Introducing CBM on the M113AS4 Power-pack Utilising HUMS Data

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Abstract

The Defence Land Engineering Agency (LEA) has introduced Condition Based Maintenance (CBM) for Land vehicles using data from vehicle Health and Usage Monitoring Systems (HUMS). The initial phase is focussed on the M113AS4 light armoured vehicle power-pack servicing, and has delivered the first end-to-end sensor-based Land CBM solution. Originally a HUMS technology proof-of-concept, the program has evolved to the point where maintainers now only perform the M113AS4 power-pack service when it is triggered by engine oil viscosity, as determined by the HUMS data. It is expected that this initiative will lead to significant savings as it has already been observed that the engine oil condition remains within acceptable limits long after the originally specified 400 engine hour maintenance period has elapsed.

The technical aspects of this paper include the data acquisition system, the analysis and assessment of engine oil condition, and the method for determining oil condition thresholds.

Introduction

Servicing equipment on fixed calendar intervals is still the most common trigger for preventive maintenance in the Defence Land domain. Unfortunately, relying on these fixed interval regimes alone can lead to inefficiencies when the amount and severity of in-service usage varies, the vehicle fleets start to age or there are changes to the vehicle's operational role. The advantage of a HUMS assisted CBM strategy is that it creates alignment between the severity of equipment use and the notification of maintenance events. This alignment reduces the risk of over or under servicing inherent with fixed interval maintenance. CBM and HUMS can also assist in developing a Predictive Maintenance (PdM) solution which can lead to identifying unexpected costly breakdowns.

Over recent years Land vehicles have continued to incorporate increasing levels of technology, to the point where the complexity must be managed through the use of electronic in-vehicle control systems. These systems exchange data between vehicle subsystems/components and use that data to ensure the systems are operating efficiently. The various systems share data through the vehicle's Controller Area Networks (CAN) data bus. Although these control systems were originally intended to support the efficient operation of the vehicle, much of the data is very useful for ascertaining the condition of vehicle systems, predicting failure and informing the need for maintenance.

To explore the potential benefits stemming from a HUMS assisted CBM, 149 vehicles from the M113AS4 fleet have been retrofitted with technically certified HUMS units, designed to collect the data harvested from the vehicle's CANbus. The data is then automatically transferred to an off-board, back-end system that has been developed to store and process the HUMS data and output the measurements needed to drive CBM and achieve maintenance savings.

This paper describes the on-board system, the off-board back-end infrastructure, the development of the algorithms used to process the data and the results obtained from this initiative. The success of HUMS assisted CBM is evident in the continuing transition from fixed interval servicing of the M113AS4 power-pack to an automated CBM approach.

On-Board HUMS

To date 149 of the M113AS4 vehicles have been fitted with an on-board HUMS that consists of:

- An interface to the vehicle's existing CAN bus;
- A range of new sensors including an oil condition sensor, accelerometers, and temperature transducers;
- A Global Position System (GPS) unit;
- A data logger for temporary data storage;
- Antennae (4G and Wi-Fi); and
- A computer to process data, apply date and time references to the sensor data, and provide the external wireless and wired communication interfaces.

The M113AS4 HUMS includes a fluid property sensor (FPS) positioned in the engine oil gallery to monitor the condition of the engine oil. This sensor uses a tuning fork like mechanical resonator (Ref. A) to determine the following parameters:

- Dynamic Viscosity of the Oil: This is the primary indicator of engine oil condition (Ref. B), and is considered to be the most important metric to measure and trend.
- Dielectric Constant of the Oil: This is the measure of the oil's ability to store electrical energy in an electric field. By monitoring changes in the dielectric constant, it is possible to estimate the level of contamination from soot, fuel, water and wear metals, as well as determining the depletion of oil additives.
- Density of the Oil: Changes in the density of oil can also indicate the existence of contaminants such as fuel, water or soot.

