concept have. Higgs et al. (2004) further imply that a CBM system is intelligent and it is capable of understanding and making decisions without human involvement. He defines a typical CBM procedure as follows:

> "A typical CBM procedure involves taking and recording CBM data at periodic intervals in order to determine the condition of the component being monitored."

The purpose of utilizing a CBM system is, according to Mobley (2002), to minimize equipment failure and maintenance cost. In addition, he further describes other long term objectives as reduced spare part inventories and improved product quality. Bansal et al (2004) support these statements and further imply that CBM can ensure high product reliability and performance. Mobley (2001) differentiates a CBM system from an extended CBM system which involves other functions as fault diagnostics and self learning. He further implies that this type of system completes the understanding of component interaction and complete system condition.

The major dilemmas of developing a suitable well performing CBM system are, according to Mobley (2002), the actual design of the program, how it is implemented in the business and how it is adapted amongst everyone else. The latter subjects are not considered since they have no relevance to the purpose of this thesis. When it comes to the design of the program, Mobley (2002) emphasizes the following issues:

- **What parts are to be monitored?**
- **How to set up condition levels and limits for warning?**
- **How to select a suitable CBM system?**

The decision of which parts that are to be monitored in the CBM system is according to Mobley (2002) almost entirely based on the importance and criticality of the part in relation to the financial situation around that specific part. In other words, deciding whether or not a monitoring system reduces a sufficient amount of maintenance related costs compensating for the initial investment in the surveillance equipment.

Forsthoffer (2005) entails a rather detailed step by step program of how to design the system and how to set warning limits of component conditions. Firstly, component and system functions need to be defined followed by normal values and parameters for each component listed. Once each component is defined baseline data needs to be obtained as soon as physically possible after equipment start-up. Forsthoffer (2005) further explains the need of baseline condition as below:

> *"If you don't know where you started, you do not know where you are going!"*

Successively, trend data needs to be gathered by periodic observation of parameter condition in time. When trending, threshold values also should be defined for each parameter. When a monitored value exceeds this threshold action needs to be taken to solve the problems. These values are usually in the order of 25 % above the baseline or similar (Forsthoffer, 2005). Mobley (2002) implies that there are two ways to detect changes in operating conditions, static or dynamic. Static alert involves a preset threshold for measurement parameters which if surpassed alerts the recipient. Mobley (2002) entails the shortcomings with this type of monitoring method by explaining that it does not consider the rate of change or historical trends and can therefore not fully predict when the alarm will be reached.

Mobley (2002) describes an additional method for monitoring rate of change, using dynamic limits. This method can detect deviation from current rate of degradation for the system, enabling anticipation of when the alarm will be reached. He states that the rate of change, or dynamic measures, rather than absolute values, or static measures, is of greater importance for condition assessment. This statement is based on the fact that it gives a direct indication that corresponds to a mechanical change in the component condition. He further argues that using dynamic limits greatly enhance automatic diagnostic capabilities and reduce manual effort.

Landqvist (2004) presents a method of determining test frequency and to visualize trending measurements of a component's condition as illustrated in Figure 4.

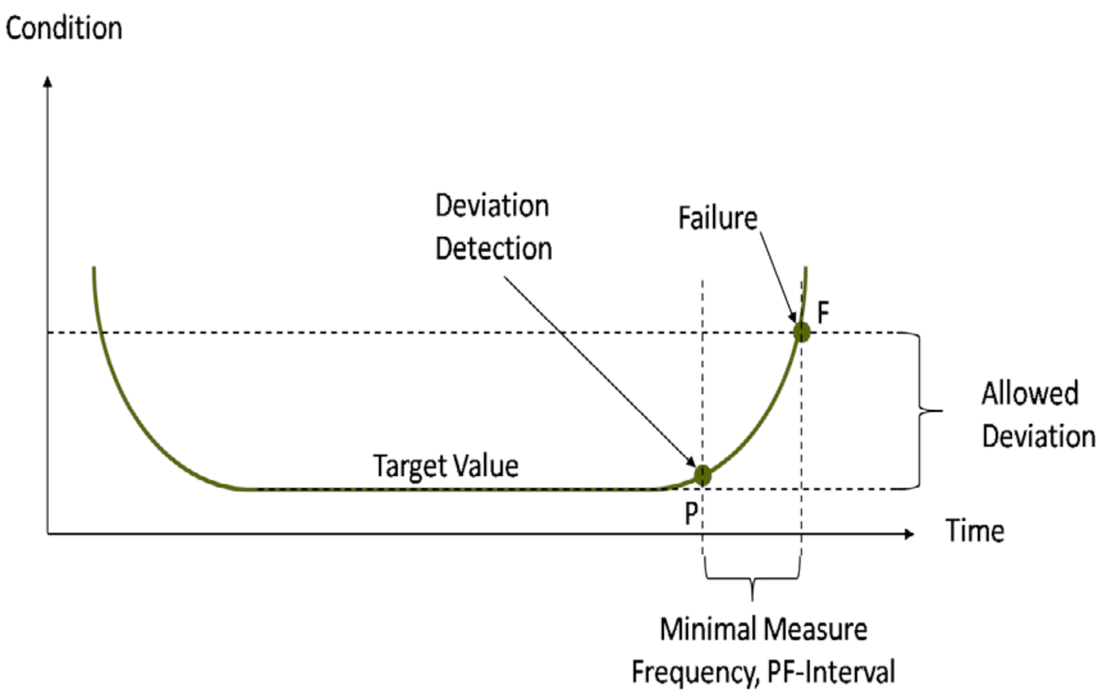


Figure 4. Trending visualization plot

The plot displays how to determine the frequency of measurements to prevent failure from occurring. The PF-interval is the time passed between possible error detection and failure and according to Landqvist (2004) the test interval should be no more than half of this time.

According to Slack et al. (2010) the complexity of estimating failure occurrence can diverge greatly. Some breakdowns are obvious through a combination of rational cause investigation and historical performance while other failures are far more complicated to foresee.

In many cases of wear, failures follow a function of time where the wear rate changes over time. The most common way of describing failure rates for a component is the bathtub curve. The probability of failure for this kind of product is great early on in the product lifetime, declines through the middle stage of its life cycle and finally increases in the later stage (Slack et al, 2010). This behavior is displayed in Figure 5.

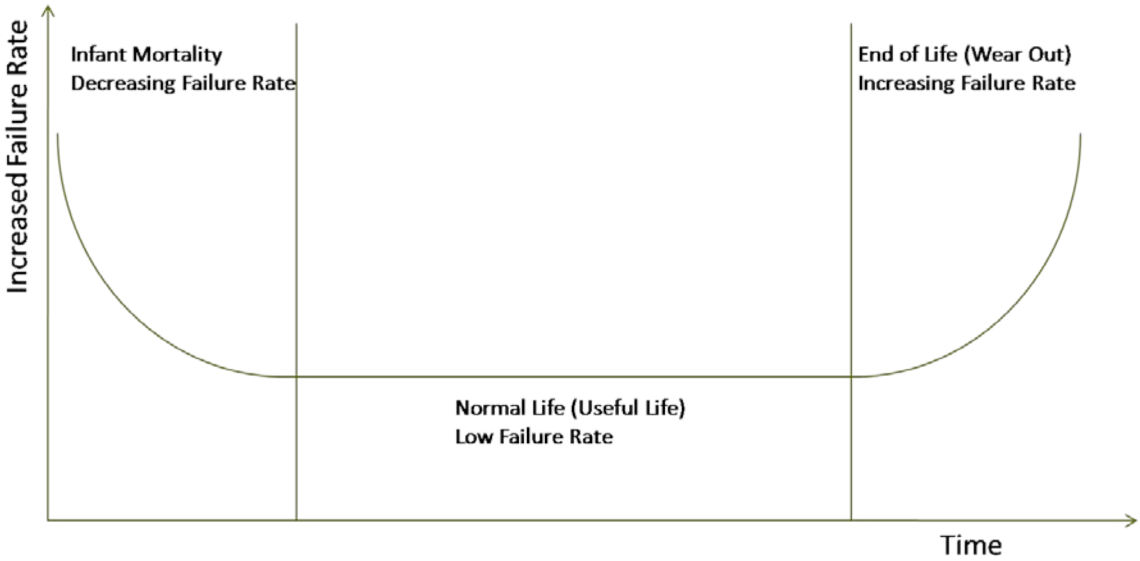


Figure 5. The bathtub curve

The bathtub curve is an idealized presentation. A realistic curve normally illustrates small variations which later can be identified with a more general appearance. Far from every component life cycle is presented in this way. There are multiple types of failure characteristics which show the probability of a failure occurring with time (Landqvist, 2004). The appearance varies with type of component and affecting surroundings and can take on one of the six shapes displayed in Figure 6.

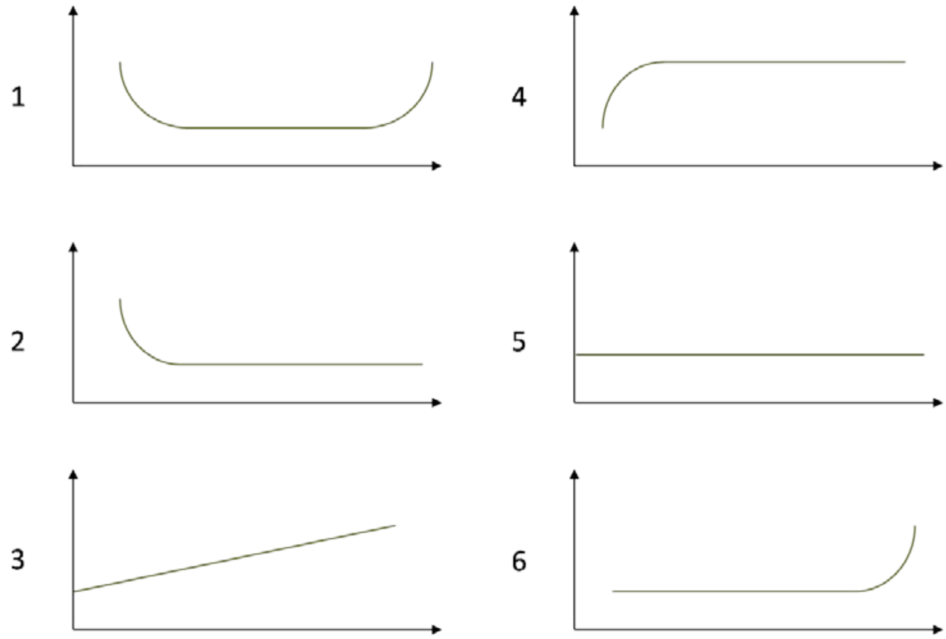


Figure 6. Six plausible failure characteristic curves

To be able to determine which curve is most suitable for a specific component Smith (1993) and Moubray (1999) declare that the following questions need to be answered.

- **Time of failure?**
  At the time of failure, how many operating hours have the machine had?
- **When and how was the failure discovered?**
- **How is the operational ability affected by this failure?**
- **When and what maintenance has been performed for this component?**
- **Does a maintenance task require operation stops? What are the costs and time for this?**

By asking these types of questions statistical measures and trends can be calculated. Trending is of great importance to determine the failure frequency and enabling activities with preventive maintenance tasks for the components of interest.

According to Patriksson (2010) maintenance is often performed too often and inspections and condition monitoring often damage the system. To manage this issue Patriksson (2010) suggests grouped or joined maintenance tasks called opportunistic maintenance which is described in the following section.

3.1.1 Opportunistic Maintenance

An important factor in industries' ability to maximize profitability is their possibilities to plan corrective and preventive maintenance in relation to planned production breaks. In order to effectively use available resources it is also required that the actual maintenance occasion is managed in an efficient way (Strömberg, Almgren, 2010).

Strömberg and Almgren (2010) further state that when existing equipment is disassembled sometimes critical components are exposed, opening a possibility for preventive maintenance on these components as well. This phenomenon of opportunity exploitation is called opportunistic maintenance. Patriksson (2010) further supports the need for opportunistic maintenance with the following statement;

"At each maintenance occasion it is possible to perform more maintenance than what is absolutely necessary"

For engineers involved in maintenance, planning and scheduling becomes very important, since it involves balancing costs for machine breaks against direct maintenance costs. The main objective is to achieve maximum revenue measured in operation time for the investment made. A model for maintenance planning developed by Chalmers University of Technology is described in the following section.

3.1.1.1 Maintenance Planning Model

The maintenance planning model aims, according to Almgren et al (2010), at minimizing the total expected cost during a predetermined time period. The optimization model is designed to consider cost for interrupted availability while minimizing the cost for maintenance. In practice this means that this model strives for creating a maintenance plan with as infrequent maintenance occurrences as possible while maintaining a healthy mixture between replaced components and parts in use (Almgren et al. 2010).

Consider the following case displayed in Figure 7. Four parts with different life times and costs shown as a colored dot at given times. The constant *d* displays the fixed cost for maintenance breakups and as it grows the more interesting opportunistic maintenance becomes as shown in the chart.

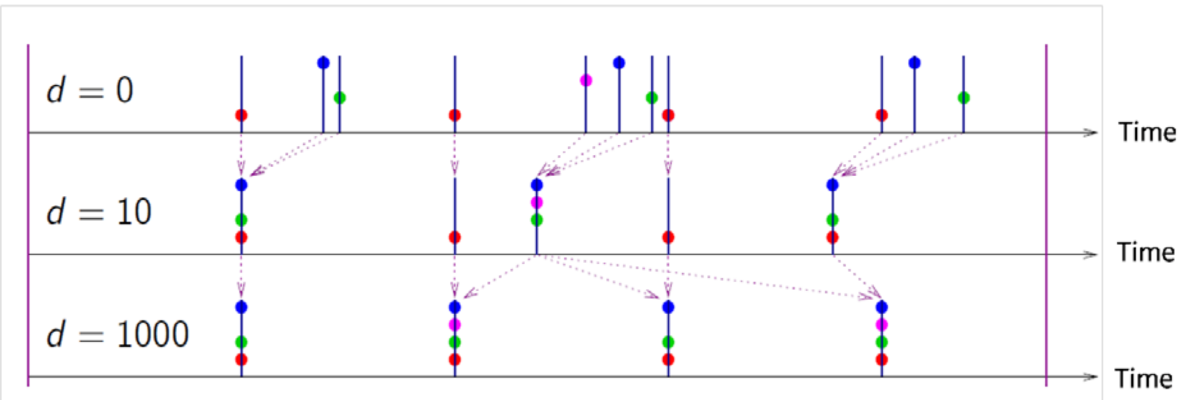


Figure 7. Opportunistic maintenance chart

3.1.2 Effective Trending

To be able to select or design a suitable CBM system for a product or production system Mobley (2002) declares some fundamental requirements for the trending system that needs to be considered. You need to decide what features or specific capabilities the system must have to support the special needs of your product. Mobley (2002) states six minimum requirements for a CBM system of interest for this thesis as follows:

- **User-friendly software**
  The system must be easy to handle with simple and straightforward operations for increased acceptance amongst users.
- **Automated data acquisition**
  The system must automatically select and set parameters without user input which minimizes the potential of human errors and reduces staffing.
- **Automated data management and trending**
  The system must store, trend and recall data enabling the user to monitor, trend and analyze the component condition.
- **Flexibility**
  The system must support different techniques.
- **Reliability**
  The system must be tested and proven reliable before implemented
- **Accuracy**
  The data collected by the system needs to be accurate and repeatable since it is the basis for maintenance decisions.

Four other attributes that contribute to an effective trending system are according to Ford et al (2008) as follows:

- **Redundant monitoring**
  Redundant monitors are back-up to one another since no single monitor can succeed for every mode of failure. More monitors ensure no failure will go undetected.
- **Monitors that correlate**
  Interrelated monitors establish a link between cause and effect. If multiple monitors alerts concurrently they are all affected by the same cause.
- **Detailed alerts**
  The more details revealed in alerts the less effort is required to solve the problem occurred.
- **Consolidation**
  As much alert information as possible shall be presented to a single interface to ease the problem management

To be able to predict future failures the CBM system needs to be able to trend data gathered. Ford (2008) describes the difference between monitoring data and trending data as follows:

"Monitoring is an important activity for detecting problems that have already happened. Trending is about identifying potential problems before they happen."

Methods for detecting trends can help significantly to achieve upgraded qualitative information from process measurements. The trends identified can be further processed with intelligent systems in order to solve diagnosis and supervisory control problems. Such intelligent monitoring systems benefit from reduction of data dimensionality, i.e. if qualitative information (trending) are used rather than raw measurement data (Flehmig and Marquardt, 2006). The reduction of noise to gather a smooth representation of data is not considered further in this thesis but required for the extended solution of a condition based maintenance system.

Historical information about a system shows diminution of resources over time and answers vital questions as "W*hen did the problem occur?"* It is also extremely crucial from a capacity forecasting standpoint. According to Ford (2008) trending involves consideration to many possible deviations to measured data. Severe changes in system performance over time can occasionally be explained by the following four issues:

- Changed utilization
- Diminished capacity
- Accumulated utilization
- Changed system characteristics

These four criteria show changes in trending patterns since they very often affect performance for the machines and a condition based maintenance system needs to be able to take these changes into account (Ford, 2008).

