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# Health and Usage Monitoring System for Military Vehicles

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# ABSTRACT

The aircraft industry has been able to adopt improved maintenance and logistics planning as a result of the technological advances in Integrated Modular Avionics (IMA) and Equipment Health Monitoring (EHM). Same cannot be said about the land system. In the land environment, military vehicles are well behind in achieving the same abilities and hence, the problem of inefficiency in the maintenance and logistics for land based system needs to be addressed. To address this and assess the viability of integrating HUMS and Autonomic Logistics on military land vehicles, this project was proposed.

Three main contributions from this research which adds to the knowledge are: (1) assessment of some real system failure which could lead to a poor operational readiness, (2) evaluation of how HUMS can improve the availability and operational readiness and reduction in maintenance cost that leads to the development of cost model and (3) a use of case studies to evaluate degradation of systems under consideration and how their continuous monitoring can help reduce the maintenance cost.

A cost modelling study presented a simple and effective method to analyse the financial implication of integrating HUMS system was proposed for military land vehicles. The model provides logical steps to estimate the yearly repair costs, operational availability and the overall costs to understand the financial implication of HUMS integration over the whole service life. The model was also used to assess the financial viability of integrating HUMS in other military platforms e.g. light armoured vehicle, Piranha and Main Battle Tank, Challenger 2. In both the cases, the analysis showed significant financial savings in the long term.

A case study was conducted on two different military vehicles to identify the frequency of different systems and sub-systems failures. The 20 challenger 2 and 40 Piranha were studied over the period of 10 years of service time. Study has found that cooling-, lubrication- and the suspension- system were the mostly affected systems in those particular vehicles.

An experimental protocol was developed to study the failure detection techniques for the suspension system. The frequency response function was used to identify the failure of the damper and hence the suspension system. The study has observed the changes in the resonance frequency of the failed suspension system with different excitation magnitudes. Effect of vibration waveform was observed to be negligible. However, the small changes in the resonance frequencies using different magnitudes of base excitation seems to suggest the excitation magnitude has the potential to identify the failure based on the frequency response function.

Another experimental protocol was developed to examine the failure detection technique for the cooling system of the military vehicle. When the failure was introduced to the cooling system, the significant variations in the temperature were observed for all the engine running conditions at the lab as well as the test with the vehicle running in the field. The variations observed in the temperature measured in different locations in the cooling system could be used to diagnose an early stage of failure in the cooling system, and it can be used to take a preventive action before the actual failure occurs.

**Keywords**:

Damper, Health and Usage Monitoring System ( HUMS), Suspension, CAN, Vehicle, Failure, Lubricant system, Cooling System, Diagnostics HUMS , Prognostics HUMS, CBM, CBM+, ALS, DIS , Cost modelling, pressure , Temperature , CAN Bus, Frequency Response, Weighted acceleration.

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## Definitions and Abbreviations

| | |
|---|---|
| AA | Accidental Allowance |
| AC | Air Condition |
| Acc | Accelerometer |
| ALS | Autonomic Logistics System |
| Alt | Alternator |
| APC | Armoured Personnel carrier |
| Batt | Battery |
| C2 | Challenger2 |
| C3I | Command Control Communication and Intelligence |
| CAA | Civil Aviation Authority |
| CAN | Controller Area network |
| CAE | Computer Aided Engineering |
| CBA | Cost Benefit Analysis |
| CBM | Condition Based Maintenance |
| CBM+ | Conditioned Based Maintenance Plus |
| CDU | Commander display Unit |
| CG | Centre of Gravity |
| Chass | Chassis |
| CITS | Central Inflation Tyre System |
| Conv | Converter |
| COTS | Commercial Off the Shelf |
| CPS | Commander Primary Sight |
| CVS | Comma Separated Variables |
| CPU | Central Processing Unit |
| CTIS | Central Tyre Inflation System |
| dHUMS | Diagnostic Health Usage Monitoring systems |
| Diff | Differential |
| DNVA | Driver Night Vision Aid |
| DoD | Department of Defence |
| DSTO | Defence Science and Technology Organization |
| DSU | Data Storage Unit |
| DT | Down Time |
| EAV | Exposure Action Value |
| ECU | Engine Control Unit |
| ELV | Exposure Limit Value |

| | |
|---|---|
| Eq | Equation |
| Exht | Exhaust |
| FAA | Federal Aviation Administration |
| FDSS | Fire Detection and Suppression System |
| FEPS | Field Electrical Power Supply |
| FFT | Fast Fourier Transform |
| F/ Sys | Fire system |
| FRFs | Frequency response Functions |
| GRLF | Gunner Range Laser Finder |
| HE | Heat Exchanger |
| HET | Heavy Equipment Transporter |
| HUMS | Health Usage and Monitoring System |
| Hyd | Hydraulic |
| I/O | Input/ Output |
| ISRD | In- Service Reliability Demonstration |
| JHSAT | Joint Helicopter Safety Analysis Team |
| JSP | Joint Service Publication |
| LCCA | Life Cycle Costing Analysis |
| LET | Light Equipment Transporter |
| LRF | Laser Range Finder |
| LTP | Low Temperature Passive Probes |
| LVDT | Linear Variable Differential Transformer |
| MBT | Main Battle Tank |
| MEMS | Micro-Electro Mechanical Sensor |
| M/ Fold | Mani Fold |
| MOD | Ministry of Defence |
| OA | Operation Availability |
| O/ Cooler | OIL Cooler |
| OSD | Operational Service Dates |
| P | Pressure |
| PC | Personnel Computer |
| pHUMS | Prognostic Health Usage Monitoring Systems |
| Prop Shaft | Propeller Shaft |
| PSD | Power Spectral Density |
| Q | Quarter |
| Rad | Radiator |
| r.m.s | Root Mean Square |

| | |
|---|---|
| Sen | Sensor |
| Shck abs | Shock absorber |
| Shft | Shaft |
| Sig Sys | Signal switch |
| Sus | Suspension |
| SPI | Serial Peripheral Interface |
| Sys | System |
| T | Temperature |
| T1,2,3,4 | Transmissibility, the ratio between output to input |
| Trans | Transmission |
| TS | Time Service |
| TVTS | Total Time Vehicle Service |
| UART | Universal Asynchronous Receiver/Transmitter |
| UK | United Kingdom |
| VMEP | Vehicle Management Enhancement Program |
| VIM | Vehicle Interface Module |
| VMU | Vehicle Monitoring Unit |
| VSI | Vehicle system Integration |
| WT | Wheeled Tanker |
| XML | Extensible Mark-Up Language |
| Y | Year |

## **Symbols**

| | |
|---|---|
| $\Phi_{CC}$ | Cost of Consumable |
| $\Delta t$ | Down Time |
| $\Phi_{HC}$ | HUMS cost |
| $B$ | Accidental allowance cost |
| $\Delta$ | Out of Service Penalty |
| $\Phi_{PC}$ | Platform Cost |
| $\Phi_{RC}$ | Repair Cost |
| $\Phi_{SM}$ | Stock Management Cost |
| $\Phi_{SR}$ | Schedule Repair Cost |
| $\Gamma$ | Total Cost |
| $\Lambda_{st}$ | Time the vehicle is in service |
| $\Lambda_{tt}$ | Total time the vehicle is in service |
| $\Phi_{UR}$ | Unscheduled Repair Cost |

## Declaration of authorship

I, Mohammed Al Abri, declare that the thesis entitled

**Health and Usage Monitoring System for Military Vehicles**

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

this work was done wholly or mainly while in candidature for a research degree at this University;

where I have consulted the published work of others, this is always clearly attributed;

where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;

I have acknowledged all main sources of help;

Where the thesis is based on work done by myself jointly with others. I have made clear exactly what was done by others and what I have contributed myself;

Signed: .........................................................................................

Date: ..............................................................................................

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# Chapter 1

# Introduction

This chapter provides an overall outline of the thesis aim and the background knowledge required for this research. The aims and objectives of this research are given at the end of this chapter.

## 1.1 Overview

In the early days, the vehicle engineering industry started to monitor and record small numbers of parameters which were predominantly related to the engine health. The main parameters recorded included temperatures, pressures, vibration, and speed. The monitored data was then taken for processing and analysis. The technique was very simple by today's standard, none the less it set the vital foundations for the future i.e. the development of Health and Usage Monitoring System (HUMS). This early system could only record information and could not determine the stress and strains being experienced during operation; neither could it warn about the components remaining operational life.

Nowadays, HUMS do more than just acquiring and recording vehicle parameters. Today, information is monitored for accuracy; and results are calculated & recorded in real time to support rapid feedback, reduced data volume and immediate output to other systems. This makes it possible for modern systems to warn about the health of the vehicle in real time. Since the introduction into the engineering sector, Health and Usage Monitoring System (HUMS) has rapidly gained momentum and expanded from air vehicles and offshore oil & gas industry to military land vehicles, unmanned aerial systems, and commercial operations.

HUMS is designed so that it can continuously monitor the health of critical components or sub-systems in vehicle and automatically feedback or warn about its health. In an aircraft, HUMS enables recording of structural wear, transmission vibrations, rotor track and balance information, and engine health data. It not only monitors the health of rotating components such as gearboxes, bearings, shafts, engines, and rotors, it also records data from an aircraft’s overall movement and flight path for usage and event analysis. For a typical ground vehicle, HUMS can provide continuous monitoring of the components wear, vibrations, stress/strain levels in each components and overall system health. Whether it is a ground based system or air system, the information extracted from the use of HUMS allows maintenance engineers to make informed decisions regarding the safe operation and timely maintenance of their vehicle. As a result, HUMS have been proved to enhance safety, minimise maintenance cost by reducing the quantity of spares, decrease the time the vehicle is out of service, and thereby reducing the overall operational costs. A schematic of a generic HUMS system is shown in Figure 1.1, which presents an outline of HUMS and its working principle.

Although HUMS has started to widely find its use in both the air and land based domain, its real potential will not be realised until it is available to a dedicated logistics system, in real time, which can process the HUMS data automatically or autonomously to initiate the fault repair/maintenance process. Such a system is called autonomic logistics system (ALS). Ordering spares for a part which is about to reach its wear or durability limit in a system, informing about the type of specialist required to repair the vehicle fault, notifying the central control about the system remaining life and its impact on the availability of the vehicle are some of the many important usage, an ALS can potentially offer. Due to the fact that the ALS can automatically handle above the routine tasks mentioned above, the manual work force is free to perform more important jobs which require direct human intervention.

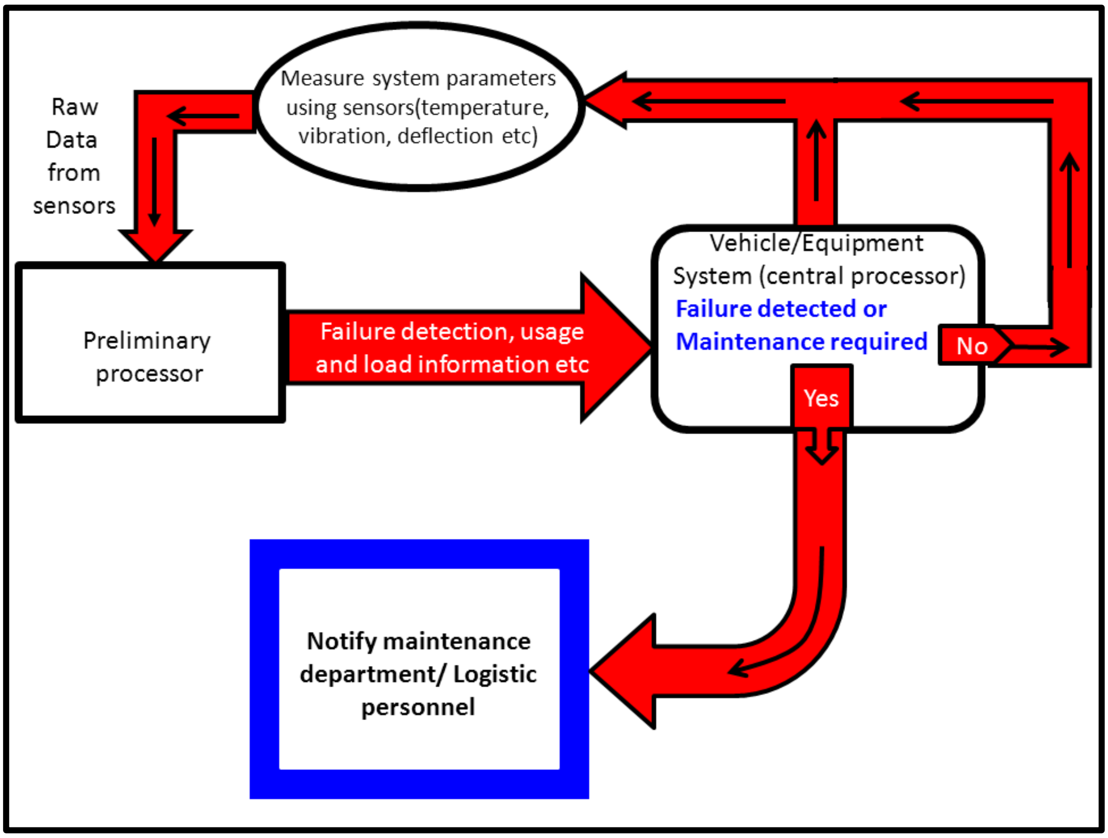


Figure 1.1 A schematic of generic HUMS system.

## 1.2 Motivation for this Research

Both civilian and military modern vehicle designs are putting a lot of emphasis on automatic/semi-automatic systems which can provide continuous information on the health of the vehicle to improve reliability in operation and to reduce the maintenance costs. This is even more critical for military vehicles because military vehicles are deployed in unfriendly and harsh terrain. This means that an inbuilt system in the vehicle to warn and update about the overall health of the system and those of the sub-components is critical so that its suitability for deployment in long operational campaigns and its remaining service life can be accurately assessed. One such solution can be an integrated module comprising HUMS and ALS. This thesis investigates the suitability of such a system in a military vehicle. The main aim of this thesis, therefore, is to review, assess and test an integrated HUMS/ALS system in a representative military vehicular platform to demonstrate the improvement in hardware reliability and reduced maintenance costs. The main novelty from this research which adds to the knowledge includes evaluation of how HUMS can improve the availability and operational readiness and reduction in maintenance cost that leads to the development of cost model, a use of case studies to evaluate degradation of systems under consideration and how their continuous monitoring can help reduce the maintenance cost and a development of novel fault detection technique for the suspension systems in the military vehicle.

# Chapter 2

# Literature Review

In this chapter, a comprehensive review of past research relevant to the thesis is conducted. This puts the research works planned here into context. This section has three main sub-sections to focus on the survey of past research which are: air vehicles, land vehicles and ALS.

## 2.1 HUMS Classification

It has already been mentioned in Section 1.1 that HUMS facilitates efficient operation of air/ground vehicles by enhancing the decision making process by continuously monitoring the operational parameter of the vehicles. Modern HUMS can diagnose faults with a vehicle or equipment before they become operationally unreliable. In addition, it can also predict the critical residual life of the vehicle components and subsystems. This ensures operational effectiveness while reducing maintenance overheads. Based on the operational priorities and structures, HUMS system can be classified into two main types: diagnostic and prognostic. Figure 2.1 shows the HUMS technology and its different types.

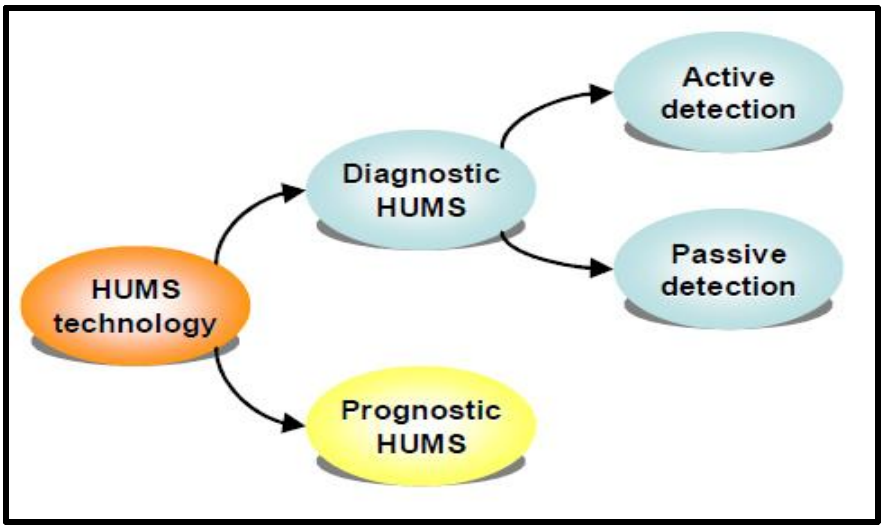


Figure 2.1 HUMS and its classification (adapted from [3]).