Off-Board Infrastructure

The effectiveness of the CBM solution is reliant on continuous and complete visibility of vehicle condition while it is being operated. One of the greatest obstacles to the management of HUMS in the Land domain is the sheer quantity of data generated by large vehicle fleets. Manually downloading data is time consuming, resource intensive, and increases the risk of data loss and data corruption. To overcome this challenge an automated wireless data transfer capability has been established which passes the compressed data packets to Data Warehouse (Figure 1) which has been established by the Capability Acquisition and Sustainment Group (CASG).

The CASG Data Warehouse (CASDW) utilises Business Intelligence and Data Warehousing technology to deliver analytical services and business reporting to the Defence organisation and is a critical enabler for HUMS assisted CBM. Built upon a dimensional modelling methodology, it was designed to host a subset of historical data from multiple corporate software systems and databases. It is used to develop the bespoke algorithms which facilitate smarter maintenance through the calculation of continuous monitoring metrics. As a result, this environment enables rapid aggregation, analysis and visualisation of HUMS data integrated with transactional logistics and maintenance information to enhance management decision making.

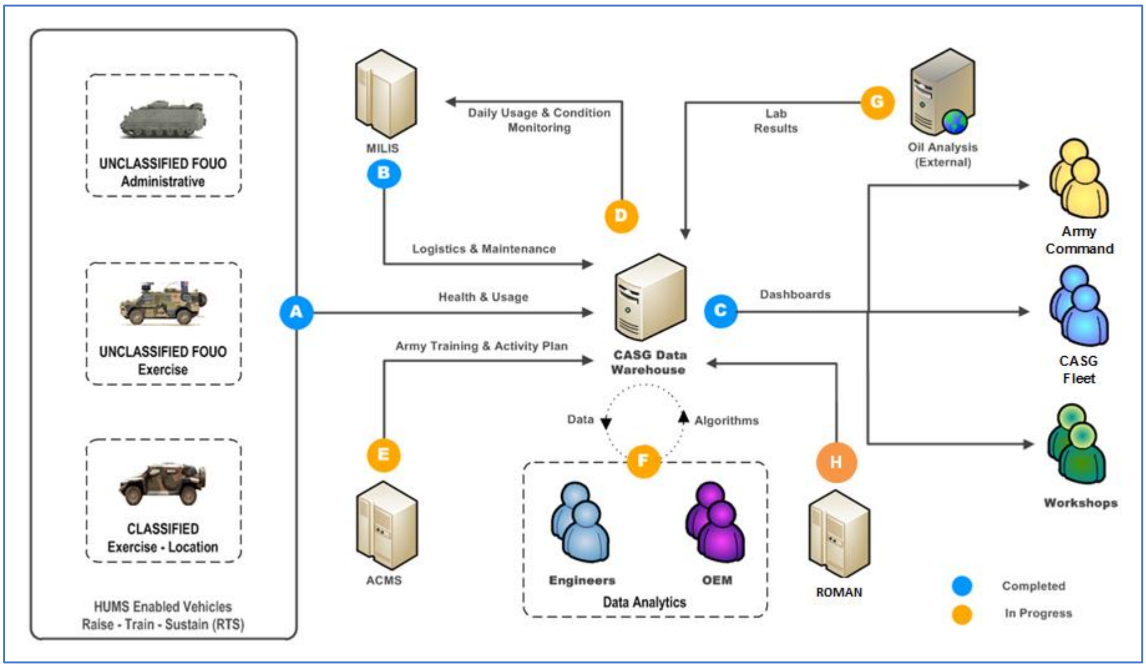

Figure 1: Data analytics Infrastructure

Design of a New Maintenance Methodology for the M113 Power-pack

Using data gathered in the CASDW, algorithms can be developed to predict the condition of equipment and notify maintainers to undertake maintenance action.

An example where HUMS has enabled a conversion from an interval-based servicing regime to a condition-based regime is the development involving the M113AS4 power-pack. The power-pack is comprised of the engine and transmission which have traditionally been serviced at a 400-engine hour interval. This service requires significant effort including the removal of the power-pack from the vehicle hull. The transition to CBM now requires objective evidence of engine oil degradation provided by the HUMS on-board sensor rather than assuming that the oil could be degraded at the 400-hour interval.