3.1.3 CBM Techniques

According to Mobley (2001) the final step that needs to be undertaken in order to develop a suitable CBM system is choosing the right techniques and computer based equipment in order to manage the measurements and satisfy the specified requirements for the system. Mobley (2001) and Dunn (2002) state seven groups of sensors of which two are of interest for this thesis. The techniques are listed below:

- **Vibration monitoring**
  - Broadband trending
  - Narrowband trending
  - Signature analysis
- **Thermography**
  - Infrared thermometers
  - Line scanners
  - Infrared image
- **Tribology**
  - Lubrication oil analysis

    - Wear particle analysis - ferrography or spectrography
- **Process parameters**
    - Pressure sensors
    - Level sensors
    - Temperature sensors
- **Visual inspection**
- **Ultrasonic monitoring**
- **Other non destructive techniques**

The techniques that are not relevant for this thesis are not explained further. The two main techniques of interest are tribology and process parameters measurements and these are clarified in detail in this section. In a latter phase of the CBM system development, when conducting a maintenance plan, the technique of visual inspection can be taken into consideration.

Tribology is the common term of operating dynamics of bearing-lubricating-rotors support for machinery. It is divided into two techniques as described above, namely oil and wear analysis (Mobley, 2002).

Oil analysis is a technique used to determine the condition of the lubrication oil used in mechanical equipment. Mobley (2002) considers this technique to be useful for oil life extension but cannot identify the root-cause of the incipient problem. He further implies the use of this technique to determine the most cost effective intervals for oil change.

Wear particle analysis is according to Mobley (2002) a similar method to oil analysis but detects wearing condition on the machine train explicitly. There are two types of particle wear analysis; spectrography and ferrography of which only the latter is considered for the combat vehicle. They differ in the sense of technique utilized since ferrography uses a magnet to separate the solids whilst spectrography separates solids into different sizes. According to Dunn (2002) the second state following the partition of particles is to diagnose abnormal conditions indicated by change in particle quantities and sizes.

Monitoring of process parameters involves routine controls of efficiency parameters to ensure that machines are operating within accepted tolerances. According to Mobley (2002) process parameters monitoring should be implemented for all machinery that affects the total efficiency of the vehicle, i.e. critical parts as fans, coolers and filters. To monitor these process parameters different types of transducers are utilized, i.e. temperature, pressure and level sensors (Mobley, 2002). The techniques of interest for this thesis are explained further in the following section.

3.1.3.1 Relevant CBM Techniques

This section describes the two types of sensors that are of interest for the vehicles maintenance system. A brief description of integrated sensors or plausible future sensors belonging to each type of these categories of sensors is also given below.

3.1.3.1.1 Tribology Sensors

As described in section 3.1.3 CBM Techniques, tribology is the common term describing the operating dynamics of two interacting surfaces. Two different sensors addressing tribology, and of interest in this thesis, are described in this section. None of these sensors are currently integrated in the vehicle but they are under evaluation.

PARTICLE SENSOR

The MetalSCAN sensor by GASTOPS is a particle sensor used to prevent surface pitting fatigue in bearings and gears. It can detect metallic particles that are either ferrous or non-ferrous and present both size and type of these particles. As shown for the wind turbine gearbox application in Figure 8, it operates before the oil filter and is integrated into a control system to give an indication about further operation possibilities as well as an estimate of its remaining life time.

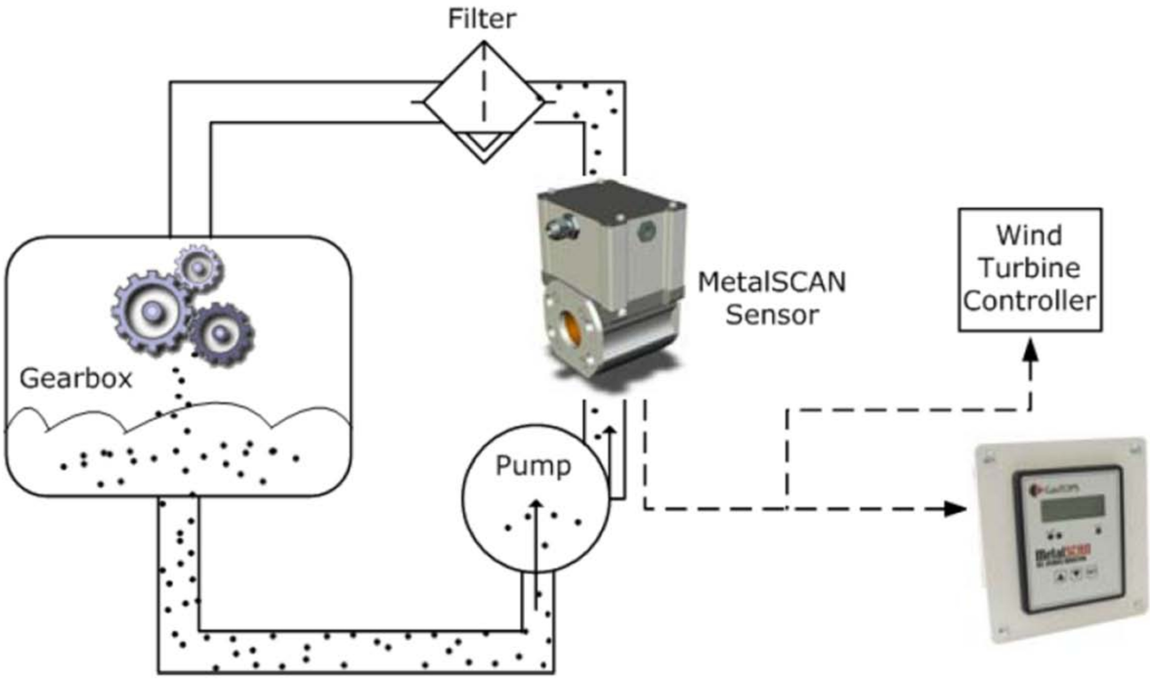


Figure 8. Schematic of MetalSCAN sensor placement in a wind turbine gearbox application

This type of sensor competes with vibration monitoring to detect surface pitting fatigue failure and is, according to NASA (2002), a better choice by stating that

> *"oil debris is **more reliable** than vibration for detecting pitting fatigue failure …"*

as well as explaining a drawback with vibration monitoring by saying that

> *"… vibration algorithms are **as sensitive to operational effects** as they are to damage"*

NASA (2002) further refers to comparisons between vibration algorithms and oil debris measurements and comes to the conclusion that vibration algorithms do not detect damage progression but it is clear that damage progression is related to an increase in oil debris.

In order to present warnings and alarms, limits for these need to be determined. The system is designed to present an alert when a specific particle mass is detected and this mass is determined according to the most fragile component in the system. A curve showing this can be seen in Figure 9. The curve is based on a real life scenario where particles are counted for a wind turbine gearbox during an eight month period until the rate of particle detection severely increased and it needed to be replaced (GASTOPS, 2010).

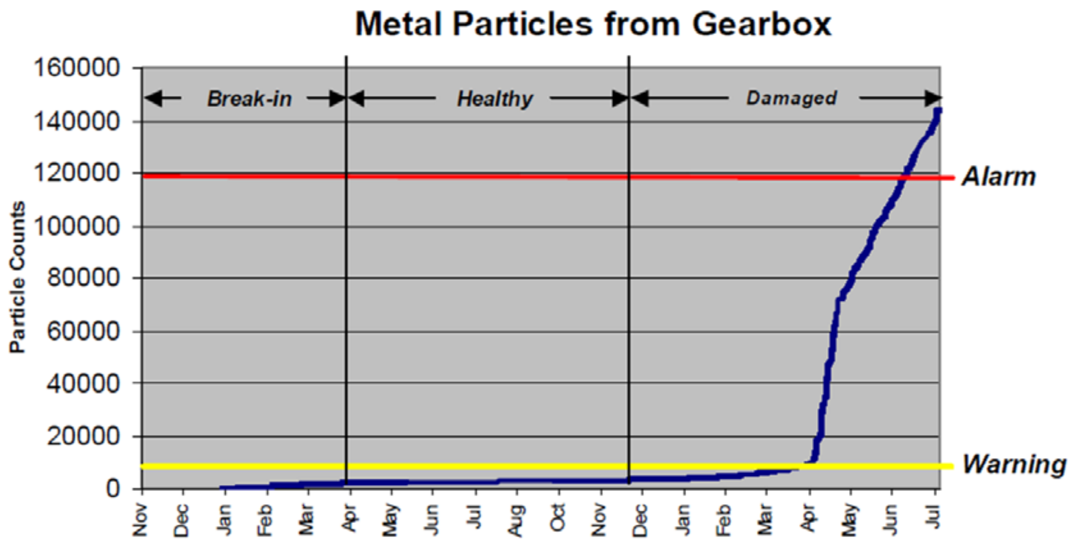


Figure 9. Metal particle detection

Oil Condition Sensor

The Delphi diesel engine oil condition sensor can detect soot and fuel dilution as well as measure dielectric constant and viscosity. Its major advantages are to maximize the oil and oil filter lifetime together with enhanced engine protection. The effects of this are reduced oil maintenance costs as well as increased vehicle availability. Sanchez (2007), an advanced engineering manager at Delphi, claims that this sensor is remarkable by the following statement.

> *"This is an incredibly elegant solution with a direct correlation to viscosity. We are getting amazingly accurate results, irrespective of oil type, soot content and other contamination."*

Holgersson and Unnerbäck (2007) have tested a pre-production sample of this sensor and found that the viscosity measurements fluctuated around three times the defined value. However, an average value of these results showed good correspondence to laboratory test values but they recommended further engine tests to verify the sensor performance. Holgersson and Unnerbäck (2007) also state that similar sensors are under development by companies like Bosch, Hella and Temic. They recommend that such a sensor is tested and compared to the Delphi sensor since their viscosity measurements are based on different methods.

3.1.3.1.2 Process Parameter Sensors

Process parameter sensors include various sensors such as temperature and pressure sensors. This section provides a short description of the most relevant sensors regarding this thesis.

TEMPERATURE SENSOR

According to Wilson (2005) temperature can be defined in two different ways. It is either a specific degree of hotness or coldness compared to a specific scale or an amount of heat energy in an object or system.

Wilson (2005) further states that sensing temperature can be performed with either a contact or non-contact sensor. The contact temperature sensor operates in direct physical contact with the media while the non-contact temperature sensor operates in the opposite condition by interpreting radiant energy of a heat source.

PRESSURE SENSOR

Wilson (2005) claims that a pressure sensor converts input pressure to an electrical output. By doing so, a pressure sensor can measure pressure, force and airflow and be implemented in numerous applications. There are different pressure sensors available depending on what kind of measurements that are of interest. As an example, differential pressure sensors measure the difference between two input pressures and absolute pressure sensors compare the measured pressure to vacuum.

LEVEL SENSOR

Wilson (2005) explains that level sensors are most commonly used for tank measurements and control operations. He further states that they can be based on different technologies depending on their intended purpose where hydrostatic pressure and radar measurement systems are given as examples. Two common types of level sensors are continuous level sensors and point-level sensors. The difference is that a continuous level sensor operates within a certain range and gives precise measurements in a defined place while a point-level sensor only indicates if the level is above or below a certain limit.

4 Technical Information CV9035

To understand the need for condition based maintenance and the application of it into the military vehicles a technical analysis of the vehicle is made. This chapter contain a description of the current maintenance situation for the CV9035 including a short assessment to common problems that have occurred regarding maintenance. A basic description of the components of interest in the propulsion system is also accomplished together with a brief explanation of what measuring and communication techniques that are used in the vehicles.

4.1 Current Vehicle Maintenance Situation

The maintenance performed on the CV9035 today is a combination of preventive and corrective maintenance. Due to demands on a maximum amount of time spent on maintenance by the customers, as well as for cost rationales, only the most critical components in the vehicle are included in the preventive maintenance schedule. The remaining components are replaced only when urgently and immediately required due to failure or breakdown.

The preventive maintenance tasks are included in a chart stating what to do and when to do it. The frequency of each maintenance task is based on how critical the part is for the system, the probability of failure and the user profile. This means that a maintenance plan is designed to each customer with the purpose of ensuring vehicle performance and availability according to a yearly usage profile provided by the customer. The plan is designed with fixed steps of calendar or vehicle usage based maintenance intervals. These can be daily, monthly or every 1000 km etc. and induce the need to assign each task an interval that may or may not be the appropriate and desired interval.

The main problem with this approach is the lack of knowledge of their component conditions throughout its lifecycle due to the shortcomings in stored data and experience from a historical point of view. This complicates the maintenance planning since the assumptions made have little or no support from previous experience regarding the components. The company lacks a proper arrangement of how to retrieve collected data regarding all maintenance performed on military ground out in the fields.

The desire to increase knowledge regarding their components condition and usage originates from the following scenario.

The vehicles are out in the field where possibilities of maintenance and availability of spare parts and fluids are limited. Various circumstances results in vehicle usage diverging from the initially reported user profile. These circumstances can contribute to consumption of the yearly operational hours during a short period of time. Since the current maintenance plan is based on a general yearly usage profile in terms of operational hours the diverging vehicle usage complicates the maintenance planning substantially. This brings forward the need of an extended usage profile to enable proper maintenance planning. This also forces the maintenance to be flexible in terms of personnel and material that needs to be on site within a reasonable time period. At the same time it is difficult for a technician to determine a part or fluid condition and to ensure its lasting performance during the complete mission to come. This occasionally forces the technician to perform certain maintenance tasks in advance of their actual deadline which results in unnecessary costs.

4.2 Propulsion System Specification

Several systems with interesting components to focus on are given by BAE Systems Hägglunds. These systems and components are presented in Figure 10. All systems and components are evaluated in order to determine which ones are suitable to the purpose and delimitations of this thesis.

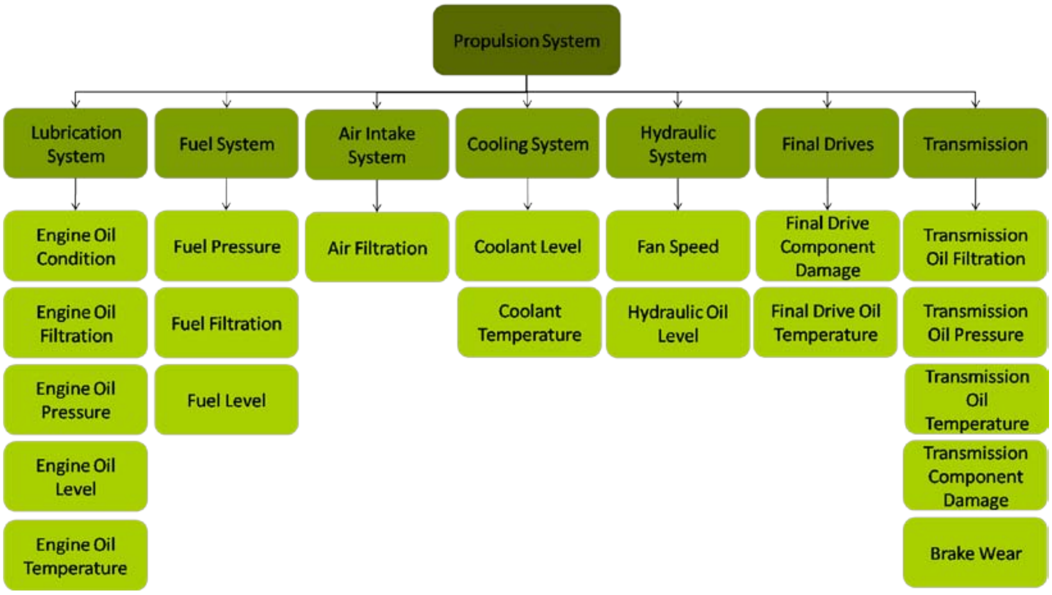
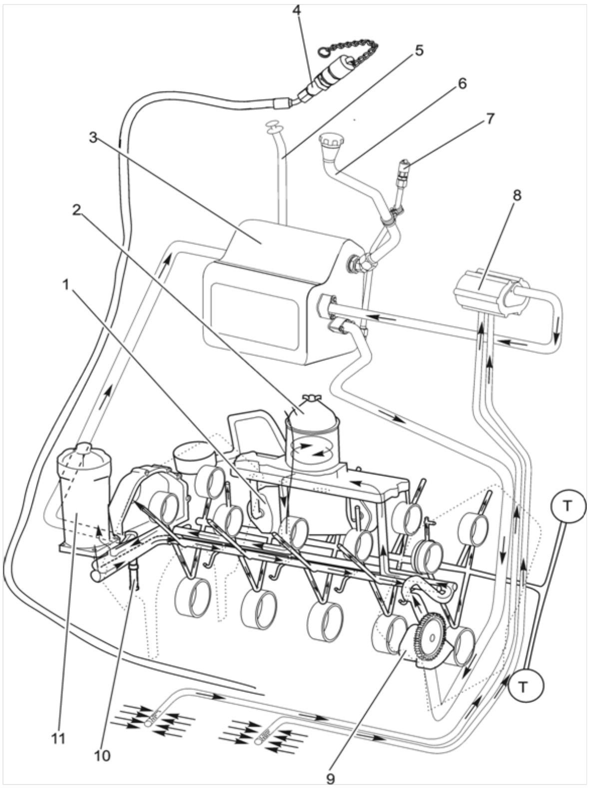


Figure 10. Original focus systems

4.2.1 Lubrication System

The engine is lubricated by a pressurized system. An oil pressure pump ensures the oil pressure and an oil drain pump collects the oil from the dry sump and returns it to the oil tank. The lubrication system and its components can be seen in Figure 11.