### 2.1.1 Diagnostic HUMS

The diagnostic HUMS (dHUMS) as the name implies, can only diagnose a fault or defect in a system if it is already present. Therefore, the system must rely on the fundamental principal of damage tolerance i.e. the component must tolerate the defect with sufficient remaining life to successfully complete its mission. The diagnosis process in this type of HUMS system consists of observing of signs and symptoms along with study of the past operational history of the vehicle.

The diagnostic signs are generally reported by the vehicle crew following the observation of irregularities in performance. These signs can be mechanical noises from the transmission or clutch slip, engine pitting noise etc. In majority of the cases, the signs only give a qualitative indication of the defects that guide an experienced technician to the root cause of the problem. Since these signs are subjective without any quantitative value, they require considerable experience and skill to utilize and hence are very unreliable for early fault detection. Similar to the signs, diagnostic history also gives a qualitative account on the past deployment of the vehicle or system e.g. vehicle log with the details of where the vehicle has been used along with any notable incidents during its life. Again, due to its qualitative feature, HUMS system can only make very limited use of the data history. Unlike the signs and history, the diagnostic symptoms are reported by the vehicle itself e.g. coolant temperature and oil pressure, fuel level in the tank. Unlike the signs, the symptoms are usually quantitative parameters and hence are particularly suited for further analysis by HUMS systems. Although some level of skill will still be required to understand the symptoms given by the vehicle in the case of manual interpretation, HUMS can be the expert system for interpreting this data automatically without the need of expert vehicle operatives [1, 2]. So HUMS is essential due to the difficulty in achieving the safety of the critical technical systems, the use of known traditional ways for system operation and the procedure of carrying out maintenance are still not effective. Failures in such component or systems can be failed catastrophic. These failures can cause losses of lives or at least can mission terminate.

Modern diagnostic HUMS are concerned with the advanced detection of symptoms. For example, faults are diagnosed by looking for certain characteristics in the measured data which are also commonly known as the fault signature. The main challenge of a modern diagnostic HUMS is to be able to identify the fault characteristics correctly and provide a reliable means of diagnosis [2]. This task is often extremely challenging and many systems are known to flag an excessive number of false detections. Typical methods of detection in diagnostic HUMS are based on either an active or passive approach. An active approach generally involves transmitting clean signals through a component and measuring the response. Examples include the use of lambda waves for detecting crack propagation through thin sheet structures, or passing an electric signal and measuring its electrical resistance, e.g. piezoelectric transducers. The use of clean input signals makes it easier to diagnose the variation in the response. However, this approach requires transducers that emit the active signal as well as sensors to monitor the response. The passive approach on the other hand monitors data while the vehicle is operational e.g. vibration monitoring of gearboxes to identify progressive faults. This approach is more suitable for heavily loaded components that require significant loads in order to measure a response. As passive monitoring takes place while the vehicle is operational it can be used to provide an instantaneous warning of failures. The computing facility must be installed on the vehicle, however, and cost and space constraints can limit the available CPU power [3].

### 2.1.2 Prognostic HUMS

Unlike dHUMS, a prognostic HUMS (pHUMS) involves continuously monitoring the status of structural health of a component and predicting its remaining useful life without the presence of a detectable defect. pHUMS is able to do this by using and processing the load data from the past on the vehicle analytically to predict the fault and its propagation with time on each component. So the prognostic HUMS has the ability to predict accurately and precisely the remaining useful life of a component or a system /subsystem.

Rather than relying on damage tolerance of a component as in the case of dHUMS, it would be preferable to have an approach which predicts the residual life of the components in the ground vehicle that exhibit no evidence of measurable faults prior to catastrophic component failure; and pHUMS provides this capability [4]. Although pHUMS approach may seem to be a relatively new capability developed as a result of technological advancement, the idea itself is not new and many similar methods have been used in the past to monitor fatigue crack growth and hence predict the fatigue life. As an example, simple devices (fatigue meters) have been in use for considerable amount of time in aircraft to count the number of fatigue cycles, and similarly devices known as ‘fatigue fuses’ have also been tried on ground vehicles to monitor and predict fatigue life. It is therefore obvious that pHUMS is the preferred choice while commissioning the HUMS capability on both military and civilian vehicles [5, 6,]. Another use of pHUMS system which is becoming extremely popular is illustrated schematically in Figure 2.2. From the figure, pHUMS can be used as a system which informs a condition based maintenance regime where the decision to replace a component can be made based upon knowledge of the health of the individual component, rather than length of time in service [7]. In other words, pHUMS can be used to predict a maintenance schedule of components based on their remaining component life and structural health, a predictive maintenance system. Generally, every critical component has a specified design life based upon the expected usage under normal operating conditions. The service life of the component, however, can be extended if the actual component usage in service is lower than the design life, and depending on the actual usage it can result in a significant cost saving. Similarly, a component may need to be replaced or repaired earlier than the specified design life if the actual usage is more severe than the predicted, which implies a safety benefit.

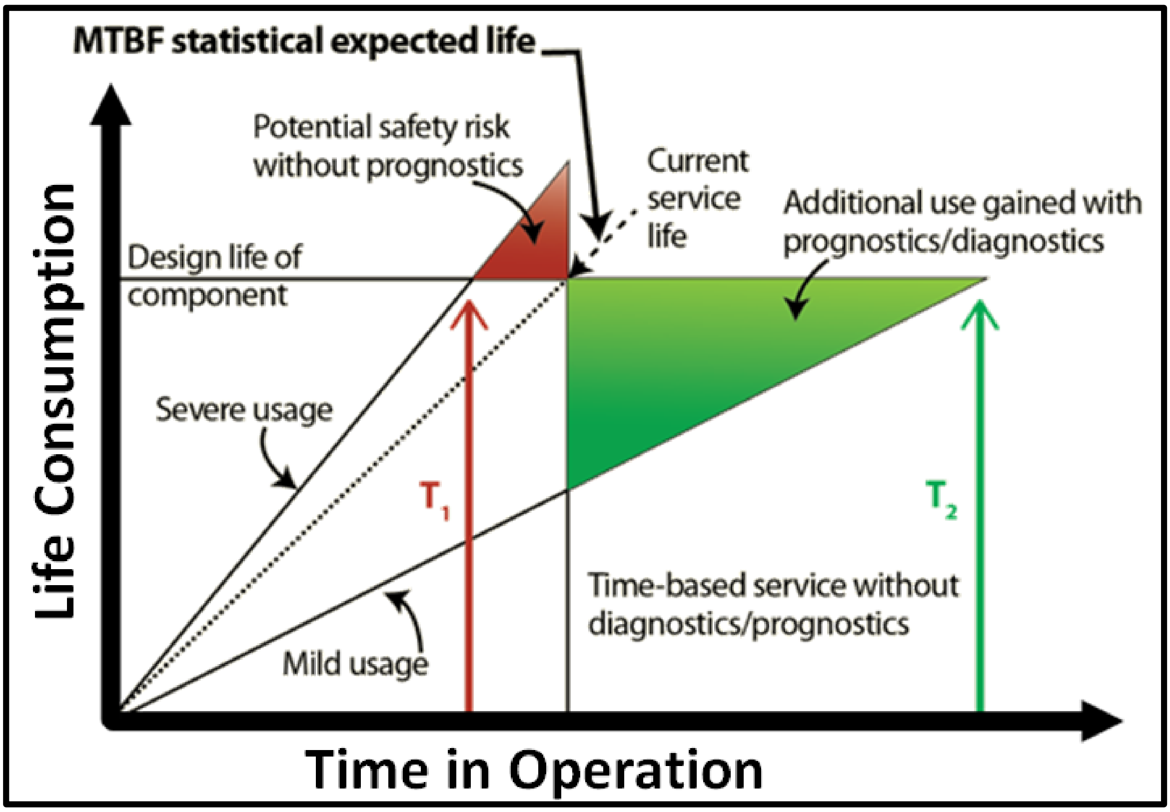


Figure 2.2 pHUMS as a predictive maintenance system (adapted from [7]).

In an ideal scenario, one would like pHUMS to monitor the loads on every critical part on the vehicle and analyze the monitored data through a dedicated analytical model individually to accurately predict the residual in-service life; however, such an approach would be impractical and prohibitively expensive in practice. Therefore, a suitable compromise between the HUMS capability and its cost is usually sought. Another approach is to reduce the number of components whose data are measured continuously on board and for the rest of the critical components the data for the analytical model to predict the residual life are taken by using the already measured data from other resources. The more we reduce the number of continuously measured parameters, the lower the cost of the system. However, this also implies that the lower that of on board measurement, the greater the uncertainty on the predicted life due to the heavy reliance on the analytical model. This compromise can be clearly evident when an aerospace vehicle is compared with ground vehicle. This is due to the fact that aircrafts are produced in low volume with considerably high unit costs and they are required to operate in hostile environment without any support where the cost of failures both in terms of life as well the equipment are extremely high. In comparison land vehicles are commissioned in relatively large numbers, which results in much lower unit costs. Additionally, and most importantly, ground vehicles are usually deployed in large fleet and hence support would be readily available in the case of equipment failures [8].

A simplified schematic of the analytical model in pHUMS is presented in Figure 2.3, which also shows the calibration process. The main requirement on the analytical model is that it has to be simple because the onboard processor usually comes with limited computing power and hence it will not be capable of analysing complex models. In normal operation, the measured data is first checked to ensure that it is free of errors and corrected if needed. The data is then fed to its structural model, which analyses the data to evaluate the signal of the overall structural load acting on the component. This signal is then further analysed to assess the 'Potential Damage scenario'. The term 'Potential Damage' is specifically used here to stress the fact that the actual damage is seldom calculated at this stage of the component operation. Potential Damage also gives a representative value of the component damage, which can be calibrated by in-service experience and design models.

Table 2.1 Comparison between diagnostic and prognostic HUMS

| Diagnostics HUMS | Prognostics HUMS |
|---|---|
| Determine the parts ability of operation and its function | Determining the RUL of the part. |
| It can only do fault detection | It can detect a fault and isolate it at same time |
| It cannot offer CBM or CBM+ | Offer both CBM &CBM+ |
| Not predicting the RUL or part Span time | Predicting the RUL and predicting the failure before its happiness |
| It cannot track /follow the component life | Can track /follow the component life |
| Cannot indicate the degradation of the component | It can indicate performance degradation |
| It is not for fault description/ reporting | It can select the fault reporting / description |
| Cannot help in repair decision making and resources management(No CBM) | It is very helpful in decision making and repair resources management(CBM) |
| Cannot accommodate faults | It can accommodate the faults |
| Limited in system availability /reliability | Enhanced very well the system availability /reliability |
| There is no changing in manpower /cost | Change fully the repair cost and manpower required for repair |
| Schedule inspection and maintenance required | Replaced all these by CBM |
| No condition based removal application | There is based condition application |
| Cannot isolate the fault ( type& location of the fault) | Self-faults isolates |
| Cannot indicate the real time monitoring of the faults or component status( no, future maintenance event information provide) | Provide a real time future maintenance events |
| Cannot catch of possibly tragic/ catastrophic failure before its occurrence | Indicate the failure before its occurrence |

| | |
|---|---|
| Initial faults cannot be detected before to failure | Initial faults can be detected before to failure and track it until just prior failure |
| Opportunistic maintenance cannot be carried out | Opportunistic maintenance is always available to reduce vehicle down time in the workshop |

Table 2.1 discusses the pros and cons of the diagnostic and prognostic HUMS and provide the detailed information about two techniques.

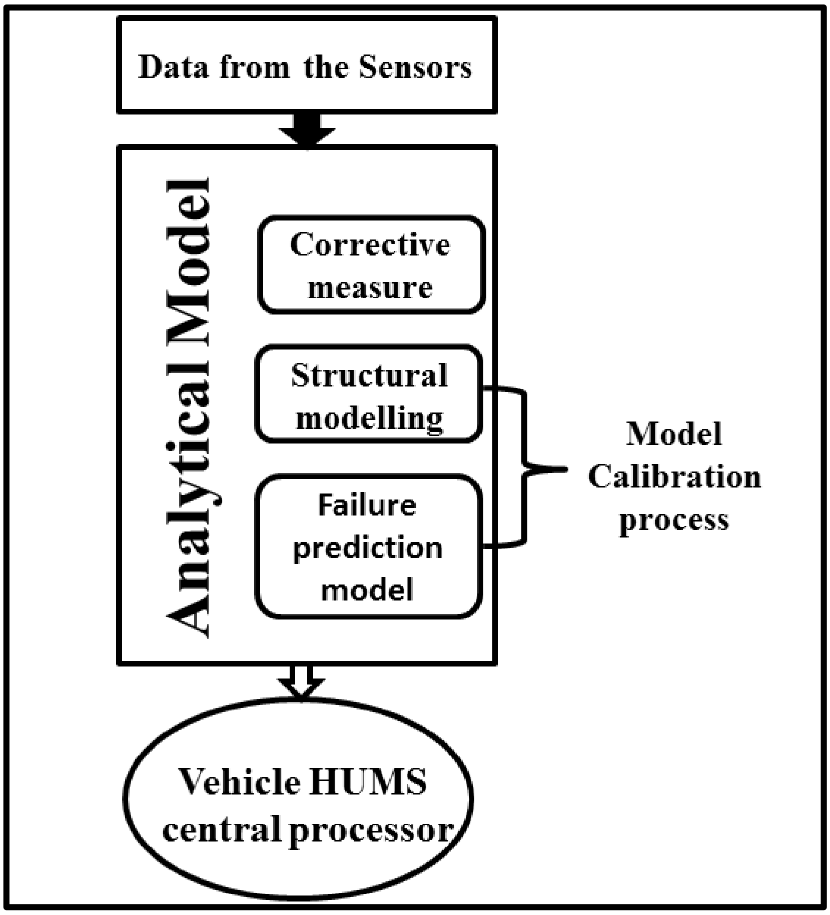


Figure 2.3 A simplified analytical model used by pHUMS (adapted from [3]).

For new vehicle designs, the analytical models used by onboard HUMS are initially calibrated using the Computer Aided Engineering (CAE) with additional refinements from prototype validation and further statistical fine tuning. In the case of existing service vehicles, integrating HUMS requires calibration using the data from instrumented vehicle test along with in-service records because the original design analysis is rarely available. Some failures are highly statistical in nature and hence the analytical models must take account of statistical behaviour so that the vehicle failure is correctly assessed according to the overall goal of the mission, its possible risk along with the possible consequence if the mission is delayed. Additionally, the model should have capability for continuous auto-recalibration using in-service data to improve the statistical confidence.

## 2.2 HUMS in Air Vehicles

HUMS has become even more important in the aviation world due to its ability to provide early warning on the health of systems and/or sub-components, which is critically important for safety and reliability of the airborne vehicles. HUMS together with ALS can provide an integral module in an aircraft which can continuously monitor the aircraft for overall structural and operational health. More importantly, it can provide early warning and indication on any maintenance requirements.

With the continuously increasing requirements for higher safety standards, reduced operational and maintenance overheads, the quest of finding methods to diagnose and predict the possibility of a system/component failure is becoming the main design requirement. With the advancement of present day technology and non-intrusive analysis [9] and monitoring methods, HUMS/ALS can act as an automatic/semi-automatic system which can provide continuous diagnosis [10] on the condition of a unit (vehicle/structure) in real time so that it can be monitored towards providing better maintenance practices resulting in reduced operational costs.