In order to lubricate effectively, oil is required to maintain viscosity within a specified range. If oil viscosity is too low metal to metal wear can occur, and if it is too high oil circulation may be compromised. Noting that viscosity readings vary significantly depending on oil temperature, oil manufacturers specify the required viscosity range using values of Kinematic Viscosity at 100°C (KV100). The raw data from the FPS is measured as Dynamic Viscosity and sampled at a rate of 1.0 Hz. This raw viscosity data then needs to be processed in order to determine a daily KV100 value using the following steps:

- All sensors contain inherent noise in their signal. Digital filtering is applied to reduce noise, after which any daily data sets with insufficient vehicle usage are removed;
- Dynamic Viscosity is converted to Kinematic Viscosity using the following formula:

$$\text{Kinematic Viscosity} = \frac{\text{Dynamic Viscosity}}{\text{Specific Gravity of Oil}}$$

- Since the vehicle engine temperatures do not always reach 100°C, the daily oil data readings are extrapolated to obtain KV100. The extrapolations are based on well-known models for oil viscosity, including Walther's Equation (see Figure 2).

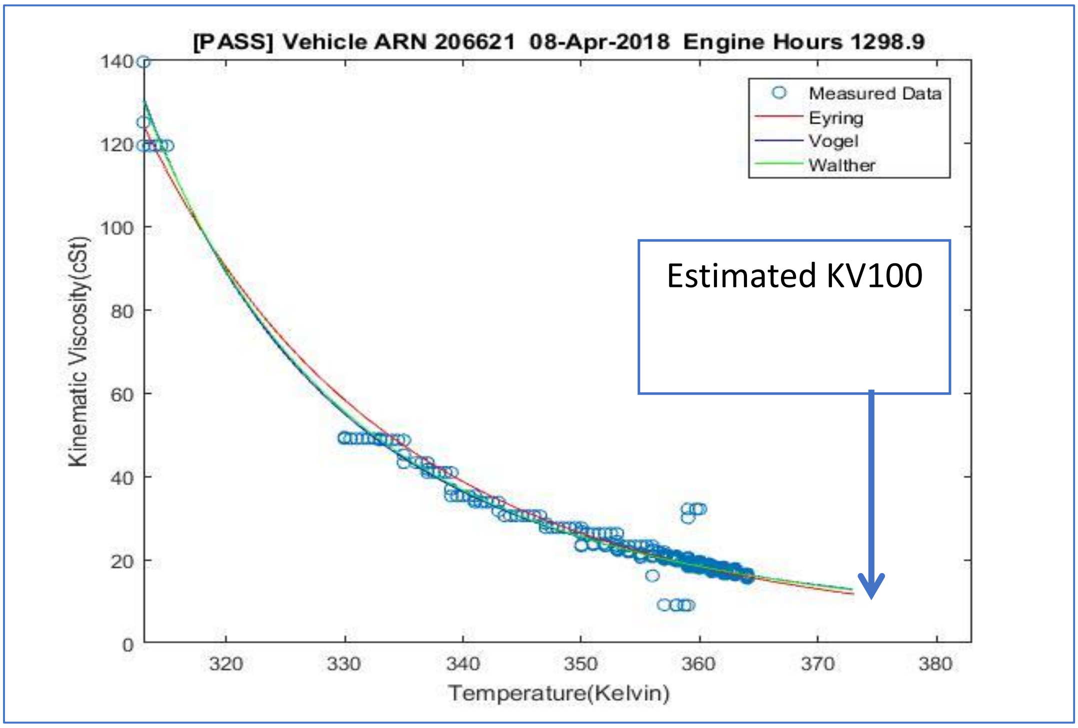

Figure 2: Estimation of KV100 using HUMS data

Validating HUMS KV100 trend results

HUMS KV100 trend results were compared to KV100 results obtained through laboratory analysis as a means of assessing their validity. Initial results showed that the deviation was low, with an average 4% error across a sample of 30+ vehicles (See Figure 3). In addition, all results fell within the set limits for normal operation. This provided confidence that the algorithm and metrics being used were sufficiently accurate for their chosen purpose.