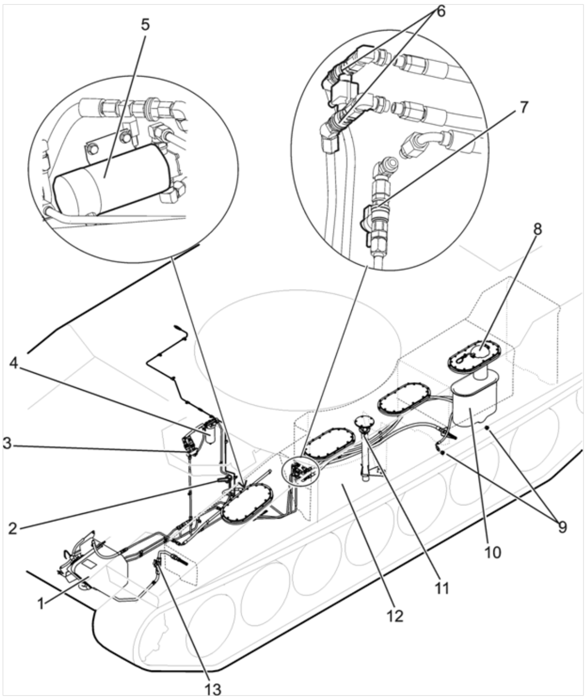
1. **Oil cooler**
2. **Centrifugal oil cleaner**
3. **Oil tank**
4. **Draining, oil sump**
5. **Dipstick**
6. **Filling, engine oil**
7. **Draining, oil**

Figure 11. Lubrication system

The oil pressure pump is driven by the engine and pumps oil from the oil tank. The oil is forced through the oil cooler located between the cylinder banks where it is cooled by the coolant. Some of it continues through the centrifugal oil cleaner where coarse particles are separated by centrifugal forces. All oil continues through the oil filter before reaching the lubrication points of the engine. A drain pump is used to evacuate oil from the dry sump and return it to the oil tank, which the oil pressure pump continuously extracts oil from. As safety precautions, an oil pressure reducing valve is connected to the oil duct of the engine and the oil filter. The valve connected to the oil duct is opened when the pressure reaches six bars and includes a pipe to the oil tank to evacuate the surplus oil. The oil filter valve is located at the bottom of the filter and designed to let oil bypass the filter if the pressure becomes too high to ensure engine lubrication.

4.2.2 Fuel System

The purpose of the fuel system is to provide sufficient fuel to the engine. The components included in the system and its layout in the vehicle is shown in Figure 12.



1. Feeder tank
2. Control lever, selection of fuel tank
3. Quick coupling
4. Water separator
5. Fuel lift-pump
6. Shut-off valves, reserve volume
7. Shut-off valves, fuel lift pump
8. Refuelling
9. Drain plugs
10. Reserve volume
11. Fuel level sensor
12. Main tank
13. Shut-off valve, feeder inlet tank

Figure 12. Fuel system, chassis schematic

Some components are included in the fuel system in order to maintain a qualitative fuel system regarding fuel quality and fuel pressure. Quality is considered by guiding the fuel through a water separator to extract water mixed with the fuel. The water separator also includes a filter to trap coarse particles and further down the fuel flow a fuel filter is positioned to trap finer particles. To maintain the desired fuel pressure a feeder tank is located downstream of the main tank. By using an overflow pipe between the main tank and feeder tank, the latter is always expected to be filled and when traveling up-hill a fuel lift pump is engaged to ensure the fuel flow to the feeder tank. From the feeder tank a fuel supply pump sucks fuel and forces it through the downstream filtration devices. To let air escape the system a hand pump is found on the engine induction manifold to bleed the fuel system by sucking fuel from the selected fuel tank to the feeder pump.

4.2.3 Air Intake System

The air heading towards the engine combustion chambers are guided through two different stages of cleaning. A cyclone cleaner performs the initial cleaning by causing the air to swirl. When swirling, dirt particles experience centrifugal forces that cause them to separate from the air and stay in the cyclone. The cyclone cleaner is illustrated in Figure 13.

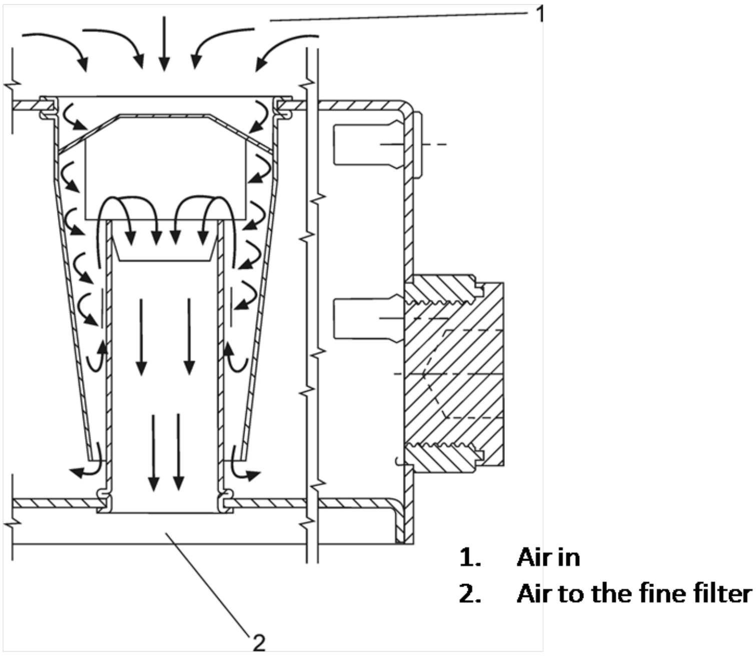
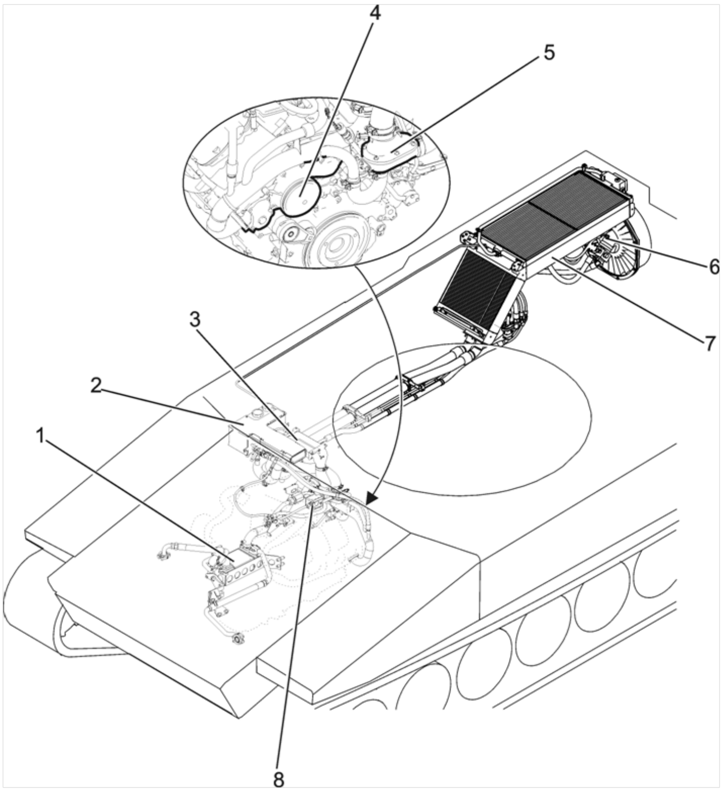


Figure 13. The cyclone cleaner

Since smaller dirt particles are not sensitive to this cleaning method an additional cleaning stage is needed downstream of the cyclone cleaner. To trap these smaller particles an air filter is used. Unlike the cyclone cleaner this air filter is more sensitive to the particles it is subjected to which shows by an increase in pressure drop as the filter clogs with particles.

4.2.4 Cooling System

The vehicle has a combined cooling system for the engine and the transmission. As long as the coolant temperature is below 71° C it only circulates internally within the engine and the transmission oil cooler. When the coolant exceeds this temperature it also circulates to the radiators located rearwards of the vehicle. The components included in the cooling system are depicted in Figure 14.



1. **Transmission oil cooler**
2. **Expansion tank**
3. **Final drive cooler**
4. **Coolant pump**
5. **Thermostats, coolant**
6. **Cooling fan**
7. **Radiator, engine**
8. **Thermostat, intercooler**

Figure 14. Cooling system

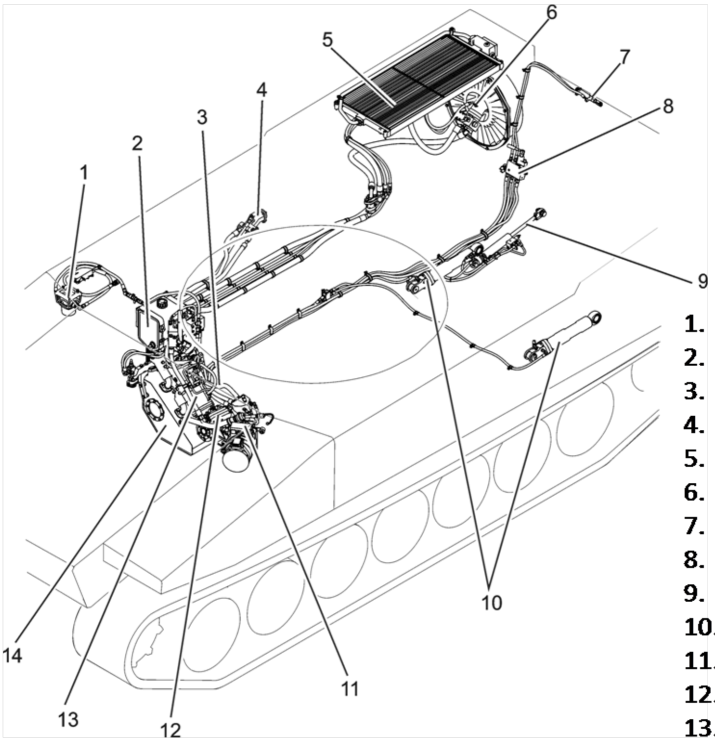
In order to achieve a higher boiling point for the coolant the system is kept at high pressure. To keep the pressure at the desired level an expansion tank is installed in the system with built in valve functions in the cap. This valve opens when the pressure exceeds 75 kPa to let air into the cooling system while the coolant cools down. To prevent engine wear or damage an automatic engine shut down is activated if the coolant temperature exceeds 110° C or if the coolant level is below a certain limit. To achieve this, a temperature sensor is installed in the system and a level sensor within the expansion tank.

At the rear of the vehicle the radiator and cooling fan are located. The air flow enters above the horizontal radiator, goes through it and exits through the cooling fan which is causing the air flow. The coolant temperature returning from the engine radiator is measured by a thermostat valve, which controls the fan speed by adjusting the fluid flow from the hydraulic pump that operates the fan.

4.2.5 Hydraulic System

Among other things, the hydraulic system is used for engine cooling as well as steering and braking. A hydraulic motor operates the cooling fan and the main radiator cools the hydraulic motor oil. By monitoring the engine coolant temperature, the cooling fan speed is regulated to provide and maintain an appropriate engine temperature.

The steering is hydrostatic and the brakes can be applied using hydraulics. An illustration of the overall hydraulic system is shown in Figure 15.



1. Filling pump
2. Upper hydraulic tank
3. Valve unit
4. Hydraulic motor AC
5. Hydraulic oil radiator
6. Hydraulic motor, cooling fan
7. Locking cylinder
8. Control circuit, ramp
9. Ramp cylinder
10. Track tension cylinders
11. Hydraulic motor, alternator
12. Pump gearing
13. Pump unit
14. Lower hydraulic tank

Figure 15. Hydraulic system

4.2.6 Final Drives

The final drives are located on each side of the transmission where they are connected to the corresponding drive shaft. Their vehicle location can be seen in Figure 16.

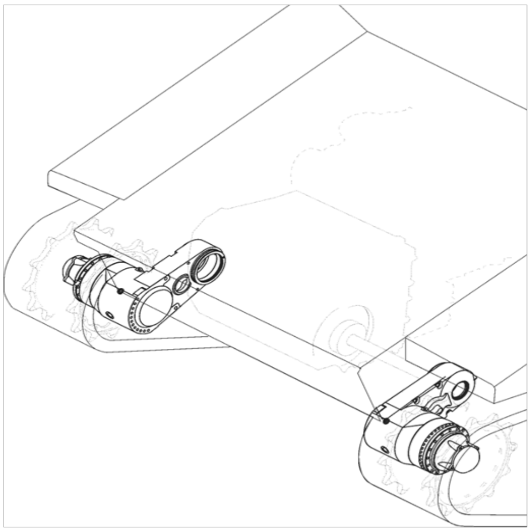
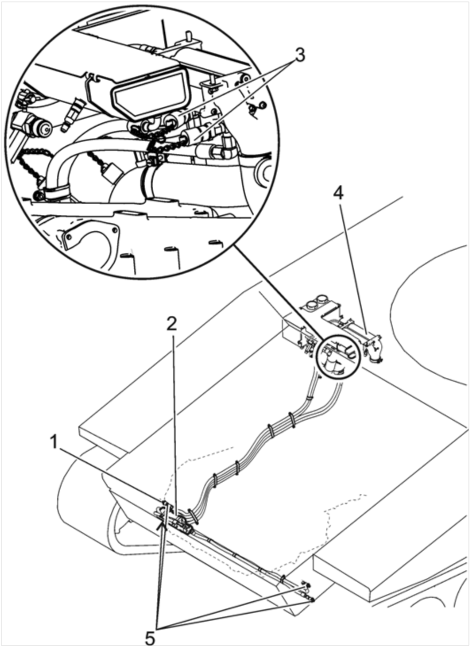


Figure 16. Final drives in vehicle

Lubrication is achieved by splash lubrication, meaning that the gearwheels create a circulation of the embedded oil. A temperature sensor monitors the oil temperature and starts a circulation pump when it exceeds 120° C and keeps circulating the oil until the temperature drops to 110° C. When the circulation pump is running the final drive oil is pumped to a cooler included in the engine cooling system. A schematic of this is shown in

Figure 17. To reduce the risk of metallic debris interacting with meshing gears chip detectors are included in the system instead of an oil filter because of packaging issues.

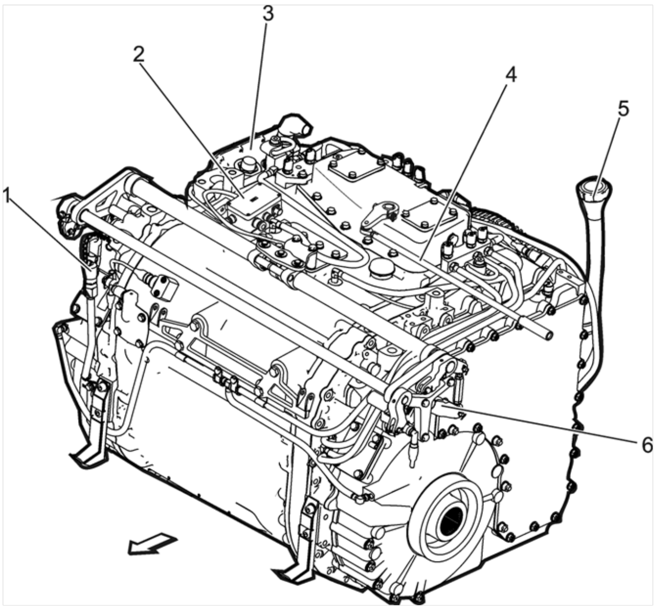


1. Temperature sensor
2. Circulation pump
3. Quick couplings, oil change
4. Cooler
5. Connections, final drive cooling

Figure 17. Cooling of final drives

4.2.7 Transmission

The transmission is fully automatic with planetary gears providing four forward gears and two reverse gears. A control unit gathers information from three rpm sensors, the gear selector and the accelerator for an electronic regulation of the transmission. An illustration of the transmission is shown in Figure 18.



1. Connection, draining the oil
2. Junction box
3. Control unit
4. Steering linkage
5. Oil dipstick, oil filler pipe
6. Brake linkage

Figure 18. Transmission

Included in the transmission are both steering and brakes. The steering is actuated by the steering linkage and is designed to increase the speed of the outer track when cornering. If the gear selector is put in neutral, the vehicle can perform a pivot turn by rotating around its centre axis. The brakes are connected to the output shafts and cooled by the transmission oil. The service brake can be applied both hydraulically and mechanically while the parking brake only has mechanical engagement.

The transmission oil is directed through the transmission oil filter. To ensure sufficient lubrication even with a clogged oil filter a by-pass valve is included in the filter. Its activation means a continued oil flow but without cleaning.

4.3 Communication and Measuring Techniques

In this section the current communication systems utilized in the vehicles are described along with their main functionalities and the systems design.