“The use of HUMS in air system gained momentum from early 1980s when the use of onboard sensors for helicopter health and usage monitoring” was first used to improve safety [11]. In particular, numerous advanced sensors and monitoring methodologies have undergone significant development to facilitate fault detection across helicopter rotor, drivetrain and engine systems. Over the years, Vibration Health Monitoring equipment has significantly matured especially on large helicopters. The use of HUMS was not just limited to the rotary wing aircrafts. In fact, HUMS was tested equally widely on the fixed wing aircrafts and it found wide range of usage in aircraft diagnostic systems as well as air-breathing and rocket engine systems [12]. HUMS was even more extensively used on diagnostic systems within main engine development programme for space. With regards to air based systems, because of the potential for catastrophic consequences associated with a failure during ground testing and in-flight operation, developments in HUMS with sophisticated monitoring and diagnostic capabilities have gained considerable importance. A comprehensive review on the use of HUMS which covers up to early 1990s for helicopter technologies, fixed with aircraft technologies and space technologies have been provided by Miller [12].

In relation to helicopter technology, after the crash of Boeing Vertol 234 in 1986 which was caused by disintegration of the forward main gearbox, HUMS was tested in helicopter platforms in North Sea operations. Later in the 1990s, the UK Civil Aviation Authority (CAA) also started to trial HUMS on certain helicopters. Numerous studies have been carried out by several authors and research organizations into the effectiveness of HUMS monitoring and analysis systems. For example, the FAA conducted one of the first review on helicopter HUMS [11] in an effort to define certification requirements. One of the most comprehensive reviews on the HUMS was performed by NASA [13-15] assessing the application of HUMS in diverse areas ranging from the transmission gearbox to engine health monitoring.

Despite these extensive studies of HUMS for air based systems in the early 80s and 90s, almost all of the systems that employed HUMS used it on component monitoring and evaluation i.e. engine monitoring or engine and drive-train monitoring. Researches that addressed HUMS for diagnostic and monitoring of integrated systems were non-existent. In other words, the author found no record of any research that applied HUMS for monitoring and diagnosing total air-vehicle performance or health. Almost all the systems monitored only a single parametric function, such as vibration, oil analysis, engine health, etc.

Building on vehicle research, the UK MOD commissioned a task at evaluating the operational benefits of using HUMS on helicopters [16]. It was trialed on the Chinook platform for In-Service Reliability Demonstration (ISRD), which showed a system reliability of over five thousand flying hours. This figure is significantly above the recommended reliability requirement for the aircraft to have a 99% probability of successfully completing an eight-flying hour per working day without experiencing a system failure. Overall, the task concluded that HUMS delivered cost savings, resulting from preventing incidents and accidents (it was found to equate approximately to £4.6 million per year in monetary terms). The report concluded that there might be potential for greater improvements by further developing the management of the HUMS data. As a result of this, HUMS has now been commissioned to be fit in all new helicopter procurements, and also it has been mandated to be retro-fit in all UK MOD rotary wing aircraft capable of carrying at least nine passengers, and with Operational Service Dates (OSD) past 2010. In another study, Land *et.al*. [17], *also* studied the potential savings of HUMS and concluded that it both increases vehicle reliability and safety while significantly reducing maintenance and insurance costs [17].

Similarly, the US Army invested heavily in HUMS research and integrated it in large number of its aircraft (over 2,500 aircrafts with onboard systems and ground support equipment). HUMS system has been installed in over 4 different rotorcraft platforms including the Apache 64D Longbow Attack Helicopter and the UH-60A/L Black Hawk. By early 2000, the US Army had conclusive evidence that the HUMS systems were capable of reducing the part/system failure by almost half [18] (for the year 2000, the US Joint Helicopter Safety Analysis Team (JHSAT) found that part/system failures caused approximately 26% of the helicopter accidents in 2000 and 47% of the part/ system failure accidents might have been mitigated by the use of HUMS). In addition, with use of active HUMS/ALS integrated system, it was found to reduce the parts cost per flight hour by 12-22% in all HUMS-equipped helicopters from 2007-2009 [19]. A postgraduate research study conducted in 2001 [20] highlighted that, HUMS technology was relatively mature within the aviation sector, partly due to rapid development in the HUMS technology triggered by several high-profile accidents and changes to the aviation legislation. Additionally, the study concluded that this technology was rapidly spreading to the civilian land-based environment.

## 2.3 HUMS in Land Vehicles

As mentioned in previous section, HUMS was first implemented in the aviation platform over 30 years ago with main focus on the safety and reliability in air transport sector. However, its implementation in land vehicles took considerable time due to the cost involved in integrating such a system and extensive training requirement. With time, commercial stakeholders in civilian sector started to recognize that the importance of predictive information, the ability to provide more cost-effective customer support and the opportunity to reduce whole life costs were paramount; all of which could be achieved by adapting HUMS. This shift in thinking about HUMS in the civilian sector was a turning point for HUMS usage. Therefore, the HUMS technologies within civilian industry are not new anymore and their usage ranges from land vehicles to industrial machinery equipment in service. With the overall costs of HUMS being driven down by wide ranging adaptation in the automotive and industrial machinery applications alike, it has now slowly found its way into military ground vehicle/equipment platforms [21]. Today most military ground vehicles leaving the production line have some form of HUMS system installed in them.  The retrofitting of HUMS in-service military vehicles, however, has been extremely limited due to the design modifications required to integrate HUMS and the cost involved. In fact, in a study commissioned by Australian Department of Defence [22], it was concluded that the costs of retrofitting an in-service armoured fighting vehicle with a full HUMS system would far outweigh the potential benefits.

In the case of civilian sector, HUMS nowadays finds wide spread usage on commercial and private automotive vehicles with the vast majority of the new vehicles rolling out of the production line with some form of HUMS integrated on them. This wide spread use has resulted in significant cost reduction and hence even the military ground vehicles designed today come with ‘fitted-with’ or ‘fitted-for’ HUMS systems. The main reason behind this seismic shift in the mentality towards the use of HUMS is due to the realization that HUMS can provide many important benefits and three key benefits among them are: through-life cost savings, safety improvements and data quality improvements. It is worth noting, however, that military ground vehicles can have in-service life as high as 30 years, which implies that there are still many fleets of military ground vehicles in service today across the world that do not have HUMS. This is especially true for vehicles that were designed pre-HUMS era (here pre-HUMS era implies time before the HUMS found wide spread use). Installation of a fully integrated HUMS system on these legacy vehicles (which often have little or no electrical/electronic infrastructure) requires significant design modifications. Also, retrofitting HUMS on these legacy vehicles was found to be prohibitively expensive and added little value. In addition, the human factors or the crew comfort were not in much consideration in the military environment during the legacy military vehicle era, thus the suspension health monitoring and the human exposure evaluation were not fully integrated with these vehicle platforms. The implementation of new legislations on the human health and comfort risk encourages the military vehicle designers to integrate a HUMS with the current or future military vehicle platform.

In relation to HUMS adoption on UK military vehicles, UK Ministry of Defence (MOD) has clear directives [23] stating that HUMS need to be implemented into all the MOD fleet of ground platform whether they are legacy or new, the only exception is that the HUMS adoption has adverse financial implications without noticeable operational enhancements. One other exception is that all the legacy land vehicles undergoing major refurbishment programmes at present will not have HUMS retrofitted. In particular, the MOD policy document specifies four different levels of HUMS integration scenarios:

- Immediate, on-board driver/operator information (basic requirement)
- Short-term, off-board preventative maintenance
- Intermediate, HQ mission planning and Logistics Support (a typical HUMS)
- Long-term, Supply chain planning and feedback to industry (HUMS-ALS integrated module)

None the less, some HUMS functionality has been implemented in these legacy vehicles by using low cost COTS sensors and data collection systems to improve reliability and safety. This, however, is less true in the case of land vehicles in the civilian sector because these normally get recycled with change in technology. Most of the older vehicles do not have engine control units (ECUs) and they generally have very limited means of external interface. Due to this, most legacy vehicles use direct method of measuring/monitoring the critical vehicle parameters which for example include temperature and pressure. A simple retrofitting of HUMS in a legacy vehicle may not come with the sophistication of a modern interfacing with driver/operator e.g. information screen, it will also have provision to record other useful parameters such as distance travelled, fuel level, surrounding temperature, battery levels and mechanical displacements/vibration behaviours etc. The main aim of HUMS implementations in these legacy vehicles is to achieve maximum surveillance of the system with the lowest possible cost and minimum intrusion to the system itself. A schematic of HUMS integration of a typical military legacy ground vehicle is shown in Figure 2.4. This particular figure gives the example of a modern version of modular HUMS (modular HUMS can be; in retrofitted to legacy vehicles as well as it can be readily integrated to a modern land system. In addition, it can also be extended or improved based on the changing operational requirements or field requirements) implemented in Land Rover platform. In the system which comes with this example, the driver is provided with simple warnings based on different coloured flashing lights and or audio signals. It is worth pointing out here that the exclusion of an audio-visual screen is purely for the cost and space issues, in other words it can be readily implemented in legacy vehicles if there are no cost and space restriction. The Land Rover platform retrofitted with the HUMS, as described, is capable of continuously monitoring the parameters as follows:

- System and surrounding temperatures e.g. engine coolant, engine oil, gearbox oil, external and cabin temperatures
- engine oil and coolant fluid pressures
- engine and vehicle speeds
- time spent at harsh terrain (from on-HUMS accelerometers) e.g. Omani mountains/sand dunes/rocky areas

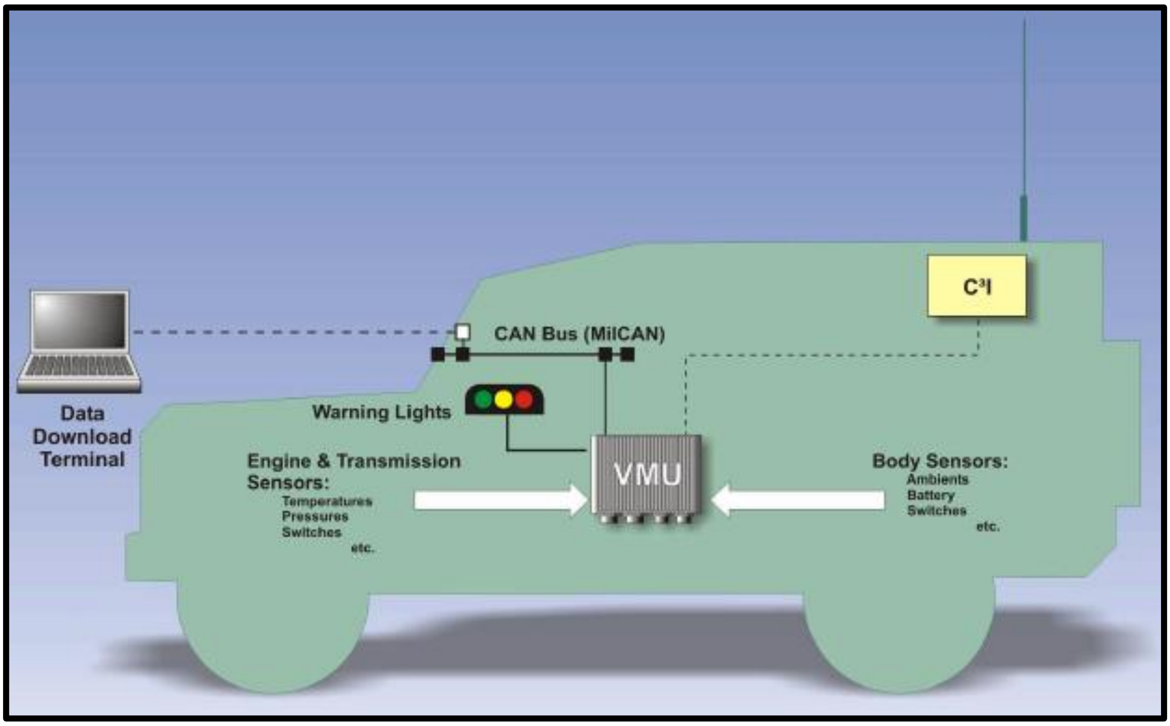


Figure 2.4 HUMS integration on a legacy military vehicle (adapted from [24]).

Although HUMS has found wide spread adaptation in ground based vehicles both civilian and military, this does not necessarily mean that HUMS is being used to monitor all the sub-systems of the vehicle. Usually HUMS based system is extensively used in the engine and transmission systems of a vehicle whereas it is seldom found in suspension. For example, nowadays it is common to find HUMS system used to receive indication of engine heating up, level of gear oil reduction and oil pressure [25], however, it is still unheard of being used to monitor a shock absorber (damper) failing or spring failing under unwarranted loads. Moreover, military vehicles with poor shock absorber will affect the ride, however, it will still allow vehicle to participate in operation with crew comfort being compromised, but a vehicle with faulty engine cannot compromised entire operation. Therefore, the engine is more critical system.

In 2004, UK MOD published a Policy Document [26] which was effectively to be standard on Health and Usage Monitoring Capability for Land Platforms [27]. This standard was developed by QinetiQ under contract by MOD, and its main aim was to outline the guidelines and requirements for a HUMS capability on Land platforms. The document also provided a generic overview of the requirements for data access, the specific environments in which the accessed data were useful and information needs. Additionally, the standard also provided extensive examples of data parameters which are essential to satisfy the information needs.

In 2005, a review was commissioned by UK MOD on the standard [28], which was found to show concern on the fact that the standard failed to mandate clearly the minimum requirements for HUMS; it only suggested the areas which could benefit by employing the HUMS technology. This in many ways limited the use of the standard to specify a consistent framework within which current and future vehicle/equipment platforms can adopt HUMS. None the less, the standard provides a wide range of parameters that could be measured using HUMS e.g. distance travelled; operating time, number of rounds fired and fuel consumption etc. These parameters suggested by the standard could assist LAND system policy makers in formulating its requirements for the use of HUMS on the battlefield.

The Defense Standard has been further refined in 2007 and updated in 2008 by the MOD through Joint Service Publication (JSP) 817, which mandates that acquisition teams must consider an appropriate level of condition Monitoring and apply a suitable condition based maintenance approach to through life support of their platforms. It directs all future land based systems must be fitted with a HUMS capability in-line with the standard. In addition, existing in-service systems are to be retrofitted with complaint HUMS where there is a clear operation and /or financial benefit. Therefore, the defence standards have gone through significant updating and the most recent version of the standard clearly directs the HUMS implementation in the all current and future land platforms. These clear directives have led MOD, within the last 10 years, to commission a number of contracts for land platforms which require capturing reliable usage information so that vehicle availability can be predicted. This in turn has triggered adoption of HUMS technology for numerous existing and all future platforms. The examples of these are: Heavy Equipment Transporter (HET), Light Equipment Transporter (LET), Wheeled Tanker (WT), Field Electrical Power System (FEPS) and Panther.

## 2.4 Main Components of Modern HUMS

A modern HUMS system has components/subsystems which collect, process, store and share information related to the usage and health of the vehicle and/or its components ultimately aimed at reducing through-life costs of the vehicle, providing efficiency in fleet management, reducing reactive maintenance and enhancing safety of the occupants. In order for HUMS to carry out these tasks effectively, it must have at least four critical components: sensors, preliminary processor, onboard central processor unit and off-board server or autonomic logistics processer unit. The usual mode of operation is that the sensors gather data from the vehicle components and pass it to the preliminary or local processor. The local processor, then, processes the data using its onboard analytical model and makes the analysed data available to the central processor unit. Finally, the central processor will share the information on the vehicle health and usage to autonomic logistics systems or the off-board processing unit, which in turn is used for further action or decision making [3].