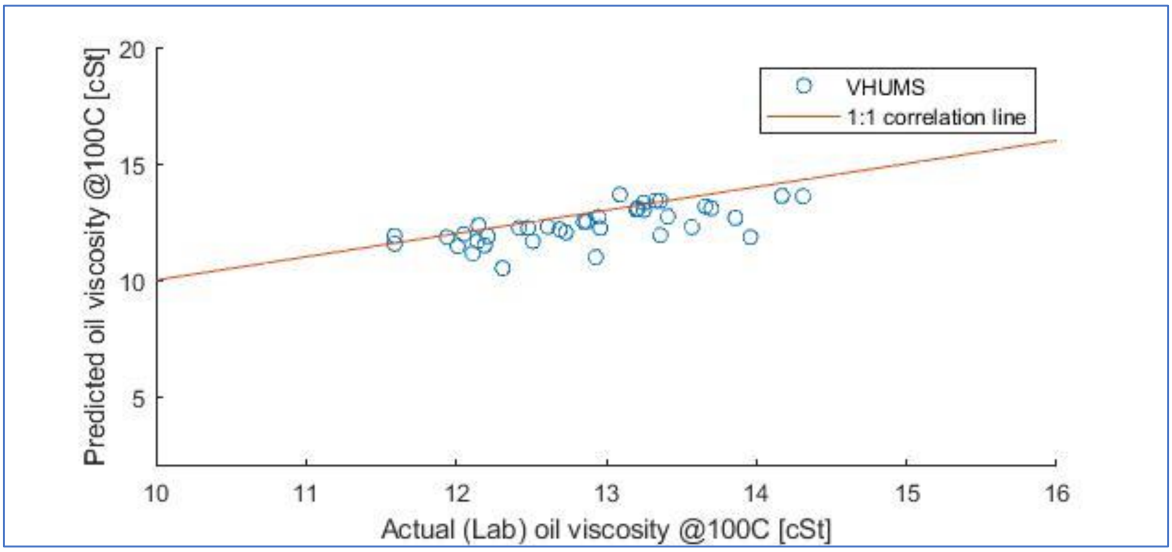

Figure 3: Viscosity results comparison Lab vs HUMS

Trend Analysis

In order to understand and characterise the typical behaviour of viscosity as the oil ages, the KV100 statistic was observed over the oil's operating life for a sample of individual vehicles.

The following modes/patterns were evident across vehicles:

- Positive linear change (increasing viscosity over time);
- Negative linear change (decreasing viscosity over time);
- A "sawtooth" pattern, defined by separate periods of positive and negative change with an intermediate sudden change in viscosity;
- Inconsistent trends, due to significant deviations between neighbouring KV100 data points; and
- Unclear or noisy trends, due to a low volume of KV100 data points.

On the basis of these observations, several choices were made with the aim of achieving a robust methodology suitable for assessing oil condition and predicting remaining useful life for the entire vehicle fleet:

- The KV100 statistics were filtered to minimise the effects of unreliable daily results that were skewing or obscuring overall trends. It was found that inaccurate KV100 results were often linked to failure to achieve minimum thresholds in at least one of several key parameters:
  - R^2 (fit to Walther's equation);
  - Maximum operating temperature;
  - Duration of engine operation.
- The KV100 trend was defined using linear regression. Moving mean and moving median trends of various window sizes were explored as alternative methods but were found to be too sensitive to outliers.
- The remaining useful life would be predicted based on extrapolation of the linear trend.
- The KV100 trend line would be used as the indicator of oil condition as opposed to the raw daily statistics. Reliance on the raw daily statistics as a trigger for maintenance, either on the basis of a single data point or consecutive values, was considered undesirable and likely to generate false alarms too frequently.

Figure 4 demonstrates the relationship between the KV100 daily statistic, trend and prediction methodology.