4.3.1 Vehicle Communication Systems

The systems within the CV9035 interact with each other to provide a complete system that gives the user important information as well as full control of the vehicle. A schematic overview of these systems, and how they interact, is shown in Figure 19.

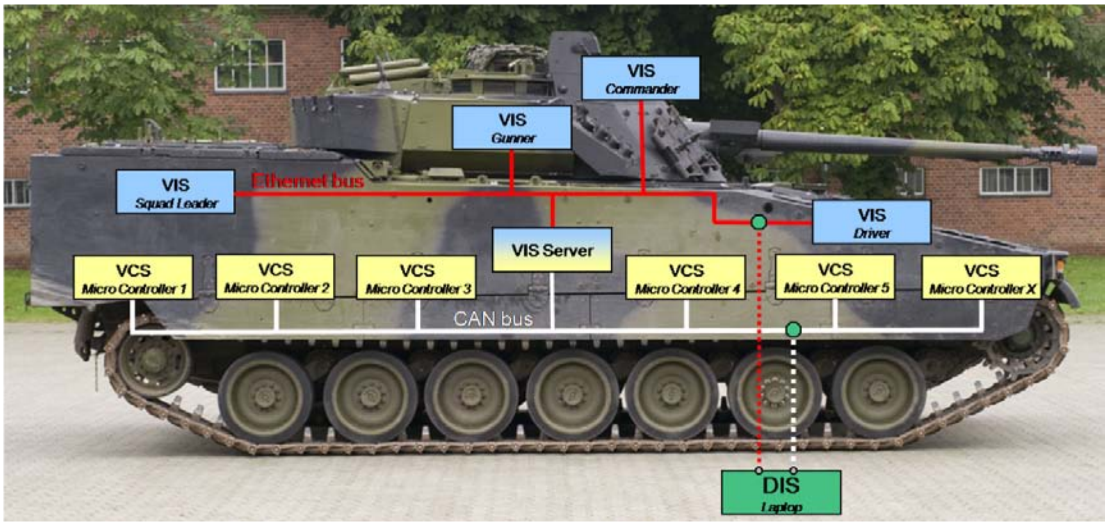


Figure 19: Schematic overview of how VIS, VCS and DIS are integrated in the vehicle

4.3.1.1 Vehicle Information System

The vehicle information system (VIS) is a link between the vehicle and the crew. It provides access to important information given by the vehicle's systems and is used to present alarms and to give fault isolation instructions. VIS can also perform different vehicle system tests and to some extent diagnose problems. Several displays to access VIS are located around the vehicle and to give the driver, commander, gunner and squad leader immediate access to information related to their position, they have their own display with a default setting. Besides vehicle control and alarm detection the crew can also use the displays for instant feedback from the onboard video cameras.

For navigation through VIS the displays have touch control with push buttons on either side of the display. A computer is connected to each display and communicates with a VIS server installed in the vehicle. The default display information viewed for the driver is shown in Figure 20.

Figure 20: Chassis status view, default setting for the driver

4.3.1.2 Vehicle Control System

The vehicle control system (VCS) executes functions in the vehicle and controls that all necessary conditions are fulfilled before doing so. To be able to do this several sensors and actuators are integrated in the system and connected to numerous vehicle control units (VCU) that handle the necessary computations. All communication is handled through a controller area network (CAN). The user interface is designed to be simple but robust and it is conducted through the multi function panel (MFP), which is illustrated in Figure 21.

Figure 21: Multi function panel

4.3.1.3 Diagnostic Information System

The diagnostic information system (DIS) is a system that can be connected to a target system, which in this report is limited to the CV9035, when different tasks are to be performed. The DIS software needs to be installed on the computer utilized for diagnostics and can perform several actions on the target system. Its main functions are divided into four areas that together complete the system; *information flow*, *diagnostic tools*, *calibration* and *configuration*. The information flow handles all data such as logs and signals and exports these from the target system to a designated external location. The diagnostics tools are used for an analysis of the target system and helps in the fault isolation procedure. Calibration is mainly used to perform adjustments or calibrations of the target system but also enables the ability to test some of the safety features within the target system. Configuration aids in the procedure when upgrading the target system software. It also gives information about the current software version within the target system. Figure 22 shows a schematic of DIS connected to a target system.

Figure 22. Schematic of DIS connected to a target system

5. Empirical Material

This chapter reveals how CBM is utilized in other companies today and an assessment of trending measurements together with thresholds and alert limits is made. Finally the system design is revealed including a requirement specification and a system communication layout to display necessary features in the system.

5.1 Market Research

To explore how CBM is utilized in today's industries three interesting actors are visited and their involvement in CBM is discussed together with recommendations for the maintenance system implementation. The choice of companies to visit is based on their success in developing a competent maintenance program for their products together with the company accessibility.

5.1.1 Chalmers University of Technology

Associate Professor Ann-Brith Strömberg, Department of Mathematics
Professor Mikael Patriksson, Department of Mathematics
Gothenburg, March 2010

Besides lecturing A-B. Strömberg and M. Patriksson and their department are occupied with research within future maintenance. Their main expertise lies within statistical based grouping of maintenance tasks also called opportunistic maintenance (see 3.1.1 Opportunistic Maintenance). Recently A-B. Strömberg and M. Patriksson completed a long collaboration with Volvo Aero, aiming at developing a maintenance schedule for their maintenance tasks to increase efficiency and lower maintenance costs. The end result is very satisfying and shows a significant cost reduction as intended and desired.

5.1.1.1 Main Study Visit Findings

- **Utilize the knowledge gathered along with schematic software developed by the department of Mathematics, Chalmers University of Technology.**
- **Group maintenance tasks to improve efficiency and lower costs for maintenance.**

5.1.2 Volvo Aero

Bengt-Åke Persson, Field service and customer support
Anders Larsson, Durability calculations
Mikael Wilenius, Automation and mechatronics
Jörgen Gahne, Test data analysis
Trollhättan, April 2010

Volvo Aero was founded in the late 1930's to supply the Swedish air force with engines. In the turbulent 90's the company progressed towards stronger specialization in large engine components and they are now market leaders in developing and manufacturing engine components.

Their current maintenance program is a runtime based preventive maintenance schedule based on years of experience of their components. Every 100 hours a thorough manual inspection is carried out to determine the condition of the components. In addition, before every take off a health check is made to ensure a safe flight. This check up is performed manually and visually and is well documented for future references. If a longer flight is planned further diagnostic information can be attained from the diagnostic system to enable preventive maintenance planning.

Currently Volvo Aero also runs a data registration system on certain parameters in the engine. The pilot is alerted only if there is an emergency that requires immediate actions to be taken, namely landing. In this case no root cause is revealed but only relevant information of precaution action that needs to be taken. In the case of less emergent failure the data is stored for the technician that runs the diagnostics after landing in order to state the condition of the aircraft.

The first maintenance program developed on Volvo Aero was not based so much on experience as it was on calculations and simulation of values in relation to the surroundings. As the years went by the engine tests and simulations together with refined calculations improved the accuracy of previous lifespan values. Experience based knowledge in the field is gathered by dismounting parts that reached their end of life time, and then analyzed and evaluated to support or oppose existing theoretical values. These inspection and hardware evaluations have also been thoroughly documented to act as foundation for future maintenance plans.

5.1.2.1 Main Study Visit Findings

- **Create a preliminary system with theoretical lifespan values and gather data throughout vehicle utilization to improve system functionality and reliability.**
- **Consider what information that is relevant for the driver to avoid distraction if not necessary.**
- **Perform frequent hardware inspections and document these thoroughly**

5.1.3 Pon Equipment

Nils Wiberg, Service Manager
Gothenburg, April 2010

Pon Equipment was founded in 1967 and their business is mainly based on servicing and selling Caterpillar (CAT) excavators, trucks, forklifts and dumpers. Currently they supply over 100 different machines and their main philosophy is as follows.

"It will last all the way. Not partly, half or almost the whole way, but all the way."

Currently Pon Equipment has an experience based maintenance schedule for their machines. They service their machines in intervals of 500 hours extended from previous 250 hours due to thorough planning of preventive maintenance activities. Every maintenance task is comprehensively documented in CAT's Dealer Business System (DBS) which lays the foundation for improved maintenance plans in the future.

Component measurements of different kinds for this type of machines are related to average power output based on current utilization profile. If two measurement deviations are recorded within the warranty time an action is triggered for CAT and a third error sets off a project to correct this failure from occurring in future lineups of machines. All Pon Equipment facilities placed all over Europe are connected to the DBS which not only handles machine and business related information but also the logistics around spare parts and other components to simplify the service of the machines.

Pon Equipment sells service arrangements charged by number of operative hours which means an equal relationship between customer and dealer. If the machines are taken out of operation both customer and supplier lose out. The first maintenance deals were created in the beginning of the 80's based on their information database founded ten years earlier and have been improved regularly ever since.

The current maintenance program is mainly preventive but in two cases Pon Equipment practice condition based maintenance. Firstly on all scheduled service points a sample of the engine oil is extracted and sent for analysis to discover its current condition. Secondly the machines on customer sites are equipped with a data gathering system which sends out frequent emails to Pon Equipment with experienced error codes and alleged time left to maintenance. This information reveals the condition of the machine, which enables planning of maintenance activities and eases the logistics around the actual maintenance tasks.

N. Viberg further emphasized the need for gathering real scenario data with the following quotation:

"Theoretical lifespan is one thing but operational experience can only be derived from history"

5.1.3.1 Main Study Visit Findings

- **Establish a suitable data gathering system to get proper information for future maintenance plans.**
- **A full service deal can be developed creating mutual gain or loss for customer and dealer.**
- **Determine a suitable way of communicating with the machines based on business situation and utilization of the vehicles.**
- **Explore the possibility of utilizing a real time monitoring unit that communicates the condition in predetermined intervals.**
- **Determine suitable parameters from the engine to which measurements can be related in order to give a clear view of the data.**

5.2. Trending

In the following section the chosen systems for trending are revealed along with a systematic trending assessment for each component. A short justification for implementation is given to motivate the advantages with realization of trending for this component. This motivation does in most cases include real life experiences with the components at BAE Systems Hägglunds.

To get accurate measures for trending to enable reasonable assumptions for component life times many of the measurements need to be normalized due to noisy signals, discrepancies, dependencies on other measures etc. (Fitch, 2010). According to BAE systems Hägglunds the measurement dependencies induces the need for other parameters than those encountered for to be trended concurrently in order to establish a proper evaluation foundation. Useful measurements in the matter could be as follows.

- **Engine load**
- **Driven kilometers**
- **Engine speed (RPM)**
- **Outer temperature**
- **Number of cold engine starts**
- **Engine temperature**

To get an extended CBM system many other aspects in addition to trending need to be considered such as failure diagnostics and opportunistic maintenance. Since this thesis focuses merely on trending the extended system needs further development to become a extended condition based maintenance system. The components chosen for the trending system are those of interest for time logging in order to enable maintenance need predictions for the system.

After evaluating the complete list of systems and components presented in section 4.2 Propulsion System Specification and eliminating systems and components without relation to maintenance activities, the systems displayed in Figure 23 are chosen. A complete list of the excluded systems and components together with motivations is displayed in Appendix A.

After this screening, eight components are left for a trending assessment. Of these components six requires hardware implementation in the vehicle. These components are marked with a red cross in Figure 23.

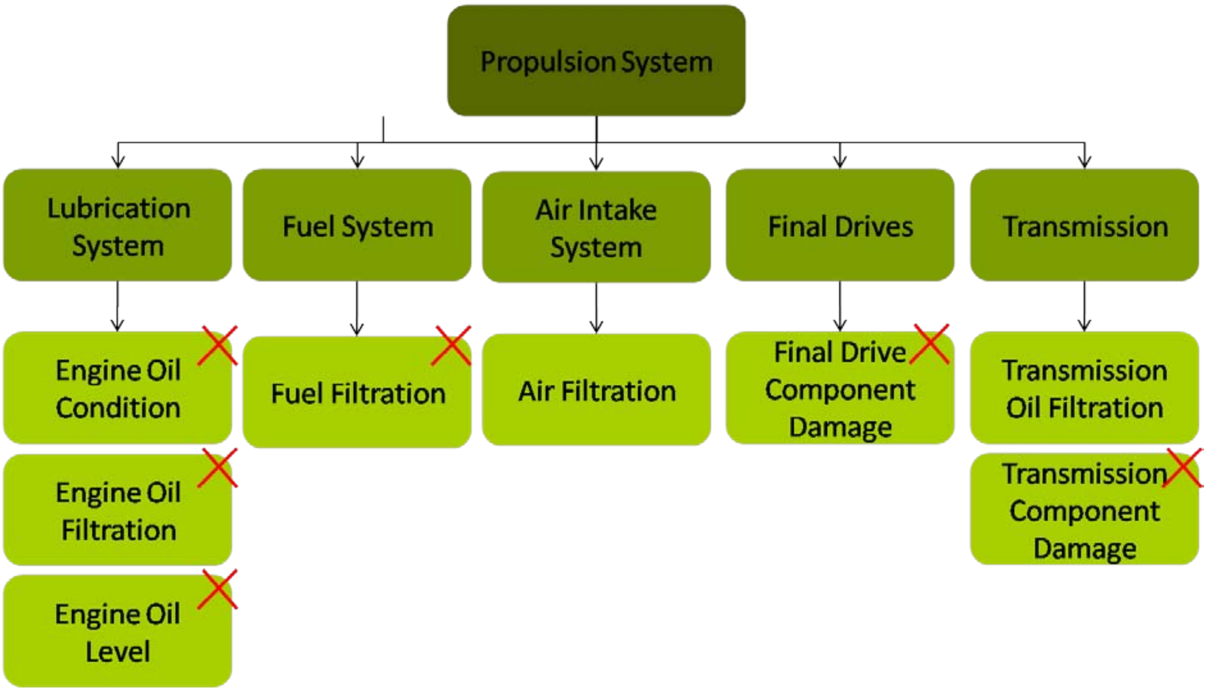


Figure 23. Focus systems after screening

As mentioned above these systems are connected to important and crucial maintenance tasks and if the execution of these tasks could be more accurately planned in advance money should be saved. The maintenance activities required when the measurement detectors alert the need for maintenance are displayed in Figure 24.

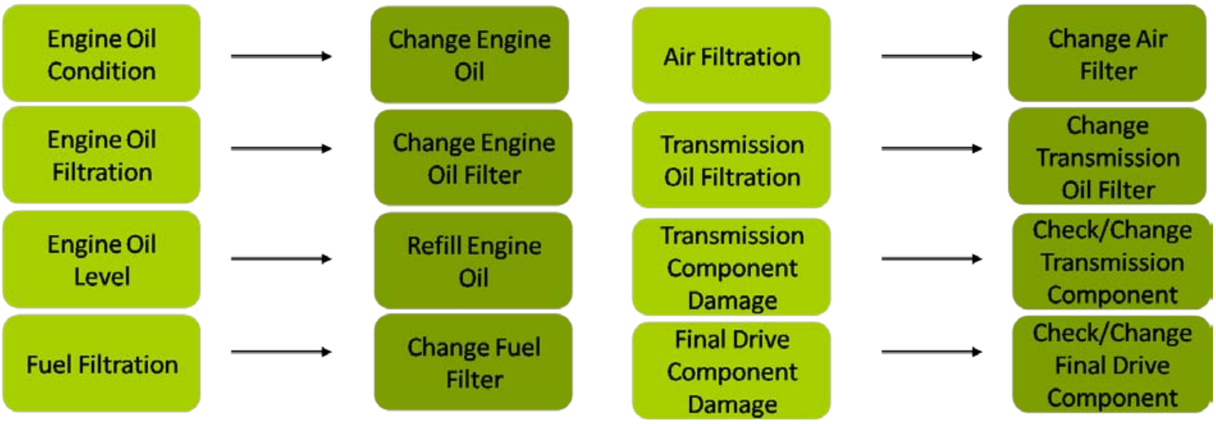


Figure 24. Components and related maintenance activities

Each component description below contains a discussion on whether or not the measurement should be static or dynamic (see 3.1 Condition Based Maintenance). The main difference is if the measurement of interest is the actual value of the parameter or the rate of change. If the component lifetime degradation is consistent throughout its life curve (see Figure 25) there is no need to monitor the rate of change since it is the actual value of the measured parameter that is of interest. In the other case of an immediate change in degradation (see Figure 26) the rate of change or curve inclination is the more interesting parameter since it indicates a close failure point.