Examples of modern HUMS system implementations are schematically shown in Figure 2.5(a) for a wheeled military vehicle and Figure 2.5(b) for a tracked fighting vehicle (main battle tank). Specifically, Figure 2.5(a) relates to the HUMS implementation on UK MOD's Command and Liaison Vehicle, Panther. The main stated requirements for this project included:

- A fully integrated system, which can continuously communicate with other sub-systems in the vehicle to monitor the health and usage status of the vehicle in real time.
- Open architecture of the data bus in order to have flexibility, scalability, and adaptability. The term "open systems" refers to the design stage of hardware, software, and manufacturing processes based on industry and expertise standards that are the supplier of the system -and the equipment-independent. SO Health and Usage Monitoring System allows for interoperability, transportability, and scalability. An open system can be used easily and extensively with several different suppliers. HUMS production, their technical specification and its capabilities can then be carefully chosen from many or multiple suppliers from COTS or other specialised manufacturers of this kind of technology.
- The system needs to comply with the Vehicle Systems Integration (VSI) guideline to interface with other systems. In other words, the HUMS system should be modular enough to sit as a component of the overall vehicle system in a networked environment.
- Capability to log data relevant to automotive parameters
- Storage & processing of the data
- Capability to report and log equipment faults to the operator, for example as temperatures, pressures and speeds
- System must be capable of recording the vehicle asset registration and maintenance schedules
- Capability to perform mission specifications (e.g. terrain type, environmental conditions) analysis
- Functionality to monitor and warn about the status of component. i.e. battery life

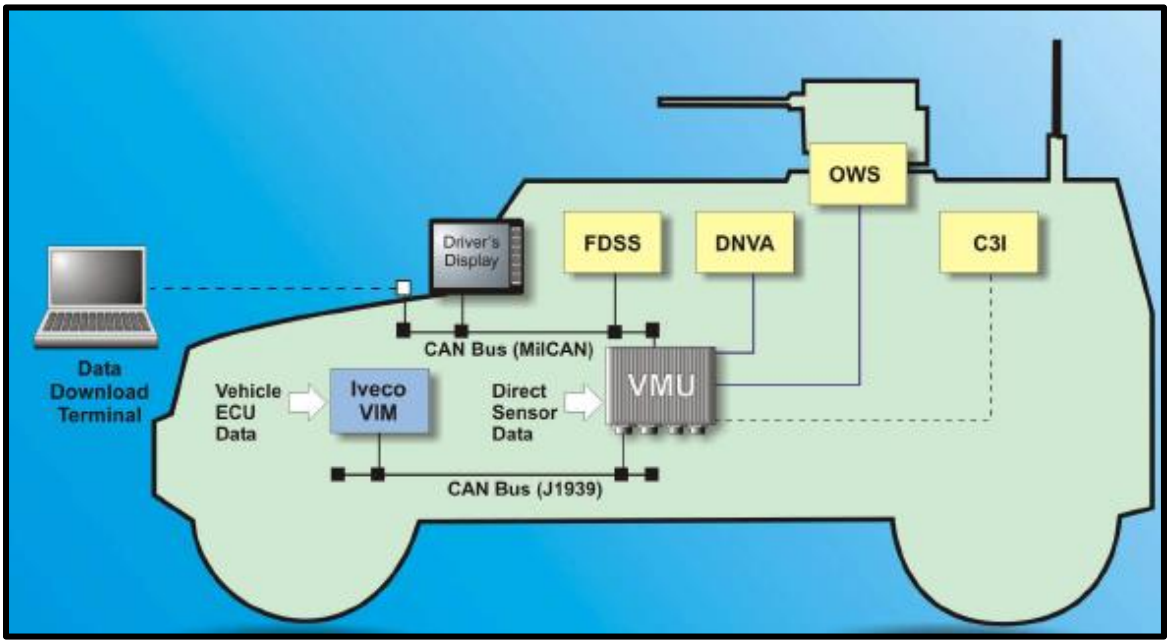
- System needs to be modular for flexibility and up-gradation

The main benefit of Health and usage monitoring system (HUMS) briefly are:

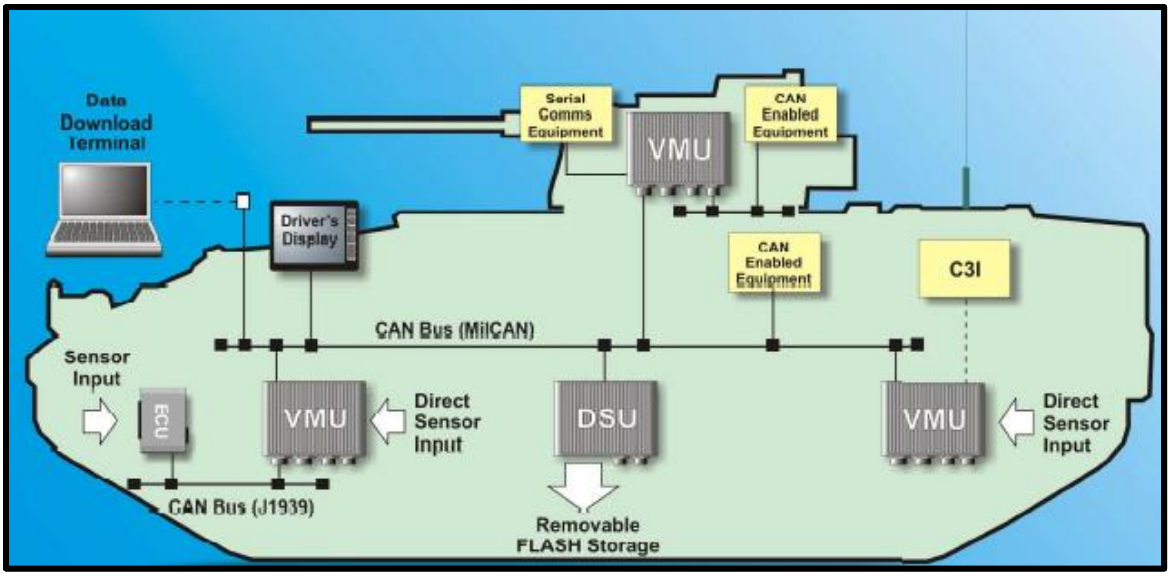
- Increase the safety of the of the vehicle
- Detect the failure of the components
- Propose the time of the maintenance to carry out.
- Identify the ruin of the components
- Forecast / detect the failure/remaining useful life (RUL) of the parts
- Saves all the data for future purposes.

The requirement also specifies that the HUMS must be able to function as a component on a networked environment and provide an effortless interface to other VSI compliant systems. In addition, the interface used by the HUMS must be widely available. Crucially, a very important part of the Panther project, is the need to provide a modular system so that it is flexible and it can be easily expanded in the future if required. In a military context, the range of vehicle to which HUMS must be applied is also extremely vast: from wheeled legacy vehicles to tracked vehicles; from vehicles with little electronic infrastructure to highly complex and integrated vehicles; from vehicles with no fitted data sources and sensors to vehicles with a wealth of built in sensors. Although many requirements may be common on the most vehicle types, there will be some requirements which are vehicle specific. For a HUMS system to be applicable across a wide range of the platforms, it must be very modular. In other words, it must be flexible, easily scalable and adaptable.

In general, data from engine, transmission and other critical systems sensors are fed into the HUMS processor. The data is processed and compared with some health logic, if the input signal is outside the health margins, system gives indication in form of coloured lights or warning sound or other kind of indication such as digital or written information.



(a) - A modern HUMS integrated on Panther.



(b) - A modern HUMS integrated on main battle tank.

Figure 2.5 Modern HUMS implementation on a wheeled (a) and tracked (b) military vehicle (adapted from [25]).

### 2.4.1 Sensors

Sensors are devices that transform physical quantities such as pressure or temperature into electrical signals so that the transformed signals can be provided as inputs to the control systems. Automotive sensors must satisfy a difficult balance between accuracy, robustness, manufacturability, interchangeability, and low cost. Specifically, sensors find widespread use in three critical areas of automotive systems, namely: powertrain, chassis and body. The sensors in automotive vehicles are used to continuously record and monitor the data related to vehicle loads, deformations, vibrations and many other parameters important to assess the health of the vehicle. The vehicle parameters recorded by the sensors are raw data which need to be further processed to understand the health and usage condition of the vehicle. Hence the sensors not only record the data, they also make these data available to the onboard preliminary processor unit for further analysis to assess the overall condition of the vehicle. Depending on the fidelity, complexity and the sophistication level of the HUMS system in the vehicle, it may have several sensors continuously providing recording of critical parameters to dedicated local processors in parallel.  This huge volume of data is channeled to their specific local processor unit (each sensor's data is fed to its own dedicated processor unit depending on its data type e.g. data measured by a temperature sensor cannot be processed by a structural data processing unit) via the dedicated data bus. The local processor units then access the data in the bus via a dedicated data interface, analyze the raw data and pass the information to the central processor unit so that an overall profile of the vehicle health can be created.

Nowadays civilian land vehicles are full of sensors, which improve the ride quality, safety and passenger comfort. As an example, modern luxury cars have up to 100 sensors per vehicle and as the technology advances, the areas of application for sensors also keep expanding. Fleming [29, 30] reviewed the modern automotive sensors and found an increase in the number of sensors use by almost 70% in the period between 2002 and 2007. This increase was predicted to cross 75% by 2013 [30]. Figures 2.6 and 2.7 show a range of sensors used to monitor and correct various car functions in a typical modern passenger car. From the figure, it is evident that sensor technology has sufficiently expanded and advanced so that it can be quite easily adapted in military land platforms as off-the-shelf product. Succeeding paragraphs provide an overview of the most widely used sensors in automobile applications and the technology behind their functioning.

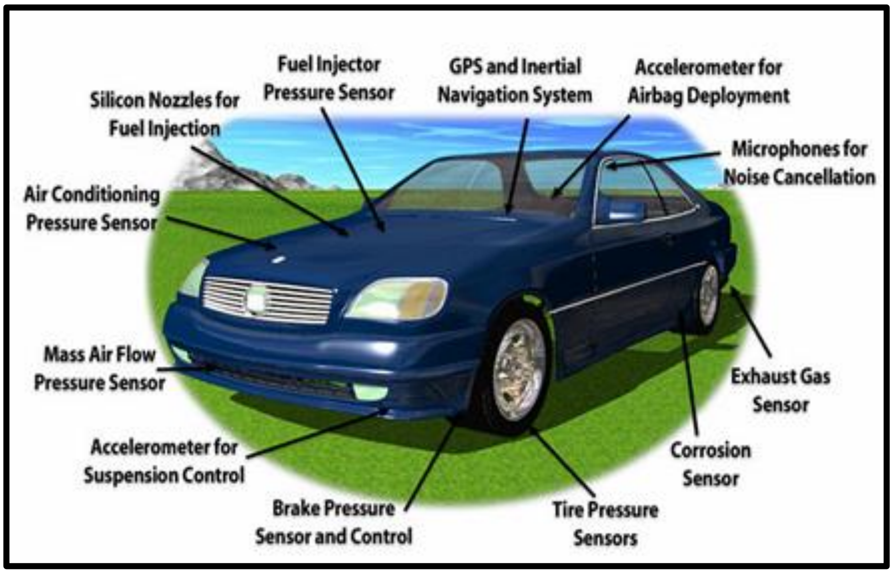


Figure 2.6 Various sensors on a typical modern passenger car (adapted from [31]).

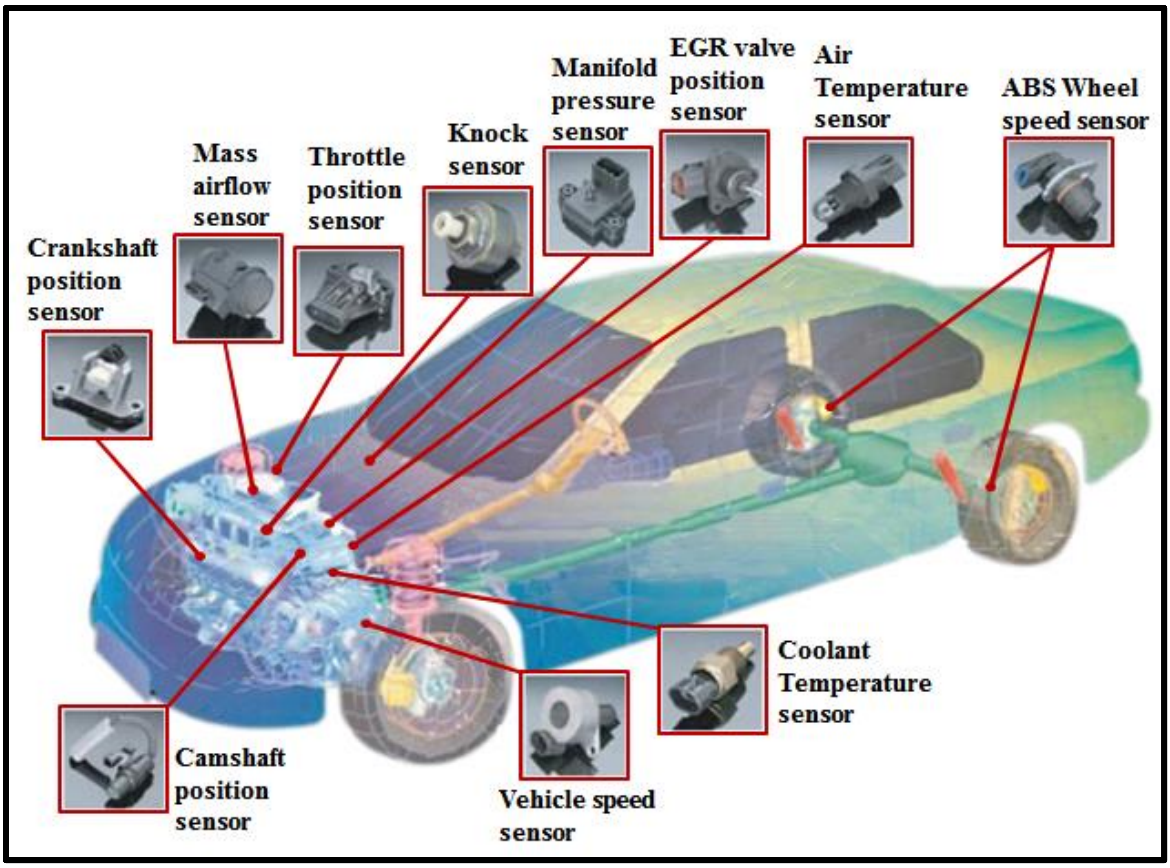


Figure 2.7 Sensors locations and hardware details on a typical modern car.

Over the past 30 years, land vehicle platforms have been increasingly adapting electronic systems to improve vehicle performance, safety and passenger comfort. This has led to a trend of mechanical systems in vehicles being increasingly controlled by sensors and actuators. Modern sensors in use today constitute a so called ‘smart sensor’ technology, which consists of in-built electronics signal processing capability inside the sensor itself [32]. Among the many important features, the smart sensor technology provides capability for automatic gain control, signal conversions, electronic interface to communication networks and operation using two-wire connection rather than the conventional three-wire approach. Specifically, smart sensor features have started to show notable presence in the sensors used for measurement of speed/timing, pressure, and inertial acceleration/angular rate. The continued advancement in the microcontroller and sensor technology is enabling the automobile industry to create even more complex systems which can provide further improvements in vehicle control and safety along with autonomous control of the vehicle. In addition, the modern vehicle platforms through the integration of the latest sensor technology are able to lower the overall production costs by minimizing development time and cost.

Selection considerations of sensors for HUMS comprise the important parameters that are to be measured, the performance requirements of the sensors, the electrical specification and physical characteristics of the sensor system, trustworthiness, and gross cost [33]. The specification of the Sensor systems is likely as follows:

Table 2.2 Consideration of sensors for HUMS

| Parameters | Ranks |
|---|---|
| Performance requirement | Long range and high rate data transmission, large on board, memory, fast on board data processing, frequency response, maximum temperature it can withstand, directional sensitivity (uniaxial, Tri-axial), sensitivity, Multiple sensing abilities (some sensors can measure two different parameters at the same time e.g. temperature and pressure. |
| Electrical specification and physical characteristics | Small size, light weight, low power consumption, requirement of external power supply, Easy mounting method, sensors must be rugged |
| Trustworthiness | Type of the sensor must be known and |

| | |
|---|---|
| | trustable |
| Gross cost | Low cost |

### 2.4.1.1 Temperature Sensors

Two different types of sensors are in use for the measurement of temperature depending on the range of the temperature to be measured. Firstly, thermistors which are made out of semiconductor materials such as cobalt or nickel oxides, are used to measure temperatures in low to moderate range (less than $150^0$C). Any variation in temperature changes the electrical resistance of a thermistor and this is converted to a voltage signal to measure the temperature. For the accuracy of measurements, the current through the thermistors must be small and the supply must be constant. The thermistors are commonly used to measure the temperatures in air intake manifold, batteries, engine and transmission, air conditioning and internal/external environmental temperature; and Oil and fuel. These devices would be suitable to measure the surface temperature of large calibre guns on main battle tank operating in hot climate of the Sultanate of Oman. However, for the measurement of moderate to high temperature variations (150 to $1500^0$C), thermistors are not suitable and thermocouples are used. Thermocouple generally consists of two dissimilar metals are joined together, forming the thermocouple junction. Among the two junctions, one junction is kept at a constant known temperature whereas the other is placed at the location where the temperature is to be measured. They are used for measuring the exhaust gas and turbocharger temperatures.