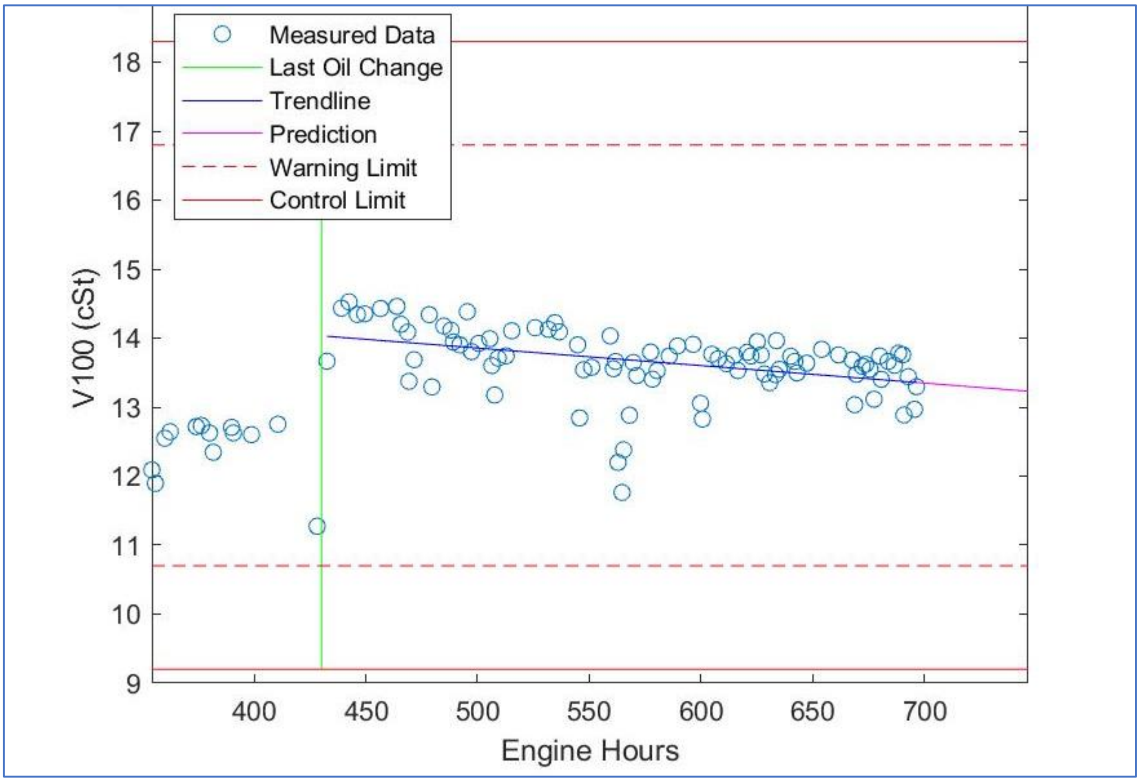

Figure 4: Trending of the KV100 daily statistic over engine operation

Establishment of Limits

Limits were developed using American Society for Testing and Materials (ASTM) methods to distinguish between normal and abnormal operating regions (Figure 4) and provide a threshold for the development of trigger criteria for maintenance. The method ASTM D7720-11 (Statistical Process Control) SPC (Ref. C) was considered appropriate as it has been developed to be used for making decisions on data sets larger than 30 samples. This analysis was based on 175 sample readings with the results shown in Table 1.

Table 1: Limits developed based on ASTM SPC methods

Limit	**Viscosity Value cSt**	**Limit Meaning**
Lower Warning Limit (LWL)	10.7	Intermediate level alarm designation warning a fault condition is present and will likely need attention in the future.
Upper Warning Limit (UWL)	16.8	
Lower Control Limit (LCL)	9.2	High level alarm designation showing significant deterioration requiring a review of other condition information and consideration of a maintenance intervention.
Upper Control Limit (UCL)	18.3	

Triggers for maintenance

With the typical trends understood and limits established, the oil's "remaining useful life" can be predicted using regression methods. The M113AS4 power-pack maintenance events can therefore be initiated based on trigger criteria (See Table 2).

Table 2 Trigger criteria for a power-pack maintenance event

Trigger Criteria	**Maintenance Event**
UCL > KV100 > UWL or LCL > KV100 < LWL & Oil remaining life < 60hours	Condition acceptable but likely to become unacceptable in the near future. Maintenance action required (window of time available).
KV100 > UCL or KV100 < LCL	Condition unacceptable. Maintenance action required (immediate).