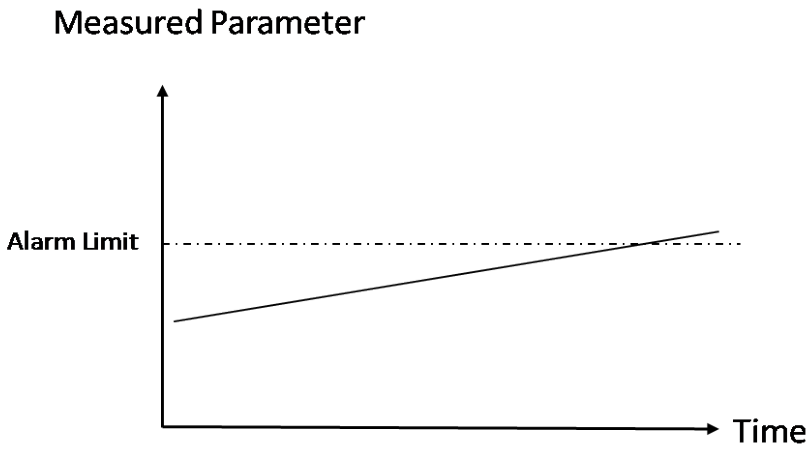


Figure 25. Static measurement curve

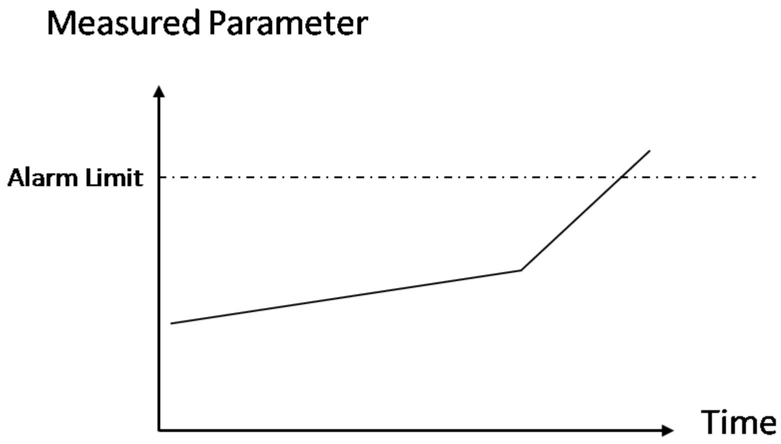


Figure 26. Dynamic measurement curve

The figures describe an ideal representation of trended parameters from a logging measurement. The dotted lines represent the alarm limit for the parameter and the point in time where the component lifetime is dangerously close to final. Figure 25 shows a measurement with expected linear degradation in component lifetime whilst Figure 26 shows degradation with an abrupt change in the latter stages of its lifetime. As explained above the latter curve induces the need to monitor the inclination change or derivative of the parameter rather than the actual value in order to foresee probable failure point in time.

5.2.1 Lubrication System

Three maintenance tasks of great importance for the propulsion system are included in the lubrication system; changing oil, changing oil filter and refilling oil. Optimization of these tasks can not only lower cost but also affect the life span for the engine. A full review of the maintenance tasks along with a trend measurement evaluation is presented below.

5.2.1.1 Engine Oil Condition

The combustion process in diesel engines produces soot that contaminates the engine oil which can cause damage to the engine if not corrected in time. The soot increases the oil viscosity which deteriorates the engine lubrication. Other dilutions as water and fuel also affect the viscosity of the oil but in the opposite manner which also affects the lubrication performance resulting in increased engine wear. To optimize the engine oil changes an oil condition sensor can monitor the status over time enabling prediction of remaining oil lifespan. The oil condition sensor is currently not implemented in the vehicle.

The sensor is able to measure soot and viscosity but certain requirements need to be fulfilled in order to attain valid measurements. The vehicle needs to be turned off since the oil is required to be stationary and the viscosity measurement needs a cool down phase from 80° C to 70° C. Furthermore it is recommended that the vehicle tilt does not exceed 15° in order to achieve accurate values.

Since the engine oil soot level is considered to have an average growth proportional to time a static measuring approach is sufficient for good lifetime estimation. Due to this the derivative is constant with no indication of condition change, which is why dynamic measurements are unnecessary. The estimation of average soot contamination distribution is displayed in Figure 27. Since the viscosity change is proportional to soot contamination its general spread over time also appears as shown in Figure 27.

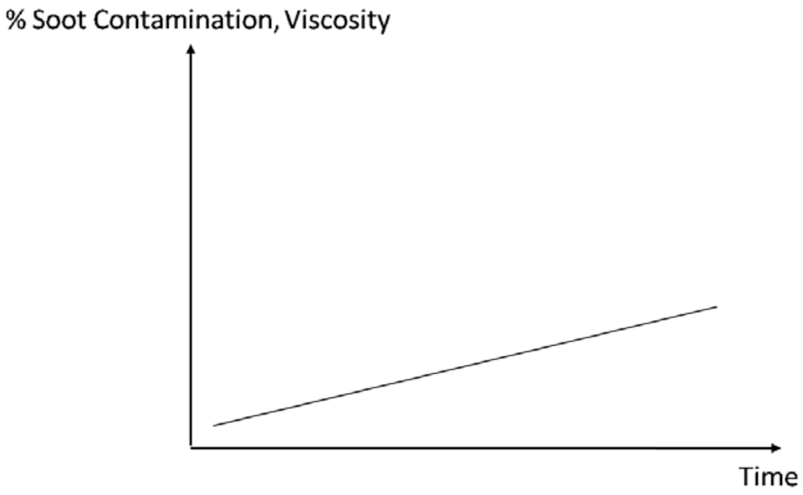


Figure 27. Life cycle curve – engine oil condition

The engine oil currently used in the vehicles is *Mobil 5W-30* from which the baseline condition can be derived. Since the oil condition sensor only can measure viscosity between 15-50 cSt at 70°C, viscosity values need to be derived from engine test runs. However, approximated starting values for the soot level contamination extracted from product specifications and expert discussions can be found in Table 2.

Table 2. Trending – engine oil condition

Trending – Engine Oil Condition					
Logging Parameter	***Baseline Conditions***	***Warning Limit***	***Alarm Limit***	***Measure Interval***	***Related Measures***
soot level	0 - 2 %	2.5%	4 %	-	Engine status Vehicle tilt Oil temperature
% over time		X days left to etc			
viscosity level	-	-	-	-	Engine status Vehicle tilt Oil temperature
cSt over time		X days left to etc	Perform corrective action instantly	Sampling frequency	

5.2.1.1.1 Justification for Implementation

When replacing the engine oil at their predetermined maintenance intervals, BAE Systems Hägglunds has discovered that its condition is occasionally better than expected. It has also occurred that water and diesel got mixed with the oil when refilling out in the field from an incorrect container. Events like these can all lead to potential engine damage, which motivates the need for an oil condition sensor. Besides engine damage it is also financially beneficial to monitor the oil condition in order to perform maintenance tasks based on actual oil condition instead of an expected condition derived from an estimated driving profile. This leads to a cost reduction due to either fewer oil changes, less oil waste and logistical savings or less engine or transmission damage.

5.2.1.2 Engine Oil Filtration

The engine oil consists of soot and metallic debris which partly are separated from the oil by the oil filter. Because of this the oil filter becomes clogged, which decreases the lubrication performance. To be able to detect deteriorated filter health the difference in oil pressure over the filter can be measured. Currently an engine oil pressure sensor exists but since its placement is too far from the oil filter, implementation of a differential pressure sensor over the filter is required to perform these measurements.

To receive valid measurements oil viscosity and oil temperature need to be considered. Increased temperature and lowered viscosity both decreases the oil filter pressure drop.

The oil filter is gradually clogged with generated particles deposited in the oil. Since these particles are produced regularly, the same amount of oil needs to flow through a filter with decreasing flow area. This means that the pressure drop over the filter will increase exponentially over time as shown in Figure 28.

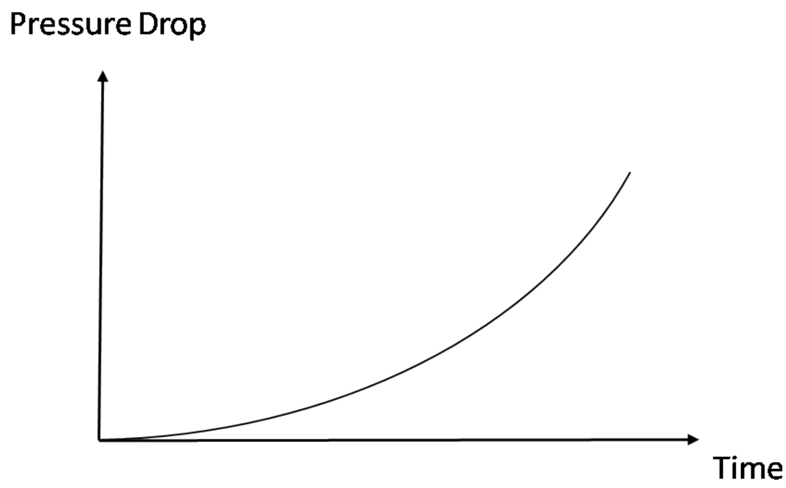


Figure 28. Life cycle curve – engine oil filtration

Since a sensor of this kind is not installed in the system today, no alarm and failure limits are established. Because of this, Table 3 only shows what to measure and what to consider but lacks important limits needed for an effective monitoring system.

Table 3. Trending – engine oil filtration

Trending – Engine Oil Filtration					
Logging Parameter	***Baseline Conditions***	***Warning Limit***	***Alarm Limit***	***Measure Interval***	***Related Measures***
$\frac{\Delta P}{t}$	-	-	-	-	Oil temperature Oil viscosity
mbar over time		mbar/X days left to etc	Perform corrective action instantly	Sampling frequency	

5.2.1.2.1 Justification for Implementation

The present procedure for exchanging the engine oil filter is to do it when exchanging the engine oil. When examining the engine oil filter after replacement, it has shown that its health is far from being critical. This is why no differential pressure sensor is implemented in the vehicles today and why it is, from a maintenance point of view, probably not cost efficient enough to implement such a sensor. On the other hand, if the oil condition sensor is installed the engine oil is most likely not to be replaced as often as today. This means that the engine oil filter health becomes more critical as the engine oil lifetime expands.

5.2.1.3 Engine Oil Level

Another sensitive parameter for lubrication performance is the engine oil level. Due to oil evaporation and oxidation in the engine a certain amount of engine oil is consumed. Monitoring the oil level secures desired lubrication performance and enables planning for engine oil refill which lowers the cost of maintenance as well as for the logistics related to the maintenance.

The accuracy of the oil level measurement is affected by the oil temperature and oil pressure. Increased temperature and pressure can cause oil expansion which can result in invalid level measurements. Because of this, these parameters need to be considered when executing the oil level measurements.

As previously mentioned, a certain amount of engine oil consumption is constantly present. Although the oil consumption is related to the vehicle operation, the expected amount of average engine oil consumption over time can be visualized as in Figure 29 where a random inclination is used. Because of this it is only interesting to monitor the actual oil level and not the rate of change, meaning a static measuring approach is appropriate for this application.

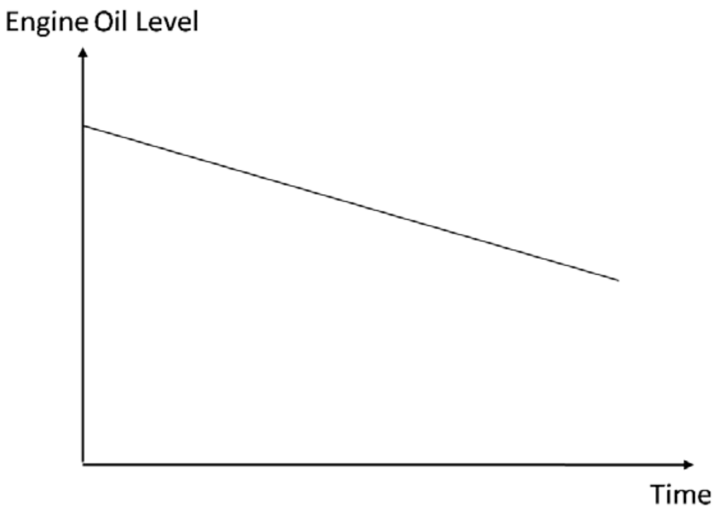


Figure 29. Life cycle curve - engine oil level

Based on the engine oil tank capacity and the engine oil consumption during a 400 hour vehicle test the necessary data in Table 4 can be derived. Depending on current vehicle tilt the oil level needs to be of a certain magnitude. Because of this, Table 4 indicates maximum oil consumption when the vehicle is experiencing maximum tilt as well as no tilt. Due to an average consumption of eight litres per 400 hours driving a ten percentage measuring interval is every five hours.

Table 4. Trending - oil level

Trending – Oil Level					
Logging Parameter	***Baseline Conditions***	***Warning Limit***	***Alarm Limit***	***Measure Interval***	***Related Measures***
V	40 L	39 L (35 L)	36 L (20 L)	5 h	Oil temperature Oil pressure
L over time		L/X days left to etc	Perform corrective action instantly	Sampling frequency	

5.2.1.3.1 Justification for Implementation

Since no level sensor of the engine oil is present today an implementation is required to trend its condition. The advantages of doing so from maintenance point of view is the awareness of when to refill oil and the assuredness of an adequate oil level for sufficient lubrication. This saves man-hours if visual inspection can be minimized and minimization of potential lubrication problems due to insufficient oil level. These factors might not motivate the sensor financially why the benefits from a diagnostic system also need to be included when justifying the cost.

5.2.2 Fuel System

Besides refueling the main maintenance task for the fuel system is changing the fuel filter. The need for refueling is already visualized in the vehicle information system why no further consideration is required regarding this. How the need for maintenance can be measured for the fuel filter is described below.

5.2.2.1 Fuel Filtration

To secure the condition of the fuel injected into the engine a fuel filter separates rust and debris from the diesel. To monitor the degree of filter clogging a differential pressure sensor measures the difference in pressure over the filter. If the pressure difference over the filter increases beyond a certain limit sufficient fuel injection pressure cannot be maintained which increases the need for monitoring further. Currently, the fuel filter differential pressure sensor is not implemented in the vehicle.

The fuel filter pressure drop depends on fuel viscosity and since different types of diesel have varying viscosity the filter life varies. In addition, the temperature of the diesel affects the outcome of the measurements since increased temperature decreases the pressure drop over the filter. The rust and debris clogging the fuel filter is continuously reducing the flow area of the filter. The degree of clogging depends on engine speed and load since these factors determine the fuel flow. Because of this the pressure drop over the filter increases exponentially as shown in Figure 30. A static measuring approach is suitable for this application to indicate when the pressure drop is greater than what can be accepted for a maintained system performance.

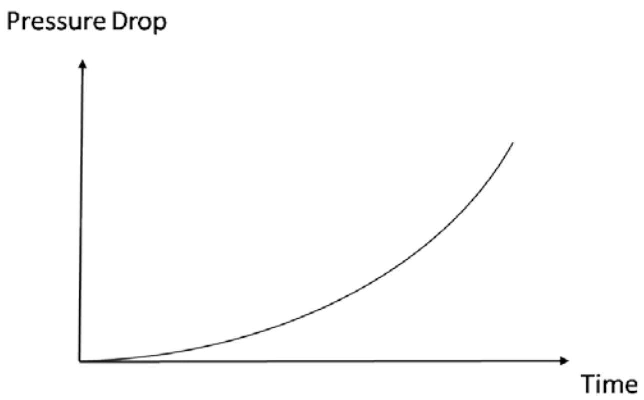


Figure 30. Life cycle curve - fuel filtration

The lack of this differential pressure sensor in the fuel system means that no warning or alarm limits are developed or known at BAE Systems Hägglunds. Unfortunately this also means that more extensive testing is needed before implementation can be fully accomplished. What to log, limits needed and what to relate the measurements to are shown in Table 5.

Table 5. Trending - fuel filtration

Trending – Fuel Filtration					
Logging Parameter	***Baseline Conditions***	***Warning Limit***	***Alarm Limit***	***Measure Interval***	***Related Measures***
ΔP	-	-	-	-	Fuel temperature Fuel viscosity/type
mbar over time		mbar/X days left to etc	Perform corrective action instantly	Sampling frequency	

5.2.2.1.1 Justification for Implementation
Since the differential pressure sensor needed to monitor the fuel filter health status is not a part of the current fuel system, motivation is needed to justify the extra cost the sensor brings. The benefits are better control of filter status with the possibility of an optimized maintenance plan. For diagnostic purposes the sensor can be used to indicate that sufficient fuel pressure is supplied to the injectors. In-house experience also reveals that the pressure relief valves located after the fuel rails not always operate in the way intended which this sensor could give an indication about.

5.2.3 Air Intake System
Changing the air intake filter is one of the most crucial maintenance tasks for the air intake system. The cyclone cleaner is not as sensitive when it comes to clogging due to a coarser filtration. The air intake filter health is related to the engine performance which makes the importance of monitoring even greater. This task is presented below.

5.2.3.1 Air Filtration
The air filter health can be monitored by measuring the difference in air flow pressure at the inlet and outlet of the air filter. By measuring the pressure drop over time the remaining life time for the filter can be derived. This enables planning of the upcoming maintenance task assuming that the anticipated life cycle curve is known. The filter and the differential pressure sensor are currently implemented in the vehicle and warns the recipient when a certain pressure drop value is reached. When measuring the air filter pressure drop other parameters need to be considered in order to extract proper data. The pressure drop is directly related to the air flow through the filter why engine speed and load need to be considered. The higher engine speed and load the greater pressure drop through the air filter. Air temperature is another parameter that affects the outcome of the measurements why this also shall be taken into account when trending the air flow pressure drop.