### 2.4.1.2 Pressure Sensors

Pressure sensors in automotive have very diverse requirements e.g. they need to be able to measure a very wide range of pressures from 10 kPa (to detect evaporative fuel leak) on the lower side, to as high as 180 MPa (in common-rail fuel injection systems in diesel engines). This enormous variation in the range of pressure measurement means that a single sensor technology will clearly be inadequate. As an example, a sensor technology suitable for measuring low pressure (10 kPa) will not be robust enough for the high pressure measurement (180 MPa). Consequently, there exist several different pressure sensor types used based on the range of pressure to be measured. For example, Piezo-resistive micro-machined pressure sensors are used to measure engine manifold pressure (absolute and barometric), turbo-boost pressure, and evaporative fuel leak pressure whereas Capacitive touch-mode micro-machined pressure sensors are used to measure tire pressure inside the rotating wheel and engine oil pressure. Similarly, capacitive ceramic-module pressure sensors (used to measure pressure in very harsh automotive environments) are used to measure brake fluid pressure (for cruise control disengagement and ABS braking regulation), suspension hydraulic pressure, and air condition compressor pressure and piezo-resistive polysilicon-on-steel sensors (for measuring very high pressures) are used to measure common-rail FI (fuel injection) pressure, and vehicle suspension dynamic-control hydraulic pressure.

#### 2.4.1.3 Rotational Motion Sensors

For measuring the rotational motion of various components in vehicle, several different types of sensors are used. For example, variable reluctance sensors are used to measure engine crankshaft and camshaft rotation so that spark plug and fuel injection timing can be precisely controlled. Additionally, these sensors are also employed to measure the wheel speed, the engine rotational speed, and to facilitate the effortless control of power transmission in the vehicle e.g. or electronically controlled gear shifting in automatic transmission. Highly Advanced Magneto-Resistor, AMR (Anisotropic Magneto-Resistive) and GMR (Giant Magneto-Resistive Sensors) sensors are used to detect engine misfire, and this is made possible by the capability of these sensors to measure the crank angles to a very high degree of accuracy. In addition, these sensors are also employed to keep track of wheel rotation in vehicle navigation systems.

#### 2.4.1.4 Linear Acceleration Inertial Sensors

With regards to the linear motion of the vehicle, the land vehicle platforms utilize Micro-Electro-Mechanical Sensor (MEMS) technology, which are used to sense and control:

- The vehicle’s stability and chassis suspension.
- The vehicle’s various mode of crash sensing (frontal, side, and rollover).
- Engine knocks detection

MEMS are micro-machines that are closely related to integrated circuits. MEMS integrate sensors, actuators and signal processors; and can monitor, measure and sense wide range of functionalities e.g. electronic, optical, mechanical, thermal or fluidic.

***<u>Chassis Acceleration sensors</u>***

These sensors are generally capacitive and function by detecting the change in capacitance due to lateral displacements between the electrodes. They have wide measurement bandwidth and are capable of providing high degree of accuracy over the full operating range of acceleration, pressure and temperature.

***<u>Vehicle Crash Detection sensors</u>***

Similar to Chassis acceleration sensors, these are also capacitive and are up to five in numbers in typical Modern vehicles (right-front, left-front, right-side, left-side and a central sensor). A typical crash sensor consists of a lateral-to-substrate displacement configuration, is flexure-supported, and the displacement between the electrodes is detected in terms of the change in the value of capacitance.

### ***Angular Rate (Gyro) Inertial Sensors***

The angular-rate inertial sensors also utilize the same technology as the acceleration sensors described in previous section i.e. MEMS technologies. These sensors function by detecting the Coriolis force effects on different types of vibrating mechanisms e.g. vibrating-ring, vibrating-tine (tuning fork), and vibrating mass. Despite the continuing advancement on the sensor technologies, the operating principles of these sensors have remained the same. However, there have been several marked improvements in terms of sensor size, which is mainly due to: replacing the ring vibration actuation from an electromagnetic type to a capacitive electrostatic type, upgrading from analog to digital circuit; using micro-machined sensor substrate box to compactly stack the electronics and the sensing elements; and utilizing surface-mount packaging. The angular rate sensors are used for varieties of sensing functions in automotive such as:

- Vehicle Electronic Stability Control: This was introduced to detect vehicle yaw rate accurately and adapted wholly in the US automotive sector from 2009 as mandated by the federal safety standard in USA.
- Active Chassis Suspension: used in vehicle Suspension control systems to detect vehicle roll-rate and pitch rate.
- Rollover-Protection Side Curtain Airbags: used to trigger deployment of rollover-protection side airbags.
- Vehicle Navigation Systems: used by Navigation Systems to detect vehicle yaw angle when the autonomous mode of navigation is required especially when the system's GPS absolute position signal is unavailable, as is the case near tall buildings or inside tunnels. In this situation, the system switches to autonomous mode of operation.
- Oscillating-Rotor Sensor: These sensors are not sensitive enough for use in the stability and control applications, where high accuracy at low angular-rate inputs are required. It is, however, widely used in the rollover and navigation applications, where higher angular rates are measured.

Dual Vibrating-Mass Sensor: These sensors are highly reliable and features high accuracy, superior signal-to-noise ratio and compact size. The dual vibrating-mass sensor is manufactured using a special process which facilitates MEMS fabrication in Silicon of larger, heavier, vibrating masses. These are relatively more expensive; however, their design meets the requirement of high accuracy at low angular-rates for use in stability control and active suspension applications.

### 2.4.2 Preliminary Processor

The main purpose of the local processor units is to access the raw data measured by the sensor and process it to predict the cumulative faults growth on critical vehicle components. Another important function of these processors is to make the results available to the central HUMS processor unit so that the central unit could inform the crew or the decision maker/engineer of vehicle health profile and maintenance requirements e.g. REME in Royal Army of the Sultanate of Oman and British Army. Most modern vehicles are fitted with a digital system which continuously monitors the inventory of the installed components.

### 2.4.3 Central Processor Unit

The central processor unit receives data from numerous local processors with information on various aspects of vehicle health. The central unit then conducts its own analysis to establish an overall picture of the vehicle health and usage level. It also sets priorities on the spare parts requirements and maintenance need based on the safety and vehicle usability i.e. critical components from the safety and reliability point of view are prioritized to be replaced or repaired first. Finally, the central unit will provide this information to the autonomic logistics system (ALS) to trigger decision making process on the supply chain.

## 2.5 Autonomic Logistics System

An autonomic logistics system (ALS) is a self-sufficient module which has capability and intelligence to perform tasks without any user feedback or command. To develop clear understanding of ALS, an analogy with the basic functions of nervous system in human body can be made. ALS can perform tasks automatically without continuous external commands just like in a human body’s nervous system, which carries out numerous activities automatically, e.g. breathing, blood circulation and sensing without constant thinking [34].

Whether it is an air platform or a land platform, an ideal ALS system should be capable of performing specified tasks automatically. For example, a typical ALS system in military platform can regulate following functions: ordering parts for a faulty system, informing the maintenance technician about the repair requirements, informing the logistics personnel about the platform’s malfunction and approximate downtime required for essential repairs and predict the suitability of a vehicle for given mission based on its remaining in-service life (estimated age). Although an ALS can perform all these routine tasks, full potential of ALS cannot be realized without a full functional prognostic HUMS system i.e. heart of ALS is a fully integrated HUMS. In other words, HUMS and ALS complement each other; and a modern platform cannot be called HUMS capable without it having a fully integrated HUMS/ALS system.

HUMS can find faults in the vehicle by performing on-board diagnostics, isolate and identify them, and this is then picked up by ALS to take further actions [35]. For example, ALS will delay maintenance if the fault can be bypassed by reconfiguring the system or if the fault is not severe enough until the next mission, and report its status, findings and actions to be taken in immediate near future. Many commercial airliners have also started to utilize the application of ALS through a dedicated sub-system called Condition Based Maintenance (CBM) which is also capable of functioning autonomously.

CBM brings together the various elements required for the performance of a maintenance event (the required component, technicians, specialist equipment and tools, hanger space, and necessary consumables). It is capable of predicting future health status of a system or component, as well as providing the ability to anticipate faults, problems, potential failures, and execute necessary maintenance actions. The most important of all, CBM's main objective is to minimize unplanned maintenance without compromising the safety. CBM achieves this by detecting wear within components, compare this to established safe operating parameters and replace them prior to failure. Figure 2.8 shows a component failure process and how it is monitored by CBM. More recently, CBM capability has been further enhanced by improving the reliability of predicting the need to perform repair/change part task. This is achieved by performing the reliability centered maintenance analysis, which involves continuously analyzing the sensors data that monitor system health and improving the prediction for maintenance need. This newer version of the CBM is also widely known as CBM plus (CBM+). The gap between fault detection (at point A) and action determined (at point B) (in the example illustrated in Figure 2.8) a sudden exponential decay occur, analogous to 'fast-fracture', potentially suggesting that the point of action determined should be as close as possible to fault detection to maximise safety. This can be effectively done by using instrumented CBM in the vehicle platform.

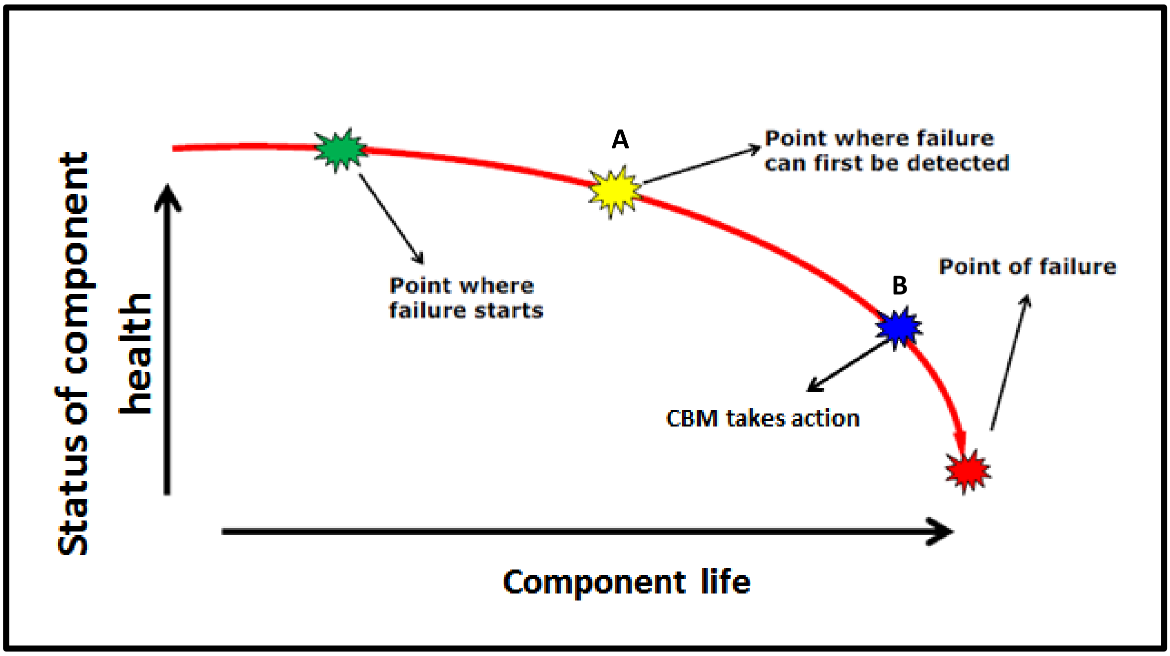


Figure 2.8 Failure monitoring and resolution by CBM.

One of the most important components of ALS is the Distributed Information System (DIS), which handles the information side of ALS. Specifically, DIS makes available the diagnosed information on the vehicle health and maintenance requirement of the vehicle to all the relevant logistics teams so that they are aware of vehicle health status, and trigger the demands for spare parts, skilled technicians and equipment. A modern platform with integrated HUMS/ALS module can be schematically represented as shown in Figure 2.9. The figure also shows how CBM and Supply Chain connect within the system.

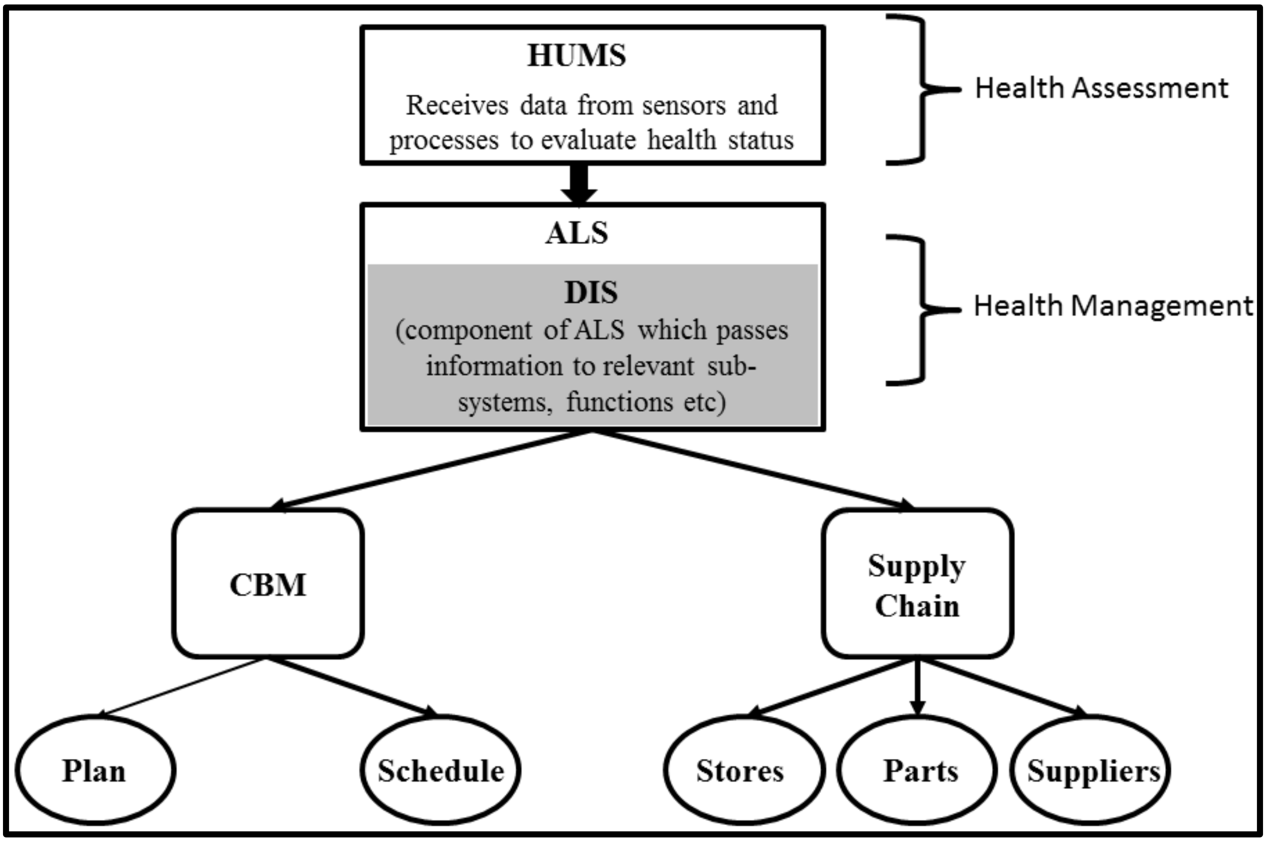


Figure 2.9 Schematic of HUMS/ALS integrated system.