Back-up processes

During planning, challenges surrounding the use and limitations of the HUMS were posed:

- How will we know when there has been a failure of the HUMS?
- How do we manage vehicle maintenance if the HUMS does fail or wireless communications are unavailable for extended periods?

These questions were able to be addressed to some extent through the inclusion of a lab sampling capability. Manual oil sampling using lab analysis procedures were integrated into the program in such a way that they served the following functions:

- As a means to confirm the need for maintenance at the point of trigger – effectively a "calibration check" for the oil sensor.
- To be a replacement monitoring mechanism for the automated system, initiated only when a HUMS was deemed unserviceable or the vehicle was out of mobile communications range for extended periods.
- To be a valuable data source for engine condition evaluation using chemical analysis and characterisation of trends in other oil parameters.

Phased Implementation of HUMS Assisted CBM on the M113AS4 Power-pack

The introduction of the CBM methodology within the Defence Land environment was much more than just a vehicle HUMS installation and the development and deployment of an algorithm. Land Systems fleet sustainment staff and the HUMS data analytics team worked collaboratively to create an implementation plan and facilitate the engineering change.

A critical step in this process was the conduct of a risk assessment to ensure that all failure modes previously treated under the existing 400-hour power-pack servicing task would still be considered under the new regime. It was determined that in most cases, these aspects could be managed by routine inspection tasks.

While the risk assessment had addressed the risks to safety there was still a need to train the personnel in the new procedures, as an engine failure would detract from the success of the program. It was also necessary to achieve a level of certainty that the algorithm and inherent trigger criteria were appropriate and would not lead to false alarms. It was decided that all alarm results would be subjected to review by a “human-in-the-loop”, for a suitable period of time to ensure that all possible scenarios had been accounted for in the automated logic.

Display and reporting concepts

As the HUMS was generally considered to be a ‘black box’ solution it was necessary to build confidence and understanding within the maintenance communities by providing visibility of the oil condition monitoring data and results. This was achieved by establishing a dashboard within the CASDW (known as Vulcan) to display and trend the KV100 data over the period of vehicle usage. This information was displayed together with vehicle maintenance history and a number of additional HUMS based usage and status metrics (see Figure 5). Such visibility provided the additional benefit of increasing the chances for anomalous results to be detected and reported.