As for the engine oil filter and the fuel filter the air intake filter is continuously clogged with debris and particles from the ambient air. The air flow depends on engine speed and load meaning the air filter health is based on how the vehicle is driven. Since the need of air flow is independent of filter health the same amount of air needs to flow through a smaller area as the filter becomes clogged over time. This situation results in a life cycle curve with an exponential shape as depicted in Figure 31. Since the average pressure drop over the filter is expected to have an exponential shape over time only static trending is needed.

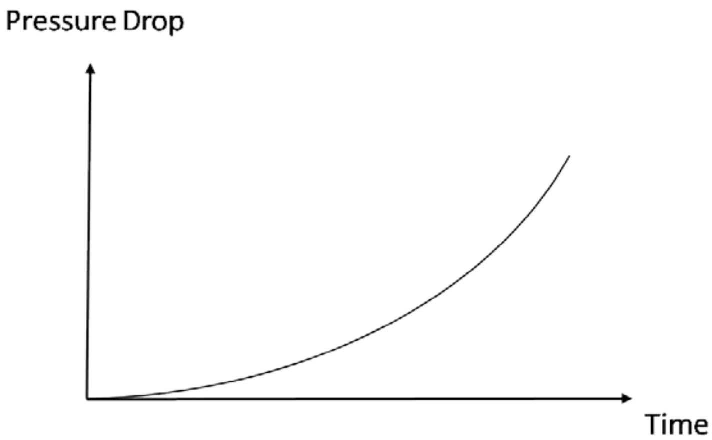


Figure 31. Life cycle curve - air filtration

The current existence of a differential pressure sensor on the air intake filter means that an alarm limit already is developed. Testing has shown that the engine can produce maximum power output as long as the pressure drop over the filter does not exceed the value shown in Table 6. The table also describes what the pressure drop measurements need to be related to as well as when warnings should be issued. The measurement interval is yet to be derived from test data gathered in the future.

Table 6. Trending - air filtration

Trending – Air Filtration					
Logging Parameter	***Baseline Conditions***	***Warning Limit***	***Alarm Limit***	***Measure Interval***	***Related Measures***
ΔP	17 mbar	21 mbar	28 mbar	-	Engine Speed Engine Load Air Temperature
mbar over time		mbar/ X days left to end of life	Perform corrective action instantly	Sampling frequency	

5.2.3.1.1 Justification for Implementation

Due to the fact that this sensor is already installed in the air intake system and an alarm level is already established the need for resources is not as large when it comes to trending compared to other systems. The advantages of trending the air filter are the ability to maximize its usage and the possibility to use its status to diagnose potential problems.

5.2.4 Final Drives

The final drives transmit power from the transmission to the tracks with a final gear ratio. Since they are needed to provide propulsion as well as steering and brakes their health is critical in order to keep the vehicle maneuverable.

5.2.4.1 Final Drive Component Damage

Surface fatigue damage on the final drive produces metallic particles which pollutes the oil. By counting these particles the actual damage on the final drive can be derived. Surface fatigue damage particles are typically larger than 200 microns which a metal detector is able to spot. Utilization of a sensor like this can ease the process of foreseeing the remaining life span of the gears and bearings.

The final drive oil is currently not fully filtered; only magnetic chip detectors are used to separate metallic debris from the oil. This has the effect that a lot of wear particles continue to flow in the oil and come in contact with all gears and bearings. This means that wear particles will interfere with bearings and meshing gears possibly causing unexpected damage or failure. Another disadvantage with an unfiltered lubrication system is that a metal detector cannot be used. Since the metal detector stores all particle mass flowing through it a filter trapping all of these particles is necessary to provide reliable component health status.

The failure probability curve (in Figure 32) and the life cycle curve (in Figure 33) for the final drive component damage has the same appearance as for the transmission component damage.

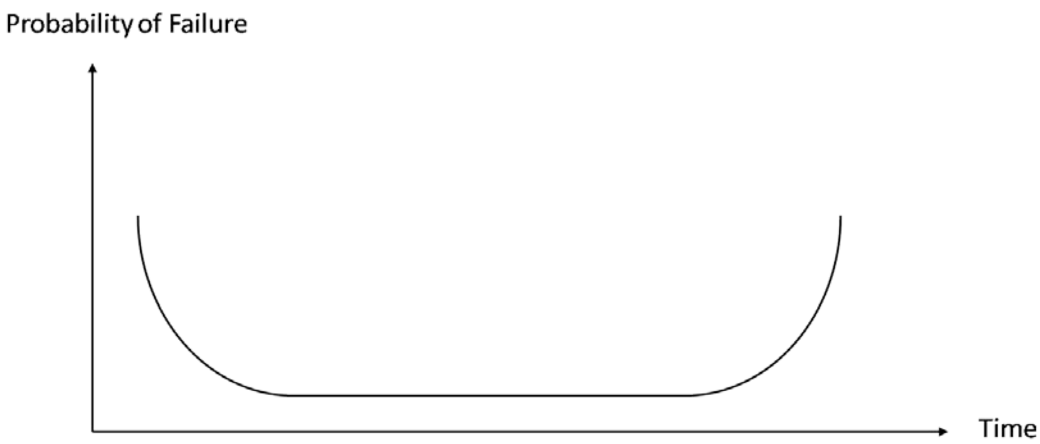


Figure 32. Probability of failure - final drive component damage

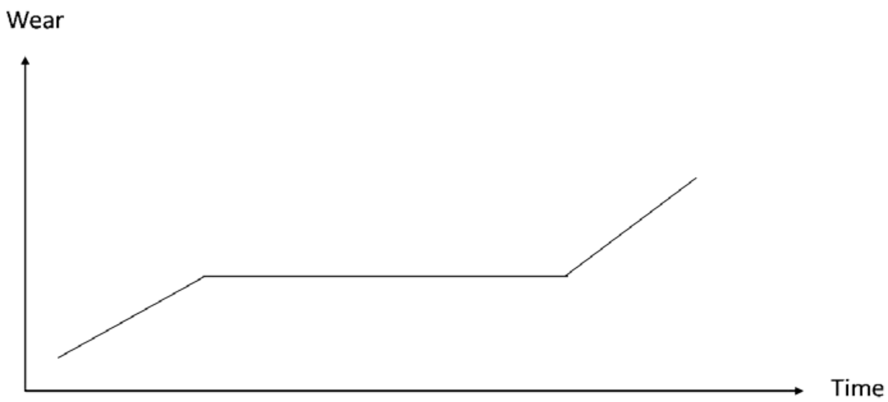


Figure 33. Life cycle curve - final drive component damage

The types of components in both systems are the same with an exception to the carbon fiber brakes, but since these particles are not supposed to influence the measurement results the systems can be considered more or less identical in this matter. This result in a recommendation of two measurements, for component damage; static measure for accumulated mass and dynamic measure for particle counting.

The manufacturer of the MetalSCAN sensor evaluated at Hägglunds provides an equation to calculate the alarm limit for bearings included in the monitored system. The equation (see Equation 1) considers type and number of bearings, the geometry of the bearings and includes a constant that is tested and developed by the manufacturer, GASTOPS.

$$\boldsymbol{M} = \boldsymbol{K} \times \boldsymbol{\theta} \times \boldsymbol{D} \times \boldsymbol{d}$$

Equation 1. Accumulated Mass

M = Detected mass

K = Constant

θ = Distance between two rolling elements (degrees)

D = Distance between two rolling elements cross the bearing (inch)

d = Diameter of the rolling elements (inch)

According to GASTOPS, the warning limit should be a tenth of the alarm limit and according to 3.1 Condition Based Maintenance, the warning limit should be 25 % above the baseline. These statements, together with Equation 1, constitute the contents of Table 7.

Table 7. Trending –final drive component damage

Trending – Final Drive Component Damage					
Logging Parameter	***Baseline Conditions***	***Warning Limit***	***Alarm Limit***	***Measure Interval***	***Related Measures***
$mass$	14.6 mg	18.2 mg	182 mg	-	None
$\frac{d\,(Particles)}{dt}$	-	-	Abrupt Change	-	None
Mg or mbar over time		Mbar or mg/ X days left to end of life	Perform corrective action instantly	Sampling frequency	

5.2.4.1.1 Justification for Implementation

There is no good way of indicating component damage in the final drives today. The only indication available is based on the amount of particles trapped by the chip detectors in the system. The problem is that these detectors only detect part of all particles flowing in the oil making the indication insufficient and the possibility to install metal detectors difficult. Because of this, the metal detector needs to be installed together with an oil filter for it to perform well and be of use.

If a metal detector is installed and the result analyzed a more accurate prediction of component damage can be established and given. Since the detector is triggered by a particle size that is typical for component damage faulty warnings caused by ordinary wear producing finer particles can be avoided. The ability to separate brake wear from transmission wear improves the prediction of component lifetime and can also aid in diagnosing problems.

5.2.5 Transmission

The main maintenance tasks of interest for the transmission system is changing oil filter and changing mechanical elements in the gearbox. To optimize the cost involved in these tasks trend monitoring can be of use since it enables maintenance activity planning and decrease the risk of unplanned failures. The systems and measurements are explained below.

5.2.5.1 Transmission Oil Filtration

Metallic particles produced from surface fatigue damage from bearings and gears as well as carbon fiber particles from the brakes contaminate the transmission oil. The transmission oil filter traps this debris to maintain oil cleanliness and thereby prevent the debris from causing further damage. It is important to avoid that oil debris interfere with meshing gears since it can cause immense damage to the gears. To monitor filter health a differential pressure sensor measures the difference in pressure over the filter.

The data extracted from the differential pressure sensor depends on oil temperature and oil viscosity which induce the need for taking these into account when assessing the measurements. Decreased temperature and increased viscosity both increases the oil filter pressure drop.

As for the engine oil filter the transmission oil filter is gradually clogged but in this case with metallic and carbon fiber particles. For as long as the transmission is used this wear is present and since the need for flowing oil remains the same the filter needs to handle a greater flow per filter area resulting in a pressure drop increase as shown in Figure 34.

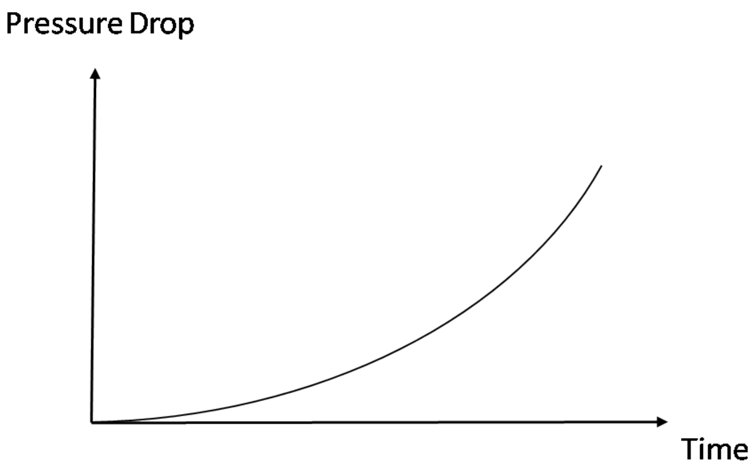


Figure 34. Life cycle curve - transmission oil filter

The current usage of this sensor means that an alarm limit is already established. The limits of interest as well as related measures can be seen in Table 8.

Table 8. Trending - oil filtration

Trending – Oil Filtration					
Logging Parameter	***Baseline Conditions***	***Warning Limit***	***Alarm Limit***	***Measure Interval***	***Related Measures***
ΔP					Oil temperature Oil viscosity
mbar over time		mbar/ X days left to end of life	Perform corrective action instantly	Sampling frequency	

5.2.5.1.1 Justification for Implementation

The fact that this sensor is already installed in the vehicles means that only trending needs to be justified. The reason to trend is to detect when the filter is about to get fully clogged by metallic and carbon fiber residuals. This can also have diagnostic benefits since it also gives an indication that either a bearing, gear or the brakes can be in a condition close to, or beyond, failure.

5.2.5.2 Transmission Component Damage

Surface fatigue damage on gears and bearings produces metallic particles which contaminates the oil. Metallic particles produced by surface fatigue damage are typically larger than 200 microns which is within a metal detector's measurement range. This enables viable monitoring of component damage which facilitates the process of estimating remaining component life time to prevent total failure of mechanical equipment.

Since transmission and brakes are lubricated and cooled by the same oil, wear particles from both the carbon fiber brakes and the bearings and gears contaminate the oil. However, since the metal detector of interest responds to detection of ferrous and non-ferrous materials the metal detector's result should not be influenced by the presence of brake wear particles in the oil.

When a completely new transmission is used an initial amount of wear particles is produced until the gears have worn themselves down to match the corresponding gears. After this initial period of increased wear the remaining usage of these components is considered to produce constant wear until component damage and failure is near. Because of this it would be of interest to apply dynamic monitoring to the system giving an indication of when the rate of change is increasing. Even so, the sensor also measures accumulated mass which in its turn would induce a statistic measurement. To ensure a comprehensive lifetime evaluation process both a static and a dynamic measurement should be extracted.

An illustration of failure probability throughout the component lifetime is shown in Figure 35. The presumed amount of wear trended over time is illustrated in Figure 36 and entails the same story for the component life cycle as the bath tub curve.

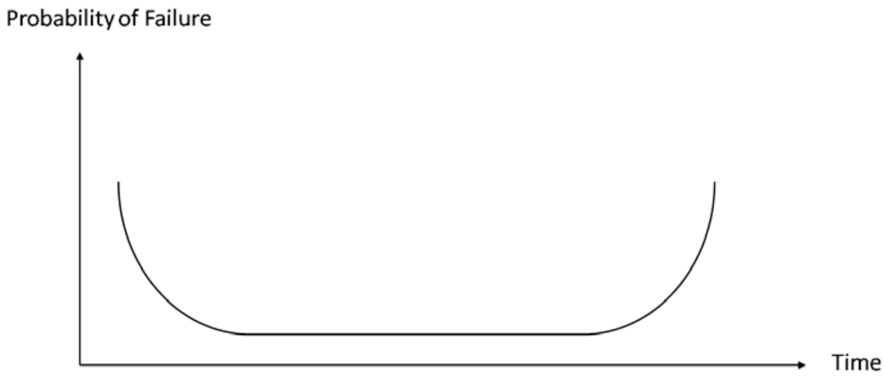


Figure 35. Probability of failure - transmission component damage

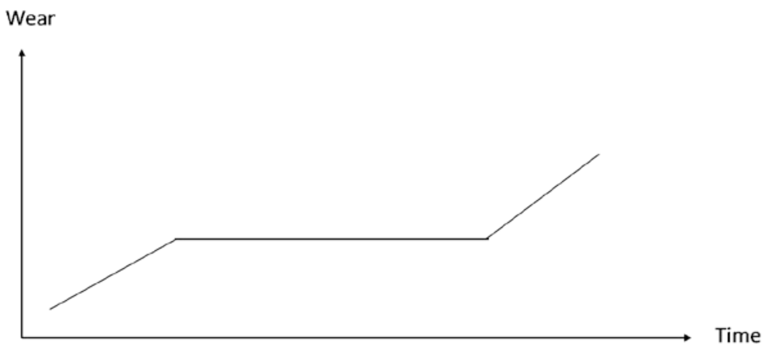


Figure 36. Life cycle curve - transmission component damage

As described in section 5.2.4.1 Final Drive Component Damage, the warning and alarm limit can be established by calculations together with given statements. Since the data required for these calculations currently are unavailable the values intended for Table 9 are not present. A thorough component evaluation is needed to discover the weakest bearing in the system. The bearing parameters can then be utilized to calculate proper values for the trending system.

Table 9. Trending - component damage

Trending – Component Damage					
Logging Parameter	***Baseline Conditions***	***Warning Limit***	***Alarm Limit***	***Measure Interval***	***Related Measures***
$mass$	-	-	-	-	None
$\frac{d(particles)}{dt}$	-	-	Abrupt Change	-	None
mg or mbar over time		Mg or mbar/ X days left to end of life	Perform corrective action instantly	Sampling frequency	

When the warning limit is triggered a technician is advised to inspect the particle size distribution of the particles detected to determine whether or not they are a result of ordinary wear or if surface fatigue damage is a fact. Since these limits depend on bearing size and type the lowest limits are introduced to the monitoring system.

If the technician considers the vehicle to be operable after the warning it can be used until the alarm limit is achieved if the component of risk is kept under supervision. When the alarm limit is achieved it is not recommended to use the vehicle unless circumstances demand it. This recommendation is due to the risk of extensive damage to the system if used further.

5.2.5.2.1 Justification for Implementation

The current indication of component damage is based on a warning triggered by a certain amount of pressure drop over the transmission oil filter. Although this gives an indication about how many particles that are worn it cannot separate carbon fiber particles from metallic particles. Another disadvantage is that it cannot interpret particle size distribution and due to this not indicate what type of wear the particles are related to. Experience from BAE Systems Hägglunds is also stating that when the warning for a high pressure drop is given a component in the gearbox has already failed. The benefits of installing this metal detector are the same as for the final drive which is described below in section 5.2.5.2 Transmission Component Damage.

5.3. System Design

To develop a suitable condition based maintenance system for the vehicle certain requirements must be fulfilled. Table 10 shows a list of the most significant functional requirements for an appropriate trending system, i.e. what the system should be able to do. Requirements regarding the financial aspect, bandwidth, external interface etc. are not covered since they stretch beyond the framework of this thesis. In addition to this a functional requirement specification for an extended condition based maintenance system is also given to clarify the magnitude of this type of system. Finally a short description of a possible system communication layout is revealed.