Despite ALS being one of the integral components of the overall vehicle control and health monitoring, it is not perfect [36]. Its merits and short comings are listed below:

***Advantages***

- Fault can be detected before they occur, therefore it can be monitored continuously or further logistical action can be taken as required.
- Continuous monitoring of faults mean that the remaining service life of the parts is known and hence parts are automatically ordered, saving time.
- Can plan in advance the maintenance of the vehicle at ideal time, i.e. when the new part is delivered to the maintenance site.
- No scheduled/preventive maintenance required saving unnecessary costs on maintenance and increasing the reliability and the availability of the vehicle.

***Disadvantages***

- ALS system is not error free, false alarms usually occur which may result on unnecessary part replacement and maintenance

- It can also sometimes completely fail to detect a failure
- In some cases, the time from detection of a worn component until its failure may be too short to exploit the benefits of ALS

SO, CBM+ emphases on forecasting maintenance requirements and responding as a result. The idea is to lessening the logistics structure and instantaneously develop logistics performance by performing arts maintenance only as required.

CBM+ has a range of usefulness along the age of the vehicle, these benefits are as follows:

- Short maintenance phases
- Low repair and service cost
- Improved the quality of maintenance and process of obtaining the required parts
- Improved very well the vehicle and tools reliability.
- Highly achievement of vehicle availability as less downtime
- Increases the operators' safety
- Increases the vehicle life
- Improve the reliability of material resources and their relative administrative issues.

Condition Based Maintenance Plus (CBM+) practices systems engineering and technical methodology to gather data, support analysis, and help to support the supervisory developments for system procurement, renovation, sustainment, and function. Condition Based Maintenance is maintained by a Distributed Information System (DIS) that easily join in with other logistics system. Thus, Conditioned- Based Maintenance Plus is leading to the adequate maintenance, the improved readiness of the vehicles used in operation, and CBM+ has a high contribution in the cost savings supplementary with lesser logistics burden. CBM+ inspires the use transportable aids to use the Reference technical instructions book and worksheets, it is also assisting in making supervision in all technical understandings, supporting data record and saving it for later requirement. CBM+ also is a tool to reduce the requirements for maintenance facilities, manpower, guide to smart use of the equipment, and other maintenance resources guidance which cannot be offered by the other maintenance types. Final words can be said on CBM+ is to perform maintenance only and when there are evidences of need according to the HUMS health assessment and ALS health management assessment or decision made by the system.

## 2.6 Main Systems in Land Platform

Despite few limitations as mentioned above, the performance, reliability and the cost benefits offered by ALS have changed the future military and civilian vehicle development approaches drastically so that ALS/ HUMS system is now integral part of the overall vehicle development from the conceptual phase. With integration of ALS/HUMS system in mind, a typical vehicular platform can be represented in a simple system level sketch as shown in Figure 2.10.

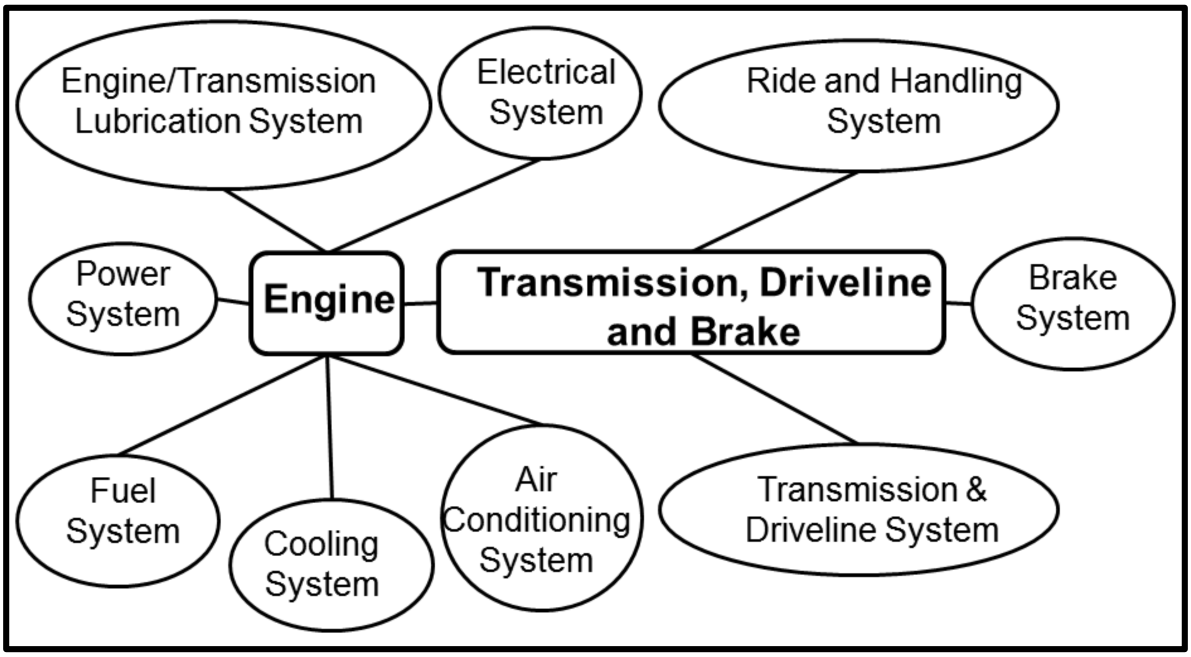


Figure 2.10 Important systems in a typical land vehicle.

Each system can be further expanded based on the main process involved, main parts in the system, its output and how the functionality of the system may be diagnosed. These details are presented below in tabulated form for each system. It is worth stating here that the only systems which are critical from the vehicle operational requirements are elaborated below.

Table 2.3 Power System

| Main Process | Main parts | Output | Diagnostic parameters |
|---|---|---|---|
| • Combustion process | • Cylinders<br>• Piston<br>• CAM &Crankshaft<br>• Valves | • Torque/Power@ specific RPM | • Engine speed<br>• Cylinder pressure |

Table 2.4 Lubrication system

| Main Process | Main parts | Output | Diagnostic parameters |
|---|---|---|---|
| • Engine Lubrication<br>• Transmission Lubrication | • Oil Pump<br>• Oil flow path<br>• &pipes<br>• Seals | • Reduced friction & reduction in component wear<br>• Reduced temperature | • Monitor oil viscosity & Temperature<br>• Oil pressure |

Table 2.5 Fuel system

| Main Process | Main parts | Output | Diagnostic parameters |
|---|---|---|---|
| • Fuel supply process | • Fuel pump<br>• Fuel line<br>• Fuel filter<br>• Exhaust flow pipe<br>• Injectors | • Metred quantity of fuel for complete combustion | • Injection pressure and timing<br>• Observing power output<br>• Exhaust combustion |

Table 2.6 Cooling System

| Main Process | Main parts | Output | Diagnostic parameters |
|---|---|---|---|
| • Cooling process | • Water Pump<br>• Radiator<br>• Ducts<br>• Fan | • Cool Engine &<br>• Maintain optimum engine operating temperature | • Coolant temperature<br>• pressure |

Table 2.7 Electrical System

| Main Process | Main parts | Output | Diagnostic parameters |
|---|---|---|---|
| • Electrical power supply | • Alternator<br>• Battery<br>• Electic supply to key location<br>• Ignition System<br>  • Coil systems<br>  • Distributor<br>  • Lead wires | • Cranking voltage<br>• Battery Charging<br>• Vehicle lighting correct voltage and amp at the desired location | • Check the voltage output from the battery<br>• Alternator performance<br>• Observe bearing noise |

Table 2.8 Ride and Handling System

| Main Process | Main parts | Output | Diagnostic parameters |
|---|---|---|---|
| • Suspension<br>• Steering | • Springs<br>• Dampers<br>• Steering system<br>• Connecting rods<br>• Shock absorbers | • Damped vibration<br>• Smooth ride quality for crew comfort<br>• Power steering<br>• Vehicle response against poor road condition | • Ride and Comfort (accelerometer, MEMS device)<br>• Steering vibration<br>• Vehicle stability |

Table 2.9 Transmission and Driveline System

| Main Process | Main parts | Output | Diagnostic parameters |
|---|---|---|---|
| • Power transmission<br>• Driveline<br>• Interface coupling | • Gearbox<br>• Torque converters<br>• Gears<br>• Clutches/Pressure plates<br>• Drive/Driven shafts | • Power transfer to the wheels<br>• Automatic gear shifts | • Noise<br>• Power loss due to poor interface<br>• Backlash<br>• Difficulty in changing gear<br>• Transmission fluid leakage<br>• Component wear<br>• Degradation of vehicle acceleration |

Table 2.10 Brake System

| Main Process | Main parts | Output | Diagnostic parameters |
|---|---|---|---|
| • Vehicle deceleration | • Brake disc<br>• Brake pad/Brake shoes<br>• Brake pedals<br>• Cylinders, pistons and hoses in Hydraulic brake systems | • Reduction in vehicle speed | • Poor braking performance<br>• Noise (squealing or grinding)<br>• Pulling to one side (or grabbing)<br>• Lost brake pedal |

After identifying candidate critical systems in military vehicle, three key systems were chosen for the implementation of HUMS so that vehicle health can be effectively monitored. The chosen systems are the vehicle cooling systems, lubricant system and ride & handling systems (shock absorber health monitoring).

The efficient and safe functioning of engine relies on the careful monitoring of the engine operating temperature, which can only be well controlled by an efficient cooling system and lubricant system. Hence, engine cooling system and lubricant system are one of the most critical systems in any automotive platforms for safe and reliable operation, even more so in combat scenario. Similarly, since the military vehicles operate in off road conditions and challenging terrains, reliable functioning of shock absorbers is paramount. For this, the following parameters and/or sensors are considered to design an effective HUMS system which will detect and diagnose the system problems to provide early warning along with automatic intervention if needed to correct it. The main parameters to be monitored are:

- Temperatures at coolant inlet, coolant outlet and engine block (various locations) using thermo couple
- Temperature of lubricating oil
- Pressures at inlet and outlet of the coolant
- Coolant flow rate measurement at inlet and outlet
- Lubricant system temperature and pressure
- The properties of lubricant fluid to improve fault diagnosis and interception.
- Displacement sensor to measure the platform vibration amplitude
- Temperature of the shock absorbers to monitor shock absorber health

## 2.7 Use of Controller Area Network (CAN) in the ALS/HUMS

Historically, hard wiring (point-to-point) methods have been used to connect electrical/electronic connections in vehicles. However, with the increase in the use of electronic devices and systems in the vehicles, the hard wiring has become extremely bulky and expensive. This has also resulted in the reduction of available space in the vehicle, which is critical especially in military vehicles. To address these issues, the vehicle manufacturers replaced the hard wiring with in-vehicle networks, this immediately resulted in reduced cost (due to reduction in the wiring needs), complexity, and weight. A major innovation in the technology happened in 1985, when Bosch [37] developed the Controller Area Network (CAN), which has been established to be the standard in-vehicle network for all the modern vehicles in the world today. In simple terms, CAN is a broadcast digital bus designed to operate at speeds from 20kb/s to 1Mb/s, the transmission rate being dependent on the bus length and the transceiver speed. Figure 2.11 shows the communication architecture in vehicle devices before and after the adaptation of CAN Bus.

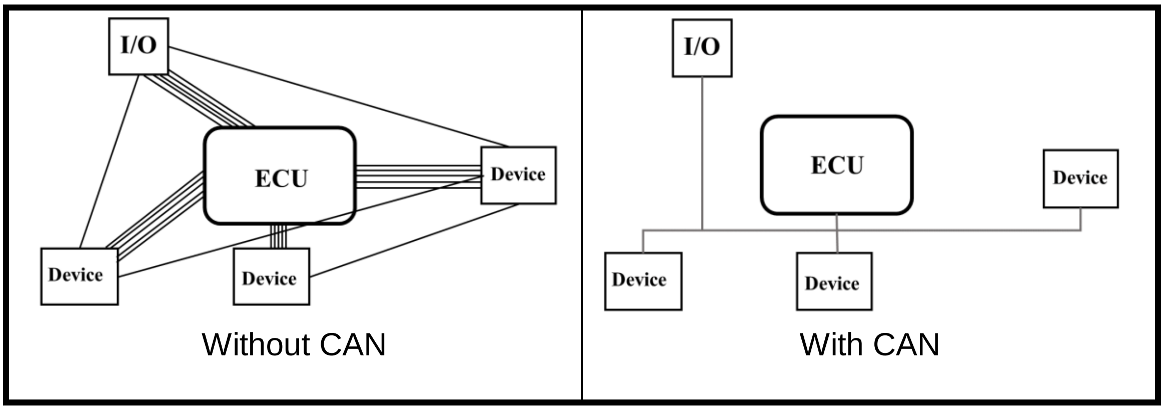


Figure 2.11 Devices communication architecture with and without CAN (Adapted from [38]

CAN provides a low cost and reliable network solution that facilitates the electronic devices to communicate through a dedicated Electronic Control Unit (ECU). More importantly, it allows the ECU to have single CAN interface rather than individual analog inputs to every device in the system. This results in the significant reduction of the overall cost and weight in the vehicles. Each of the participating devices on the network has a CAN controller chip which is capable of transmitting as well as receiving data, and therefore behaves as an intelligent unit. All the transmitted messages are seen by all the on-board devices and each device can decide whether to use the data (if the message is relevant) or filter it. As the use of CAN rapidly expanded in the automotive industry, it was standardized internationally as ISO 11898 [39], and a separate standard was introduced as the low-speed CAN for the car body electronics [40]. For high speed application, CAN provides a transmission speed of 500bit/s, [37] whereas it operates at 125bit/s at low speed [40]. Nowadays, the high-speed CAN Bus are widely used for the data communication in the automotive as well as aircraft electronic systems whereas the low speed CAN Bus is often used in the systems related to the safety equipment e.g. direct motor control and small factory machines. Nowadays, controllers supporting the CAN communication standard are widely available as well as sensors and actuators that are manufactured for communicating data over CAN. Since its emergence in late eighties, CAN technology has evolved to a stage where it is successfully replacing point-to-point connections in many application domains, including automotive, avionics, plant and factory control, elevator controls, medical devices and possibly more (see Figure 2.12).

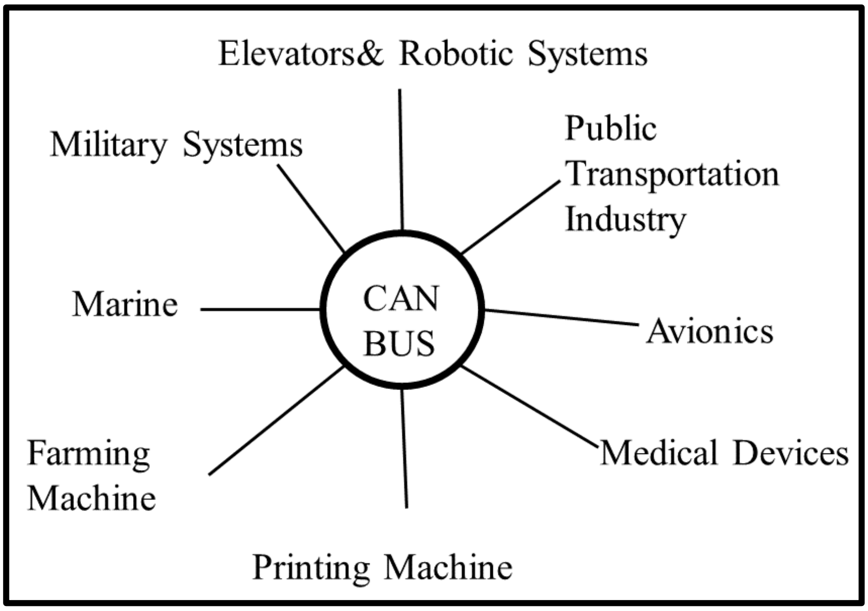


Figure 2.12 Various applications of CAN Bus.