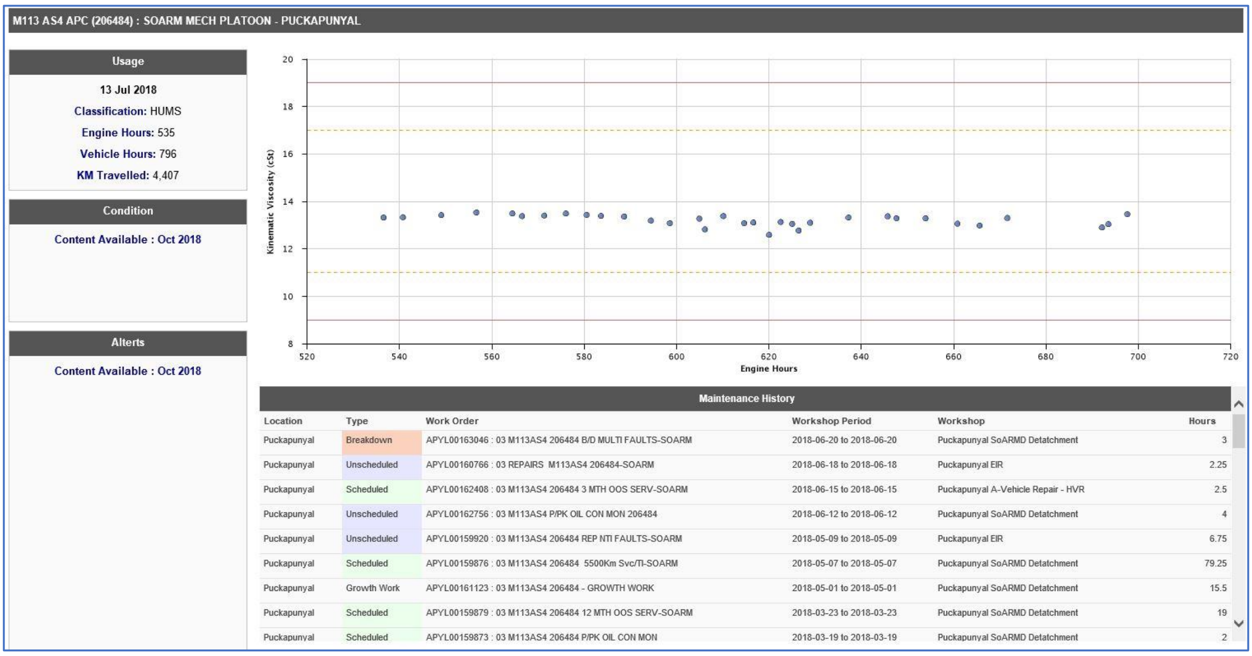

Figure 5: CASDW dashboard display

In the interim the Vulcan dashboards were for ‘advice only’ and maintenance units were instructed that any observed maintenance events would be notified via an email request for action. The reason for this was to provide centralised control and tracking of CBM initiated maintenance activities during the initial implementation/learning phase. It is intended that once mature, the maintenance trigger metrics and criteria would be integrated into the Computerised Maintenance Management System (CMMS), to generate work orders automatically.

Conclusion

The M113AS4 power-pack CBM implementation activity has demonstrated that condition monitoring via HUMS, coupled with an automated maintenance decision logic, can be utilised to establish an effective maintenance program leading to cost savings.

Whilst not yet mature, this program is well underway and results to date have been promising. An algorithm has been developed and deployed and has generated results consistent with those obtained from commercial oil laboratories. The M113AS4 fleet is being progressively transitioned to a HUMS assisted CBM solution, and user communities have been supportive throughout the process. Several vehicles have already surpassed 400 oil hours with no power-pack issues or maintenance events triggered (Figure 6).

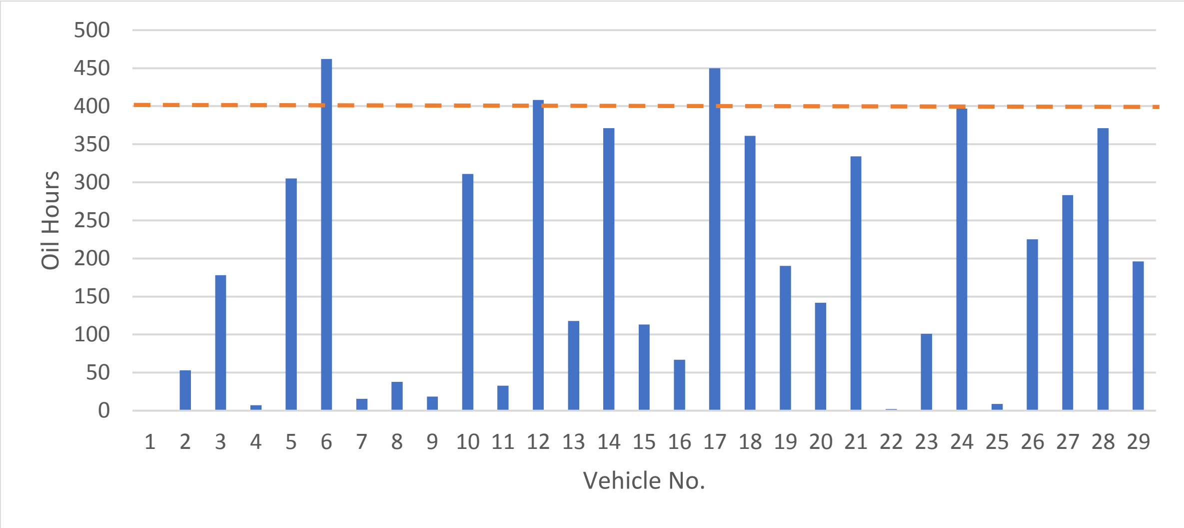

Figure 6: Current oil Hours across sample fleet

The progress and on-going success of the HUMS enabled CBM capability has positioned Land Systems ready to take on the challenges inherent in maintaining modern military equipment.

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