Table 10. Requirement specification – trending system

Area	Criteria	Area of Responsibility
Functional Requirements		
Automation	The system must automatically set baseline conditions without user input which minimizes the potential of human errors and reduces staffing.	Programming
Automation	The system must automatically store, trend and recall data enabling the user to monitor, trend and analyze component condition.	Programming
Flexibility	It must be possible to extend the system with additional sensors depending on future needs.	Design/Construction
Flexibility	The system should be able to adapt to condition changes such as utilization and surroundings.	Programming
Flexibility	The system should support different measurement techniques.	Design/Construction
Accuracy	The system should be self-learning. If life time predictions are incorrect, the system should adjust future predictions accordingly.	Programming
Accuracy	Data collected by the system needs to be accurate and repeatable since it is the basis for maintenance decisions.	Design/Construction
Consolidation	As much alert information as possible shall be presented via a single interface to ease the problem management.	Design/Construction
Reliability	The system must be tested and proven reliable before implemented or implemented and tested during current maintenance program duration.	Design/Construction
Usability Requirements		
User Friendly	The system must be easy to handle with simple and straightforward operations for increased acceptance amongst users	Design/Construction
User Friendly	The system should only present the most necessary information to the user. Additional information is kept for the technician.	Design/Construction
User Friendly	Data extraction should be fast and reliable.	Design/Construction

The trending system almost exclusively considered in this thesis is only one part of an extended condition based maintenance system able to draw conclusions from facts presented with diagnostics functionality and task grouping. Therefore, in addition to the requirements above, some further requirements have been established for the extended system and are presented below in Table 11.

Table 11. Requirement specification – extended condition based maintenance system

Area	Criteria	Responsibility
Functional Requirements		
Redundant monitoring	Redundant monitors are back-up to one another since no single monitor can succeed for every mode of failure. More monitors ensure no failure is undetected.	Design/Construction
Monitors that correlate	Interrelated monitors establish a link between cause and effect. If multiple monitors alerts concurrently they are all affected by the same cause.	Design/Construction
Detailed alerts	The more details revealed in fault diagnostic alerts the less effort is required to solve the problem occurred.	Design/Construction
Opportunistic Maintenance	The system should group maintenance tasks automatically.	Design/Construction
Failure Severity	Degree of failure severity should be displayed to the user for determination of further vehicle usage.	Design/Construction

5.3.1 Communication Interface

Every sensor implemented in the system shall be connected to a computerized unit which performs all necessary calculations, reduces the noise from the inlet data and transform it to smoother representations (see Figure 37).

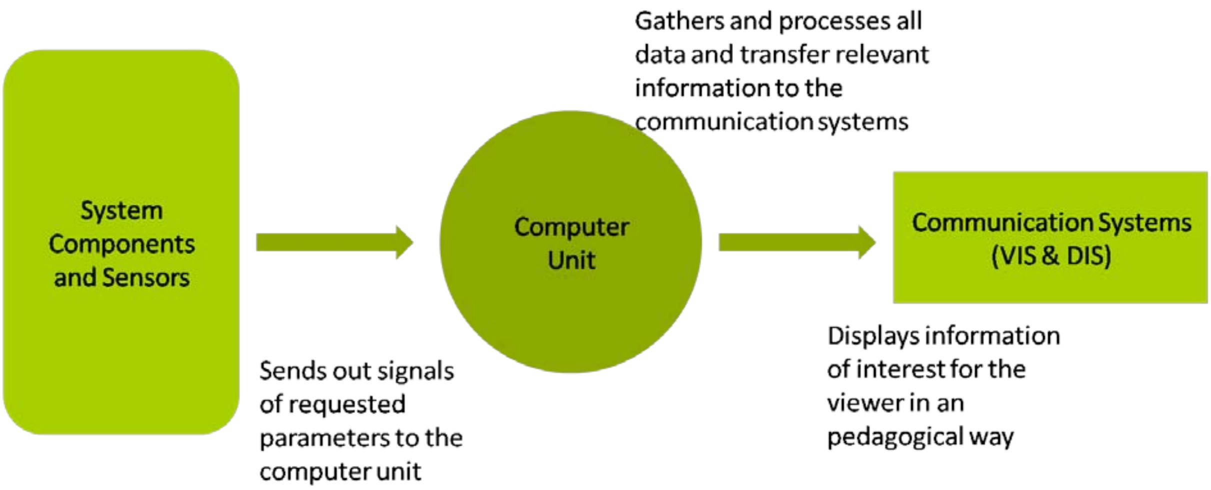


Figure 37. Communication interface

The processed data is then evaluated in the computerized unit based on thoroughly compiled algorithms. When limits for warning and alarm are reached the receiver is alerted. The alert is then illustrated in the vehicle information system (VIS) preferably with color marked alert limits as displayed in Figure 38 to ease severity level understanding. The alert levels also correspond to certain time left for each component in the system.

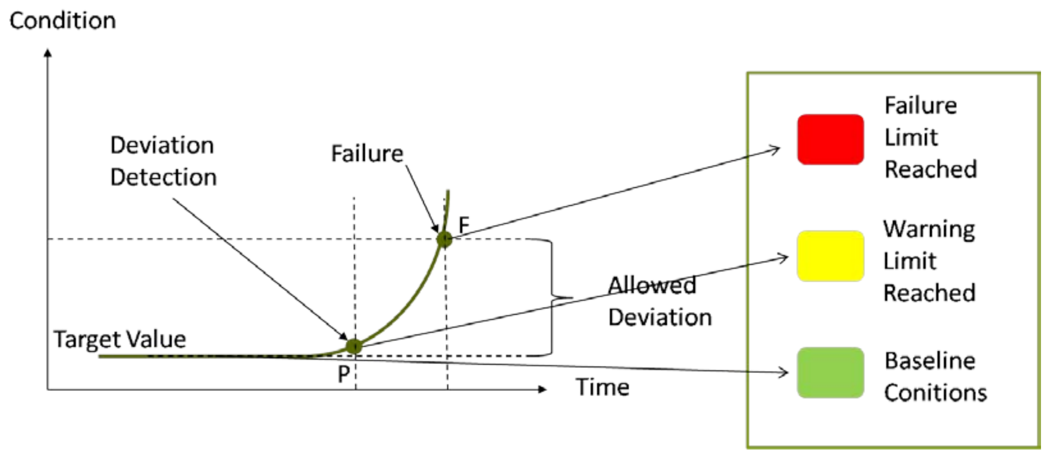


Figure 38. Vehicle information system alerts

6. Analysis

The analysis is divided into three sections directly derived from the work performed with the empirical material. In addition a short credibility analysis is conducted to enlighten the reader of the questionability of the material collected and the evaluation methods.

6.1 Market Research Analysis

In this section the main findings derived from the study visits at the chosen companies are discussed. Each finding presented is evaluated for relevance and significance and whether or not it is possible to utilize in a future CBM system for the CV9035. An assessment of what further work needs to be completed in order to make use of the recommendation given is also presented for each finding. Some findings have little or no relevance to the expected outcome of this thesis and are thereby only presented shortly in the end of this section.

- **Group maintenance tasks to improve efficiency and lower costs for maintenance.**
  Since BAE Systems Hägglunds began investigating the possibility of selling maintenance packages along with their vehicles lowered maintenance costs are of even greater importance than before. Furthermore, efficient maintenance opportunities and increased availability of the vehicles are extremely powerful sales points for the company. Optimization of the maintenance activities over time does not only fulfill these desires but also provide complete control of the maintenance of the vehicles.

  Developing an opportunistic maintenance plan requires an extreme amount of work especially since very little data is available for evaluation. An extended condition based maintenance system for the vehicles should incorporate automatically grouped activities to reduce human errors and to optimize the maintenance opportunities. To accomplish this task a lot of calculation data is required which can be attained through close observations, calculations and tests of vehicle components. The task itself is very time consuming and requires severe knowledge in mathematics and programming and could be a plausible research subject for a doctoral student.

- **Create a preliminary system with theoretical lifespans and values and gather data throughout vehicle utilization to improve system functionality and reliability.**
  Since BAE Systems Hägglunds does not have any test data or documented material of probable component life lengths, a preliminary system with theoretical values could be developed. This system should be used concurrently with the current maintenance program and the main use should be to gather proper data in order to improve the system reliability. Since there currently is no data available this approach is more time and cost efficient due to that it does not intervene with the current maintenance plan. Also the risk of having a poorly developed and unreliable system that jeopardizes vehicle component condition is diminished.

To be able to develop and implement a preliminary system much work must still be executed. Besides the actual programming of the system some "*best guess*" parameters for warning limits need to be compiled. Furthermore, compatibility with the existing vehicle computer system and how to visualize the program for the user needs an evaluation. When the system is implemented in the vehicles for a trial period the data gathered needs to be processed in order to further develop the system.

- **Consider what information is relevant for the driver to avoid distraction unless it is necessary.**
  In the current vehicle information system numerous parameters are visible to the viewer to enable understanding of the vehicles condition if urgently required. Despite this, too much information confuses rather than enlightens the observer which induces the need for an evaluation of what information that should be displayed.

  To take on this recommendation only a simple analysis of the information available in regards to information required for the observer is needed. Though it can be of interest to consider the enormous amount of information currently available to the observer and if it is relevant to even consider eliminating some material from the new system.

- **Perform frequent hardware inspections and document these thoroughly.**
  In addition to an electrical system, human hardware inspections could be held in order to inspect the actual component condition and compare to the system values. The result from these inspections is a proper foundation for system improvements and decreases the risk of missed or false alarms and undetected failures.

  These inspections need to be a part of the maintenance program developed for the vehicles. A profound and well compiled document shall be filled out and gathered in a proper manner in order to enable future system improvements.

- **Establish a suitable data gathering system to get proper information for future maintenance plans.**
  Currently little or no data is available regarding the vehicles previous maintenance situation. To increase the knowledgebase and to support or adjust current maintenance programs data needs to be gathered in an efficient and useful manner. Creating a data management system where all desired parameters are logged produces an immense foundation for future decisions about the system.

Creation of a data management system requires consideration not only to the data that are to be collected but also to the usability of the system. The simpler and easier the system the more is the likelihood of it being utilized correctly.

- **Determine suitable parameters from the engine to which measurements can be related in order to give a clear view of the data.**
  As explained in section 5.2. Trending the data gathered from sensors depends on other parameters such as engine load, engine speed etc. why data normalization is required to obtain understandable and usable trending values. In order to compare the data retrieved with other data some suitable parameters could be used as a reference.

  This decision requires a profound assessment of the components including tests to discover what parameters control the final values of the component condition. Many parameters could be related to the measurements obtained and an evaluation of these curves can be of interest to increase the knowledge about the vehicle components.

The following findings from the company visits have little or no relation to the main subject of this thesis why they are not fully discussed. A short review on the subject is made together with some evaluating comments in order to enlighten the company of other possible solutions to maintenance issues.

- **Utilize the knowledge gathered along with schematic software developed by the department of mathematics, Chalmers University of Technology.**
  Since the department of mathematics has been involved in maintenance over some time much knowledge has been gathered, especially in the area of opportunistic maintenance. They offer an industrial doctoral studentship to BAE Systems Hägglunds where the object is to develop an opportunistic maintenance plan for a predefined set of components for the vehicles. Since BAE Systems Hägglunds has expressed a desire of having their maintenance activities grouped a suggestion of this kind could have great significance for the company.

  To execute this task a complete breakdown of the maintenance activities is needed including costs, duration and material required for each maintenance task. Furthermore compilation and evaluation of these parameters as well as schedule programming and simulations are required for task completion. Employing a doctoral student is merely a question of economics in relation to possible gain. Since this work is truly desired by the company the remaining issue is whether or not it is a financially supported activity to undertake.

- **A full service deal could be developed creating mutual gain or loss for customer and dealer.**
  In order to increase the demand of the maintenance packages sold a change in the actual deal could be made. One market research solution is to have a package that ensures the companies full engagement in maintenance activities. A package of this kind where a vehicle operational stop induces equal loss for both customer and supplier increases the trustworthiness of the company and thereby also the demand of its products. Despite this, the company is now extending their knowledge into condition based maintenance a suggestion of this kind for preventive maintenance actions is not taken into further consideration.

- **Determine a suitable way of communicating with the machines based on business situation and utilization of the vehicles.**
  Human interaction with the military vehicles can happen in limited ways since any type of real time transfer of data during usage can compromise the vehicle location. Therefore data needs to be transferred to the company in secure zones after an operation which gives little or no room for communication decisions. Nevertheless these options should be further explored to find the most efficient solution for this type of vehicle. In certain ways this suggestion is already taken into consideration by the company since they launched CBM investigations due to high availability demands and high maintenance costs.

- **Explore the possibility of utilizing a real time monitoring unit that communicates the condition in predetermined intervals.**
  Instead of creating a trending system discussed in this thesis monitoring units could be placed on each of the components chosen to detect probable failure and communicate it at chosen intervals. These units have detection technique, computer based evaluation and communication equipment all in one package. These units are much more costly to implement and the real time communication possibility cannot be utilized due to location security of the vehicles. Although the possibility of implementation should be evaluated further in order to enable proper decisions for rejection or acceptance of these units.

6.2 Component Implementation Review

Eight components are presented as possible targets for trending. Some of these components are already equipped with the necessary sensor while others even need additional hardware besides the sensor to function properly. This hardware implementation demands resources but the costs cannot only be considered in relation to trending benefits since a sensor implementation can result in other advantages as well.

However, before an implementation of the new sensors can begin certain aspects need to be considered to establish if it is even possible to accomplish what is intended. For sensor types used in the vehicles already experience about their performance can be sufficient for evaluation but for new types of sensors, such as the oil condition sensor and the metal detector, intense testing is necessary. Initial tests are performed on both the oil condition sensor and the metal detector but they should be installed in a vehicle and tested during realistic operating conditions to be fully evaluated. Special aspects to consider when testing the oil condition sensor are the environmental requirements that need to be fulfilled, such as the degree of vehicle tilt and oil state and temperature. If these requirements are assumed to be difficult to meet and accept by the user it is possible that this consumes the advantages.

When it is decided which sensors to include in the system their actual installation needs to be established. Since it is crowded around the engine and its subsystems packaging issues are likely to occur. Another problem regarding this is the need of a final drive oil filter if the metal detector is expected to deliver its full potential.

Since a cost evaluation is not a part of this thesis, the relation between costs and benefits is not investigated. This is obviously needed in a future study and when doing so it is important to expand the scope of the study to get a more complete vision regarding the benefits. Two important factors to include are opportunistic maintenance and diagnostics.

Opportunistic maintenance is important, independent of maintenance approach because of fixed costs, and affect on vehicle availability, related to maintenance occasions. In addition to a trending system this should be considered in order to create a comprehensive and intelligent condition based maintenance system.

Diagnostics can be useful for several reasons. When problems occur the diagnostic features can deliver more comprehensive information of system and component status enabling a faster troubleshooting. If a problem is unknown out in the field diagnostic information can narrow down possible errors which is important information when sending appropriate personnel and material to the site. It can also aid the vehicle users when problems occur. With the help of diagnostics it might be possible for the crew to perform minor repair work themselves if information regarding the problem is present.

6.3 System Analysis

To develop a trending system alert limits and a baseline level are required. For some of the systems presented these are given by previously gathered knowledge from experts within the company. Though for many systems no expertise knowledge or data exists of the kind that is needed to make proper trending estimations. To enable trending curves and measurements and to set alert limits, long-term data logging answers to the following questions are required:

- **How often is the component changed?**

- How is the status of the component at that time?
  - If completely broken, how does it show?
- **How is the status of the component after 1000, 2000, 3000 … 20000 km and 50, 100, 150 … 500 operating hours?**
  - Initial failure characteristics?
- **When and how was the failure discovered?**
  - Specific surrounding conditions?
- **How is the operational ability affected by this failure?**
- **When and what maintenance has previously been performed for this component?**
- **Does a maintenance task require operation stops? What are the costs and time for this?**
  - Important questions for opportunistic maintenance analysis

Currently little or no data of this kind is available why some components only have assumed life curve characteristics based on mechanics and probable failure causes. These curves can be utilized in a trial version of a trending system or the data required can be gathered in order to compile more reliable values and curves.

The system requirements and the proposed system communication interface are compiled along with discussion with employees at BAE Systems Hägglunds. These requirements are a mixture of gentle desires and unambiguous needs for a comprehensive trending system. The more requirements counted for the better and more reliable system.

When a trending system is realized and implemented into the vehicle the final condition based maintenance system is far from complete. As mention in section 3.1 Condition Based Maintenance a high-quality CBM system is intelligent and can without human interaction present root cause in case of an alert, corrective action and optimal time for next maintenance occasion. For this to happen there are a tremendous amount of work left. The first two system functions are related to a fault diagnostics system where much work lies in complete system breakdowns followed by system relation evaluation and thorough root cause analyses. The latter function involves financial analysis of maintenance tasks including data gathering to enable lifetime assessments. Some requirements for an extended CBM system containing these criteria have been presented due to theoretical relation to the trending system and can be used as a foundation for further work on developing a CBM system for the military vehicle.