Speed of the data transmission by the CAN bus depends on the distance e.g. a distance of 1 Km can reduce the speed to as low as 10 Kbit/sec whereas transmission speed can be as high as 1 Mbit/sec for distances up to 40 meters [41]. Typical values encountered in the field for CAN Version 2.0 are:

Table 2.11 CAN Speed against Distance

| **Distance (m)** | **Controller Area Network (CAN) Speed (Kbit/sec)** |
|---|---|
| 40 | 1000 |
| 240 | 250 |
| 500 | 125 |
| 13 00 | 50 |
| 3300 | 20 |
| 6600 | 10 |
| 130 ,000 | 5 |

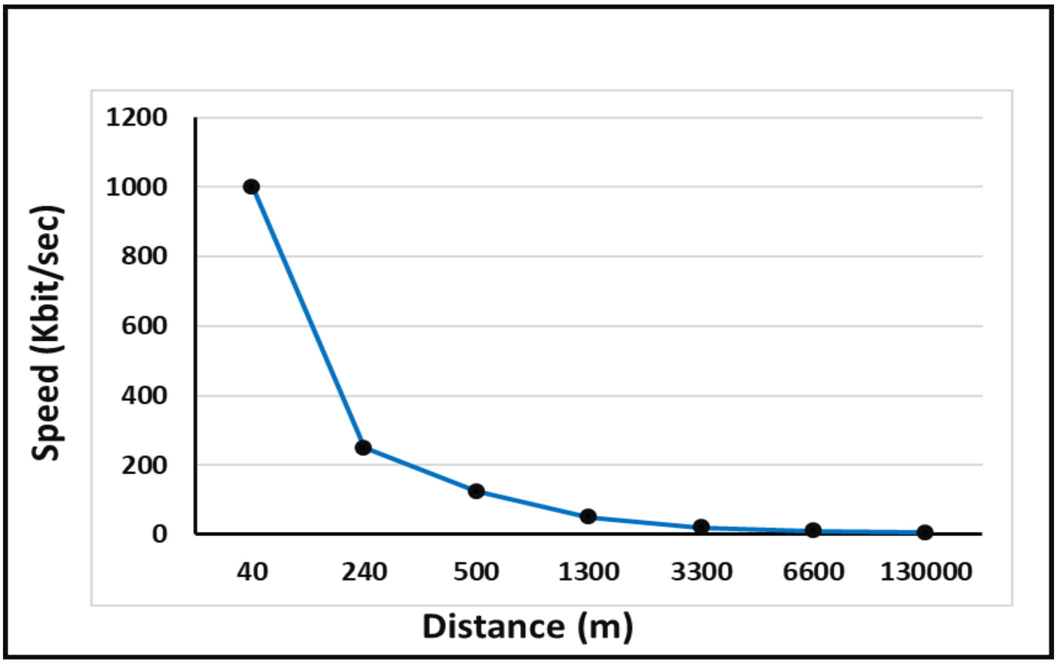


Figure 2.13 CAN Speed against Distance.

As with any other technologies, CAN Bus system also has some limitations as listed below [42].

- Modest speed.
- Stream signals (Voice, Video, etc.) cannot be accommodated in the old model of CAN.
- Not suitable for timed reliable delay applications.
- The messages have variable latency and thus, not a suitable for a time critical control bus for drive by wire
- Reasonable software expenditure.
- Undesirable interaction more probable.
- Danger of incomplete technology for the customer

More recently, High layered protocols bus like Time Triggered CAN (TTCAN), CAN Open is used widely in industrial automation application, Device Net, MilCAN, is as the perfect Integration Standard for the Military Land Vehicle systems transport network, SAEJ1939 [42] and others have been available to address some of the drawbacks listed above e.g. transmission of mixed voice and video data and provide solutions for all critical controls. However, these come with increased cost and added complexities. Thus, a CAN Bus is still the best compromise in terms of a low cost and reliable communication solution available today for land vehicles. So a high-speed CAN is used for the power train (brake system) and a low-speed CAN be presently used for the body electronics (doors, windows).

## 2.8 Chapter Summary

This chapter has provided a thorough review of the progress on the development of HUMS technology and its adaptation in both the military as well as civilian sector. The chapter covered the introductory background of HUMS, different types of HUMS technologies, the main sensors utilized in HUMS and ALS. Figure 2.14 shows the vehicle system operating in two different environment with preventive maintenance (scheduled maintenance) and CBM with HUMS, the HUMS provides efficient and economical CBM for the vehicle systems compared with the preventive maintenance without HUMS – HUMS provides real time information about the vehicle systems health condition, and thus helps CBM more efficient by indicating the maintenance or replacement of the component well in advance before it reach to the failure stage.

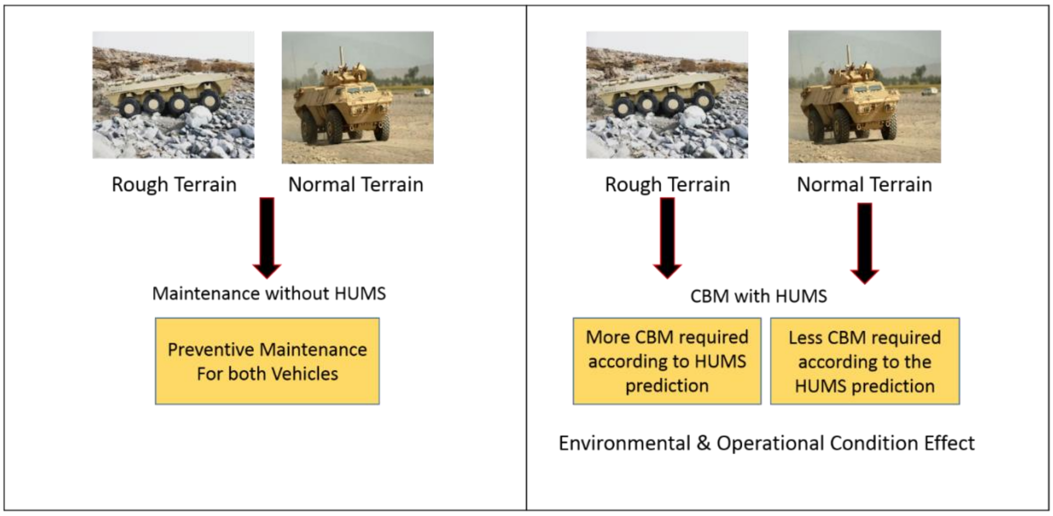


Figure 2.14 Comparison of preventive maintenance (scheduled maintenance) and the CBM with HUMS with different operating environment.

The review in this chapter has set out the current state of the art in the HUMS/ALS technologies, and has completed important ground work for this thesis. The succeeding chapters will present cost modelling aspects of the HUMS implementation, and provide the details of the experimental investigations to demonstrate the HUMS model developed. Finally, the results will be discussed in detail and main conclusions will be presented along with suggested future works.

## 2.9 Scope of this research

The state of the art of the HUMS in the vehicle systems were discussed in the literature review systematically. It is known that together diagnostic and prognostic HUMS have come to a level of progress that leaves no small suspicion such as to their ability to provide the data/ information necessary to improve maintenance managing with the speed and the accuracy required. Combined diagnostic and prognostic HUMS technology in an integrated health monitoring system is still in its early stages on the military land vehicles, but it has the capability to decrease expansion, implementation and repetitive part costs. In respects to the ideal of maintenance using integrated HUMS technology there are scopes on an extreme focus on both reducing maintenance cost or downtime of the vehicles. The several technical challenges in the Health and Usage Monitoring System (HUMS) remains unsolved that is the scope of this research.

# Chapter 3

# Experimental Methodology

In this chapter, experimental methods and the necessary hardware for the HUMS/ALS system are discussed. A brief review of the most widely used sensors and typical experimental layout is also under taken.

## 3.1 Introduction

The experimental approached presented here describe the three key HUMS architectures: Vehicle engine cooling, lubricant and suspension system health monitoring. The HUMS system is being extensively used on the modern vehicle health monitoring, however its full potential is yet to be utilized. Therefore, this experiment was specifically designed to assess and demonstrate the use of HUMS in vehicle cooling, suspension and lubrication systems, with the main aim of developing an effective HUMS architecture that will improve the reliability of the platform. Another important aim of this experimental set up was to test the proposed systems on a representative military land platform and prove its effectiveness. With this in mind, the Land Rover 110 (4×4), which is used as a light personnel carrier in the British army, was chosen as the test platform. Also, the architecture of the experiment was set up to make it modular so that it could easily be adapted in different kinds of legacy as well as new land military vehicle fleets, without major modifications to be carried out to the body or to the other components of the vehicle. Firstly, the architecture relevant to the suspension system and the cooling system monitoring is described.

## 3.2 Suspension System Health Monitoring

The Land Rover 110 platform was also used to study the health status of the shock absorbers on the suspension system of a typical military land utility vehicle using Health and Usage monitoring system (HUMS). As far as author's knowledge, its use on monitoring the health of a land vehicle suspension system & ride quality has not been done before. Therefore, this experiment was designed to assess and demonstrate the use of HUMS in vehicle suspension system, with the main aim of developing an effective HUMS architecture that will improve the reliability of the suspension system, quality of ride and handling. In addition, the experiment was set up to demonstrate an effective way of collecting data and validating the vehicle model. Another important aim of this experimental set up was to test the system on a representative military land platform and prove its effectiveness. Specifically, the performance of shock absorbers, effects of temperature & operating environment on its performance are investigated. The temperature & environmental effects are considered with especial consideration of harsh operating environment faced by the military vehicles in the Sultanate of Oman. Further details on the shock absorber health monitoring and the challenging operating environment are provided in the Appendix A.

In the civilian land vehicle platform, suspension system health monitoring is not the primary focus primarily because the probability of failure of suspension system in this land platform is very low. The dynamic behaviours of the shock absorbers have long been investigated. The frequency response function is widely used to study the health condition of the shockabsober by many researchers. The changes in the resonance frequency and the phase of the frequency response function is used to identify the health condition of the shock absorbers. The vibration exposure of the on-road civilian vehicles is within the narrow band range (low magnitude). The changes in the frequency response function within this narrow band vibration exposure is negligible. This brings many challenges for the health monitoring technique to identify the failure within this narrow band exposure rage. On the other hand, the probability of failure of the suspension system in the military vehicle land platform (mainly in the off-road vehicle) is high and the vibration exposure range and the duration of operation is also high. These military land platform requires a systematic health monitoring unit to identify the failure and evaluate the vibration exposure limit values to the crew in the vehicle. There is no such health monitoring system available at the moment with the land vehicle platform and this study will focus to develop such system to fill gap in the knowledge.

In addition, the architecture of the experiment was set up to make it modular so that it could easily be adapted in different kinds of legacy as well as new land military vehicle fleets, without major modifications to be carried out to the body or to the other components of the vehicle. As set out extensively in the previous chapter, the HUMS system is employed to diagnose the system faults in its early stages so that it can be intercepted and repaired before the failure without significantly increasing the out of service time (down time). The experiment had both the hardware, as well as the software components to represent a complete HUMS module as shown in the Figure 3.1. While designing this experiment, the financial aspects were also carefully considered to ensure that the system remained low cost without sacrificing the reliability. It is worth pointing out here that an efficient data transfer technology using Controller Area Network (CAN) Bus has sufficiently matured and it has been used extensively in all new automotive platforms. CAN replaces the need for hard-wired point-to-point connection for data transfer, which in turn, results in reduced weight (since wire connection is significantly reduced) and cost along with simpler data connection architecture. Further details on CAN Bus technology and its usages are provided in the section 2.7 (pp. 2-31).

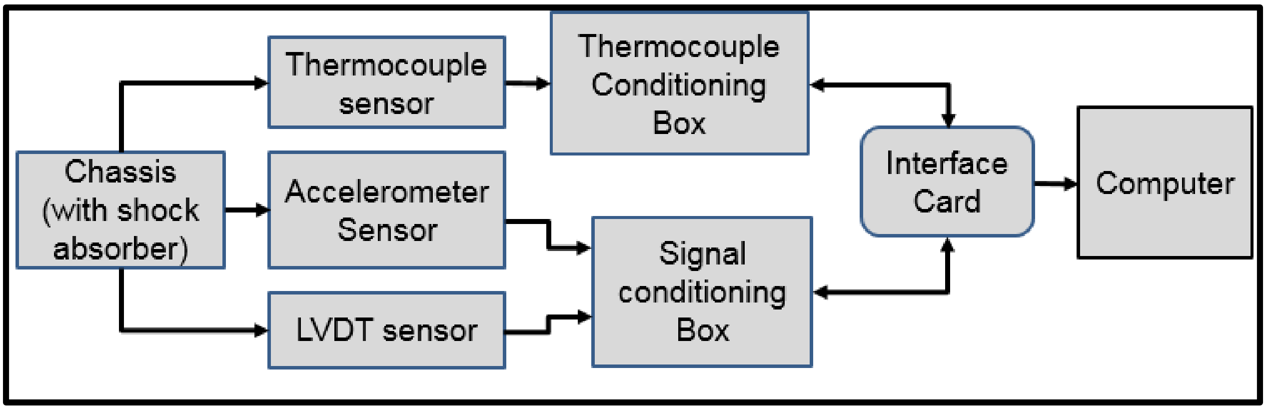


Figure 3.1 Experimental set up with sensor data measurement flow chart.

## 3.2.1 Experimental Apparatus

### 3.2.1.1 Instrumented vehicle

As stated before, the test platform is the Land Rover 110. Figure 3.2 shows the Land Rover test bed on the Cranfield University's four-poster vibration test facility at the Defence academy. A schematic of the sensor types and locations in the experiment is diagrammatically represented in Figure 3.3. The key details on the size and geometrical lay out of the test platform is given in Table 3.1 as follows:

Table 3.1 The key details on the size and geometrical lay out of the test platform

| | |
|---|---|
| Type | Land Rover 110 Defender |
| Total Weight | 14.02 KN |
| Pay Load | 11.07 KN |
| Front Axle | 7.85 KN |
| Rear Axle | 6.17 KN |
| Wheel Base | 2794 mm |
| Track Width | 1690 mm |
| Height | 2076 mm |

Figure 3.2 Picture showing Land Rover 110 which is used in the experiment.

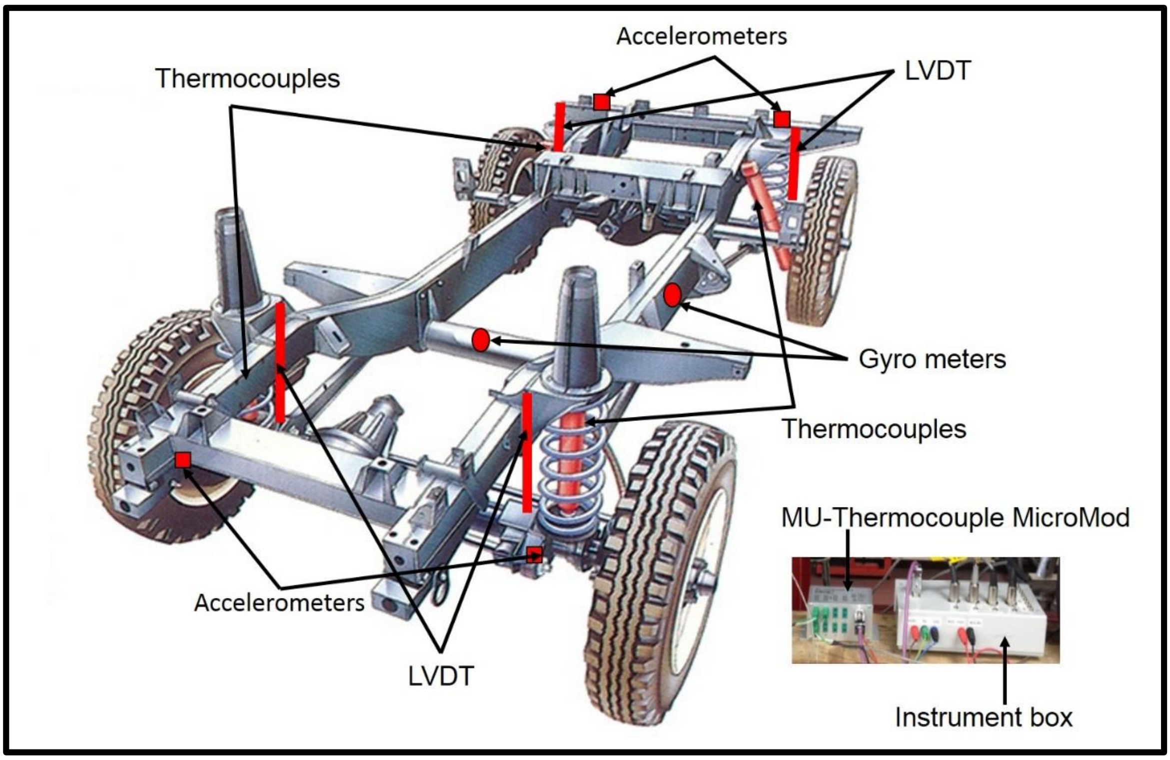


Figure 3.3 Schematic of the experimental setup.