6.4 Credibility Analysis

This thesis is an evaluation and analysis of the possibility of implementing a trending system for a military vehicle. The final conclusions and recommendations are almost entirely based on market research findings, existing theories from printed sources and knowledge extracted from the company.

Credibility has two building blocks: trustworthiness and expertise, of which both can be of an objective and subjective nature. Trustworthiness is mainly about established reliability and utilization of approved methods. The reliability of this thesis can be considered to be rather low due to the inexperienced authors but by the utilization of established methods the end results are considered to be sufficiently supported and trustworthy. The amount of expertise taken advantage of in this thesis is extensive. The knowledge gained throughout the project is retrieved by interpreting printed scientific sources together with discussions and interviews performed with highly experienced persons at both BAE Systems Hägglunds and other companies.

7. Conclusions

Early on in this thesis the magnitude of work required to implement a CBM system was discovered and the massive data and information required was defined. This brought forward a slight direction change since currently very little of the data needed exists within the company. Therefore much of the work completed has been to unravel in the actual foundation of CBM systems and what the needs are in order to develop a system of this kind for the vehicle. The final outcome is recommendations and a solid basis for a trending system.

In this chapter the answers for the research questions are concluded. Moreover an assessment is made as to how this thesis has contributed to theory and what future studies that can be fulfilled to continue the study of the subject. The research questions derived from the main purpose are displayed below.

- *"**What** components shall be part of the monitoring system and **what** properties are to be measured?"*
- "**How** shall the system be designed in terms of functionality and communicative performance?"
- *"To ensure a comprehensive and intelligent system that meets all requirements, **what** work must further be accomplished?"*

Based on the analysis and the empirical material presented in chapter 5 and 6 conclusions of what components that ought to be a part of the final system is made. Table 12 shows all systems and if they are suggested to be a part of the trending system or not.

Table 12. Final trending system components

Component	Implementation	Use	Measured Parameter	Hardware Requirement
Engine oil	Yes	Monitor oil condition	Viscosity and soot	Oil condition sensor
Engine oil filter	Not initially	Monitor filter health	Differential pressure	Differential pressure sensor
Engine oil	Not initially	Monitor oil level	Oil level	Oil level sensor
Fuel filter	Not initially	Monitor filter health	Differential pressure	Differential pressure sensor
Air filter	Yes	Monitor filter health	Differential pressure	-
Transmission oil filter	Yes	Monitor filter health	Differential pressure	-
Final drive components	Yes	Monitor mechanical component damage	mg of metallic particles and no. of particles	Final drive oil filter Particle detector
Transmission components	Yes	Monitor mechanical component damage	mg of metallic particles and no. of particles	Particle detector

The decisions are based on the potential benefits an implementation brings regarding maintenance. The systems that are not considered to be of greater importance for an enhanced maintenance system compared to the current approach are initially not suggested to be included in the trending system. Their use is of greater magnitude if a diagnostic system also is to be designed why an implementation is not fully disregarded.

The trending system's main objective is to visualize component condition and calculate remaining lifetime. To ensure reliable values a comprehensive algorithm needs to be written based on requirements suitable for this system. Functional requirements for the trending system are displayed in section 5.3. System Design and are necessary for system development in order to enhance the system reliability and intelligence. Requirements for an extended CBM system are also defined along with communicative functions for the system.

As explained, an extended CBM system involves an unyielding trending system able to foresee future maintenance need, an intelligent diagnostics unit able to detect and diagnose failure and finally other intelligent maintenance optimizing tasks as automatically grouped maintenance activities. Below follows descriptions of further work needed in order to establish a solid trending system and also a comprehensive CBM system.

TRENDING SYSTEM

- **Technical implementation evaluation**
  The next step in creating an onboard trending system for the vehicle is to evaluate the sensors and their capabilities an if they are able to do what is asked of them. An assessment of whether or not there are enough bandwidth, storage space and similar is also required to enable implementation and testing in the vehicle. Finally the actual data from the sensors needs to be dealt with. The noise of the data extracted needs to be reduced in order to get a smooth trend representation that enables an evaluation of future maintenance need.

- **Programming**
  Following the implementation evaluation is the actual algorithm writing and programming where many functions need to be considered in order to get a durable system. An ideal program would on a long term basis diminish the human effort to next to nothing to reduce possible unwanted errors.

- **Implementation and testing**
  The subsequent action required is the actual implementation of the system for testing purposes as well as data gathering. This needs to be performed on a long term basis and on several vehicles in order to get proper data as a foundation to future decisions.

- **Evaluation and further improvements**
  The final step is to evaluate the system, the data gathered and the financial aspect. This evaluation shall be used as a foundation for further system improvements or, if proven unbeneficial, for system closure.

EXTENDED CBM SYSTEM

- **Fault diagnostics system assessment**
  To get an extended CBM system fault diagnostics is a desired feature. Developing a system of this kind requires a tremendous amount of work. The initial step is a complete system evaluation of the powertrain including a comprehensive root cause analysis of each possible failure for the components. Furthermore an implementation into the existing trending system needs to be evaluated in order to discover or not the system needs to be further extended.

- **Opportunistic maintenance assessment**
  Grouping maintenance activities either automatically or manually to optimize the maintenance related cost is a desirable feature for an extended CBM system. To accomplish this all maintenance related costs for each activity needs to be defined and maintenance scheme needs to be compiled.

- **Complete system evaluation**
  As for the trending system an evaluation of actual benefits against drawbacks must be accomplished in order to support or reject further improvements to the system. This review shall be based on financial as well as technical aspects and whether or not the usability is satisfactory.

7.1 Future Studies

As discovered through industrial connections established throughout this project condition based maintenance has a little extension in the Swedish industry. Companies with high focus on maintenance have in most cases put more effort into a solid preventive program based on a massive amount of information and experience.

Future studies in the subject undertaken in this thesis could be focused on any of the following aspects.

- **Researching why CBM has so little extension in Swedish industry**
  Why are not more companies involved in this maintenance technique? Is it based on lack of knowledge or is it possible that they perceive the benefits to be overtaken by the drawbacks?

- **Increased availability and lowered costs with condition based maintenance**
  Determining whether or not CBM implementation in production processes and or separate machines results in increased availability and lowered costs. The question is if it is beneficial to implement a condition based maintenance or if there is more to gain by developing a solid predictive maintenance program?

8. Recommendations

Below follows recommendations compiled to BAE Systems Hägglunds. The recommendations are divided into three sections; *trending system recommendations*, *extended CBM system recommendations* and *other recommendations*. Three of the major suggestions are compiled into project or thesis proposals for the company to undertake and are showed in Appendix B.

8.1 Trending System Recommendations

- **Trending system implementation evaluation**

  The answers compiled for the first two research questions reveal what components that should be included in the system together with suggestions of proper measurements. In addition they reveal how the system should be designed both in terms of functionality and communicative layout.

  Utilizing the groundwork completed in this thesis the following step would be to make an actual implementation evaluation of the trending system (see Appendix B). This evaluation should consider no less than the following actions:

  - Data gathering method evaluation in order to obtain a smooth representation of the information.
  - Computer system and sensor evaluation to ensure they are capable to accomplish what is required of them.
  - Physical implementation evaluation of sensors and components regarding packaging issues and necessary connections.
  - How the data gathered shall be stored and communicated during operations to the vehicle crew and afterwards to the technician.

- **Trending system programming**

  The following step is to compile the actual algorithms and the final computer program where the specification of requirements is of great importance.

- **Implementation, data gathering, evaluation and improvements**

  Once the computer program is finalized the system, both hardware and software, can be implemented in the vehicles for testing, data gathering and evaluation. In this stage it is truly important that data is collected and kept to provide a solid foundation for future system improvements. Some data of interest is presented in a list in section 6.3 System Analysis.

- **Frequent hardware checks for system evaluation support**

  In order to further extend the foundation for system evaluation it is recommended that frequent hardware checks are made and properly documented and stored.

- **Withdraw and trend other measurements from the engine ECU**
  To make proper measurement evaluations later on, the following parameters can be trended concurrently.

  - Engine load
  - Engine speed
  - Driven kilometers
  - Operating hours
  - Outer temperature
  - Number of cold engine starts
  - Engine temperature

8.2 Extended CBM System Recommendations

- **Fault diagnostics**
  It is suggested that a fault diagnostics system is added to the trending system in the future to extend the CBM system. Developing this system includes a massive effort including system breakdowns and a thorough root cause analysis for each component. A thesis proposal of an initial assessment is shown in Appendix B.

- **Opportunistic maintenance**
  In order to get a more beneficial maintenance schedule an opportunistic maintenance program should be developed and implemented in the extended CBM system. A thesis suggestion of an opportunistic maintenance schedule creation can be viewed in Appendix B.

- **Extended CBM system evaluation**
  Furthermore it is recommended that the extended CBM system is evaluated in order to make further improvements to the system. In addition, a further extension of the system should be evaluated. A minimum of the following questions should be taken into consideration.

  - What shall be included in an extended system? More or less features than those suggested in this thesis?
  - What level of system intelligence is financially beneficial?
    - Should the system be self learning?
    - Should the system include complete diagnostics including suggestions of corrective action?
    - Should the system know the level of severity of each fault and adjust the warning thereafter etc.?

8.3 Other Recommendations

- **Establish a database system where all data related to maintenance is gathered**
  In order to provide a solid foundation for future system improvements data needs to be stored and evaluated in a proper manner. Without historical data regarding maintenance and component condition future maintenance decisions will be insufficiently supported. A database system of optional kind should therefore be developed where all data related to maintenance shall be stored to provide the company with a solid maintenance edge.

- **Consider the proposition made from Chalmers University of Technology.**
  Since the work effort required to create an opportunistic maintenance schedule for the vehicles is massive it could be of interest to employ an industrial doctoral student with great knowledge in the area to perform this task.

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Appendix A

This appendix includes all trending parameters excluded from this thesis together with a short motivation.

System	Parameter	Implementation Purpose	Motivation for Exclusion
Lubrication System	Engine Oil Pressure	Example: Low pressure detection could indicate a possible leakage, pump failure, changed viscosity (pollution) etc. and by cross referencing with other sensors a probable cause can be outlined.	Trending this parameter is for diagnostic purposes only. The engine oil pressure has no direct relation to a maintenance task which is the main criteria when selecting systems for trending.
Lubrication System	Engine Oil Temperature	Example: Changed oil temperature could be used as a reference for oil pressure to discover the root cause of the problem. The temperature can also give an indication of the engine working conditions which induce the need for cross reference with coolant temperature etc.	Trending this parameter is for diagnostic purposes only. The engine oil temperature has no direct relation to a maintenance task which is the main criteria when selecting systems for trending.
Fuel System	Fuel Pressure	Example: A fuel pressure measurement, in this case the actual feed pressure to the injectors, could be used to indicate a malfunctioning pump. If the fuel pressure is low and the fuel filter differential pressure is within limits a probable cause could be pump failure.	Trending this parameter is for diagnostic purposes only. The fuel pressure has no direct relation to a maintenance task which is the main criteria when selecting systems for trending.
Fuel System	Fuel Level	Example: A fuel level trending measurement could be correlated to the actual engine fuel consumption to indicate a possible leakage.	Trending this parameter is for diagnostic purposes only. Low fuel level indicates that there is a need for refueling which is a common maintenance task but this measurement already exists. Using the sensor in a diagnostics manner has no relation to a maintenance task, which is the main criteria when selecting systems for trending and thereby the reason for exclusion from this thesis.
Cooling System	Coolant Level	Example: Currently the sensor only warns at low level but an additional sensor could trend the current level and thereby indicate possible leakage if drastically changed measurements.	Trending this parameter is for diagnostic purposes only. The current coolant level sensor has a connection to the maintenance task of refilling the coolant but the additional sensor has no direct relation which caused the exclusion.
Cooling System	Coolant Temperature	Example: Changed coolant temperature could be used as a reference for oil temperatures to discover possible failure causes.	Trending this parameter is for diagnostic purposes only. The coolant temperature has no direct relation to a maintenance task which is the main criteria when selecting systems for trending.
Hydraulic System	Fan Speed	Example: The coolant temperature regulates the fan speed. An incorrect relation between these parameters indicates a problem.	Trending this parameter is for diagnostic purposes only. The fan speed has no direct relation to a maintenance task which is the main criteria when selecting systems for trending.

Hydraulic System	Hydraulic Oil Level	Example: Measuring the hydraulic oil level over time could be a good reference to a complete failure detection system to out rule probable leakage in the hydraulic oil system.	Trending this parameter is for diagnostic purposes only. The hydraulic oil level has no direct relation to a maintenance task which is the main criteria when selecting systems for trending.
Transmission	Transmission Oil Pressure	Example: Logging the transmission oil pressure over time could give an indication of the oil pump health status.	Trending this parameter is for diagnostic purposes only. The transmission oil pressure has no direct relation to a maintenance task which is the main criteria when selecting systems for trending.
Transmission	Transmission Oil Temperature	Example: Changed transmission oil temperature could be used as a reference for transmission oil pressure to discover the cause of an incipient problem. The temperature can also give an indication of the transmission working conditions which induce the need for cross reference with coolant temperature etc.	Trending this parameter is for diagnostic purposes only. The transmission oil temperature has no direct relation to a maintenance task which is the main criteria when selecting systems for trending.
Transmission	Brake Wear	Example: Currently the brake wear sensor is analogous and requires manual reading and adjustment. A new sensor could trend the wear and warn digitally when adjustment is required.	The reason for exclusion of brake wear trending is the efforts of implementing a new sensor against the actual gain.
Final Drive	Final Drive Oil Cooling Temperature	Example: Measurements of the oil cooling status could be correlated against the outer temperature to establish whether or not the conditions are normal or not.	Trending this parameter is for diagnostic purposes only. The final drive oil cooling temperature has no direct relation to a maintenance task which is the main criteria when selecting systems for trending.

Appendix B

This appendix contains thesis proposals constructed in order to continue the work this thesis has started. Their purpose is to further evaluate the possibilities of implementing a trending system and to broaden the system with fault diagnostics and opportunistic maintenance.

THESIS PROPOSAL 1

- Trending system implementation evaluation

PURPOSE

Evaluate the possibilities of implementing a trending system in the military vehicle CV9035. The outcome is expected to be a positive or negative recommendation based on documented research.

BACKGROUND

There are desires of implementing a trending system and an evaluation of such a system is performed. Before an implementation is started there are concerns regarding the possibilities of succeeding which is why an evaluation is necessary.

WORK STRUCTURE

Evaluate sensors and computer systems to ensure their performance.
Determine if it is physically possible to implement all sensors and components needed.
Establish a reliable representation of sensor data.
Determine possibilities of data storage.
Establish data communication to the crew and technicians.

GENERAL INFORMATION

Technical area:	Subsystem development, Propulsion systems
Targeted Students:	Two students with at least a bachelor degree or equivalent
Preferred background:	Mechanical Engineering and/or Electronics Engineering background
Performed at:	BAE Systems Hägglunds in Örnsköldsvik

THESIS PROPOSAL 2

- Fault diagnostics

PURPOSE

The purpose is to design a diagnostic system with the help of information from existing sensors in the military vehicle CV9035 produced at BAE Systems Hägglunds. The expected outcome is a system that can identify faults for more efficient fault localization and use of corrective resources.

BACKGROUND

When being on a mission the military vehicle CV9035 can experience numerous problems when being positioned far from its maintenance site. This might force the crew to fix the problem themselves, disregard the problem and continue if possible or stay in its position awaiting help. By the help of a fault diagnostics system it is more likely to identify the problem and its severity aiding the crew and their superiors to decide appropriate actions.

WORK STRUCTURE

Identify existing sensors in the CV9035.
Evaluate possible faults in the systems these sensors are located in.
Evaluate if more sensors are needed as well as what sort of sensors.
Determine sensor relationships and related measurements for reliable fault diagnostics.
Design a fault diagnostics system for the propulsion system and integrate in the condition based maintenance system.

GENERAL INFORMATION

Technical area:	Subsystem development, Propulsion systems
Targeted Students:	Two students with at least a master degree or equivalent
Preferred background:	Mechanical Engineering and/or Electronics Engineering
Performed at:	BAE Systems Hägglunds in Örnsköldsvik

THESIS PROPOSAL 3

- Opportunistic maintenance

PURPOSE

The purpose of this thesis is to determine a maintenance scheme with focus on maximizing vehicle availability and minimizing maintenance resources. The thesis outcome should be an algorithm or similar providing the desired maintenance scheme.

BACKGROUND

The need for maintenance varies for different components. This means that vehicle availability suffers if maintenance is performed to maximize the lifetime of each component. In order to obtain a balance between vehicle availability and costs opportunistic maintenance is required.

WORK STRUCTURE

Identify maintenance tasks within the propulsion system.
Determine the fixed cost for a maintenance operation.
Determine the cost for each maintenance task.
Determine necessary vehicle access time for each maintenance task.
Derive the desired algorithm.

GENERAL INFORMATION

Technical area:	Subsystem development, Propulsion systems
Targeted Students:	Two students with at least a bachelor degree or equivalent
Preferred background:	Industrial Economics Engineering, Mathematics or similar
Performed at:	BAE Systems Hägglunds in Örnsköldsvik