### 3.2.1.2 Accelerometers

Six accelerometers were used in this study to measure the response accelerations at the different parts of the vehicle to evaluate the transmissibility of the motion transmitted to and through the vehicle body and the seat. The accelerometers include, MTN/7000-5 with serial number 550744, MTN/7000-5 with serial number 550740, MTN/7000-5 with serial number 550742 and MTN/7000-5 with serial number 550784. Each accelerometer has the sensitivity of 500mv/g and the range of +-5g. Figures 3.4 shows the arrangement of accelerometers for the calibration.

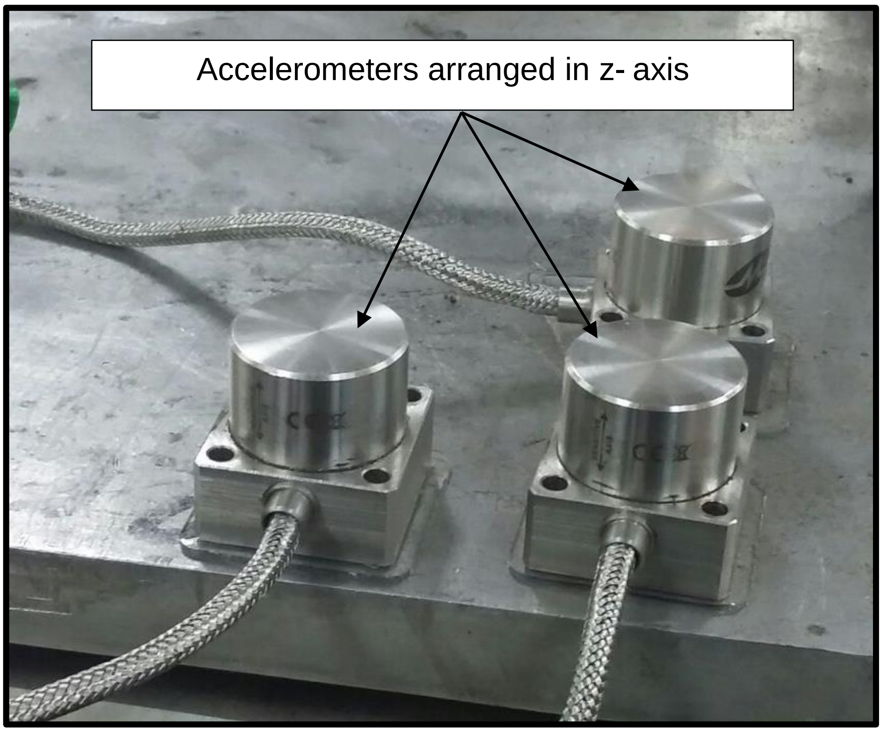


Figure 3.4 Picture showing the accelerometer used in the accelerometer calibration test.

### 3.2.1.3 Accelerometer calibration

The accelerometers were calibrated dynamically before and after each experiment and were checked during the experiment. Two random excitation with different magnitudes were used for the calibration and the transmissibility between two identical accelerometers mounted closely on the horizontal surface of the test bed in the vibration test facility were calculated and shown in the Figure 3.5. Ideally, the modulus of the transmissibility should be flat across the frequency range of interest and should be equal to 1 (Figure 3.6).

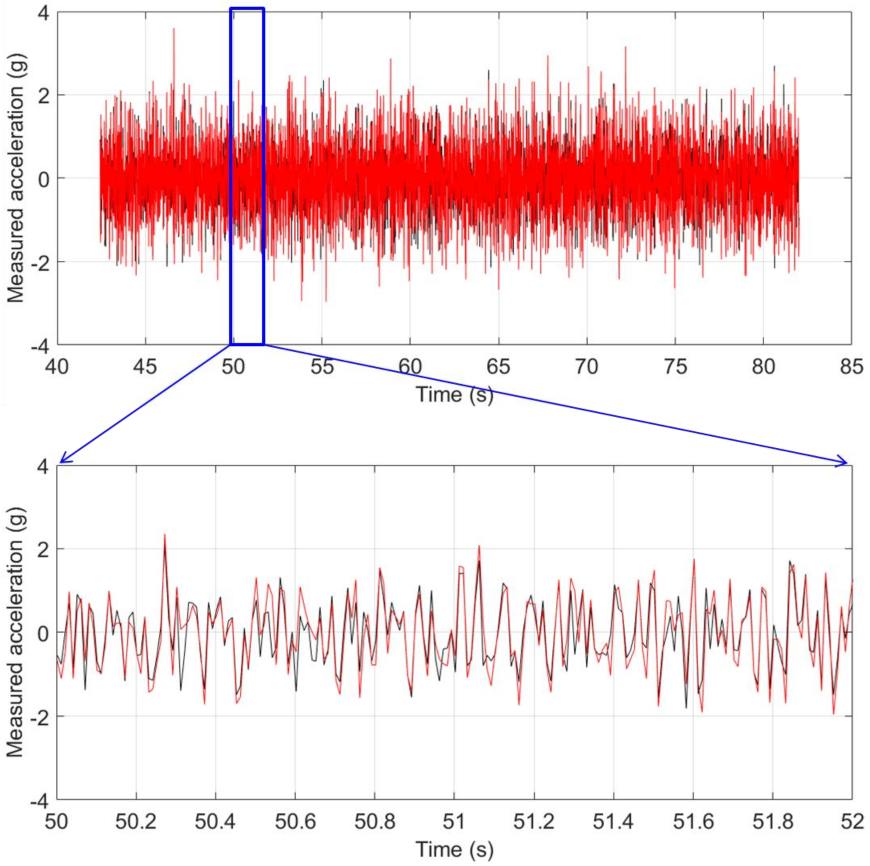


Figure 3.5 Time histories of two accelerometers mounted closely on the horizontal flat shaker table.

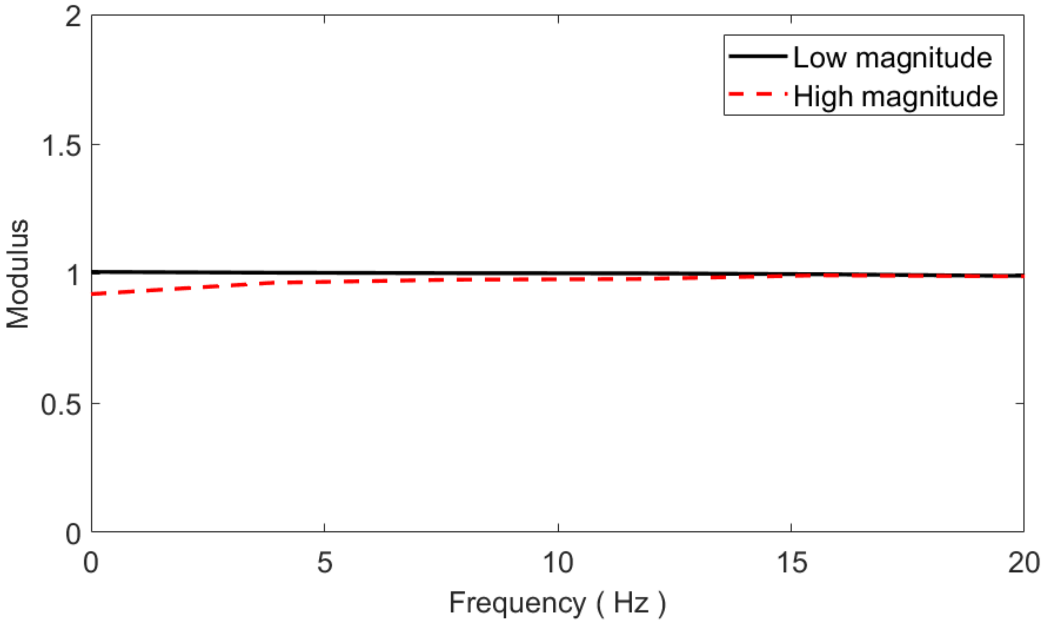


Figure 3.6 Modulus of the transmissibility between two measured accelerations: black solid line – with low magnitude of excitation, red dash line – with high magnitude of excitation.

### 3.2.1.4 Hydraulic shakers

The four servotest hydraulic shakers were used in this study to excite the vehicle. Each shaker having the model number of 172S/A4 and the serial number of 936 (Figure 3.7). Each shaker has a load capacity of 75 kN, stroke of 165 mm (left rear), another shaker having the model number of 172S/A4 and the serial number of 937 (front left), the load capacity of 75 kN, stroke of 165 mm, shaker having the model number of 172S/A4 and the serial number of 938 (front right), the load capacity of 75 kN, stroke of 165 mm, another shaker having the model number of 172S/A4 and the serial number of 938 (rear right), the load capacity of 75 kN, stroke of 165 mm.

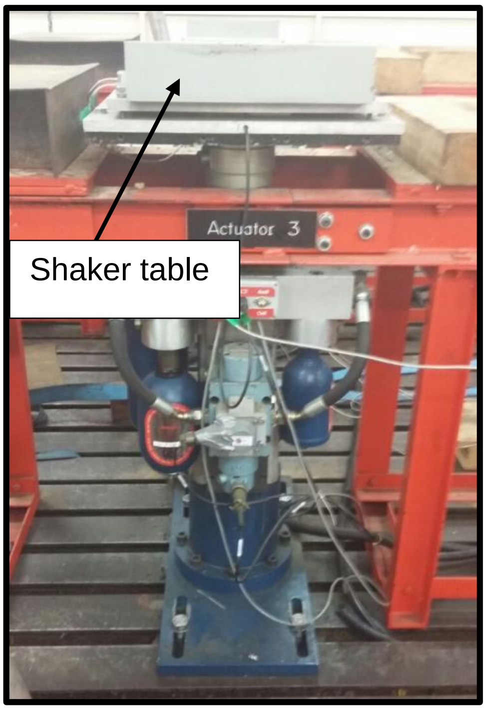


Figure 3. 7 Picture showing one of the hydraulic shaker used in the test.

### 3.2.1.5 Hydraulic shaker rigidity check

The rigidity of the hydraulic shakers was checked using the cross-axis transmissibility. The rigidity check is important so as to see whether shaker produce any cross-axis motion during the vertical motion. The rigidity check should be carried out across the frequency range of interest (0 – 20 Hz). The accelerometers were mounted on the shaker table in three orthogonal directions as shown in Figure 3.8. The measured accelerations in three orthogonal directions were used to evaluate the shaker rigidity. Ideally, the modulus of the transmissibility should be flat across the frequency range of interest and should be equal to 0 indicating there is no cross-axis motion in the shaker (Figure 3.9).

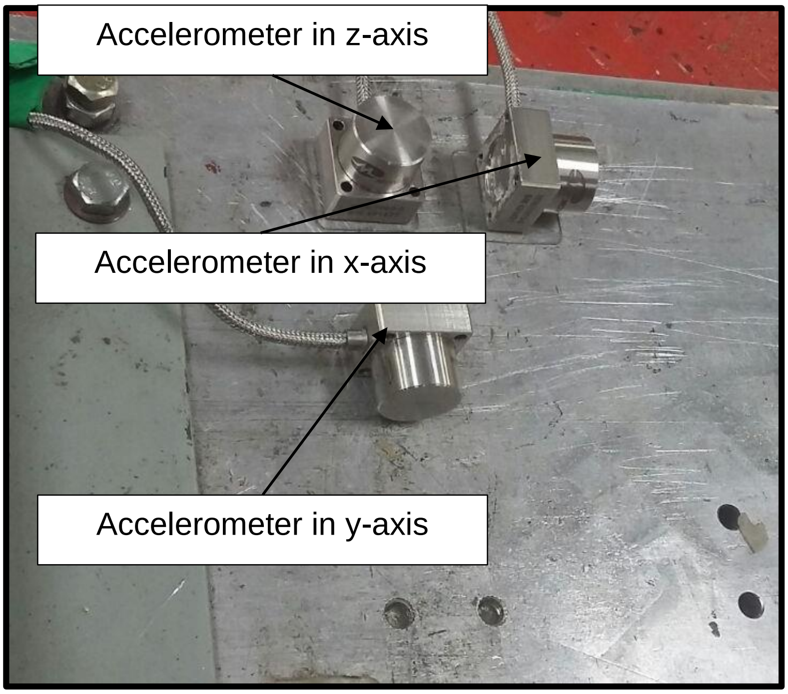


Figure 3.8 Picture showing the accelerometer in three orthogonal directions used for the shaker rigidity test.

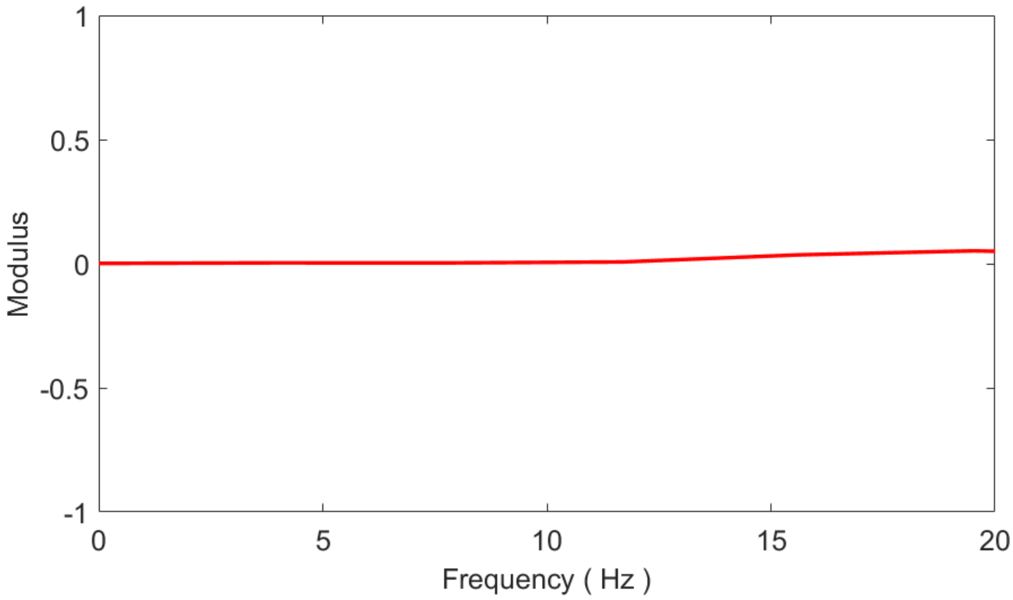


Figure 3.9 Modulus of the cross-axis transmissibility between two measured accelerations in the orthogonal directions z-x axis.

### 3.2.1.6 Data acquisition system

Based on the above design, the necessary sensors are mounted in the key locations around vehicle suspension system and the body and are connected to the two modules or nodes. Figure 3.10 and 3.11 show the picture of the vehicle suspension system with respective positions of the sensors along with the overall architecture. The key part of the HUMS system hardware consists of two micro-processor unit, M1 and M2 (nodes) with each able to take inputs from several sensors.

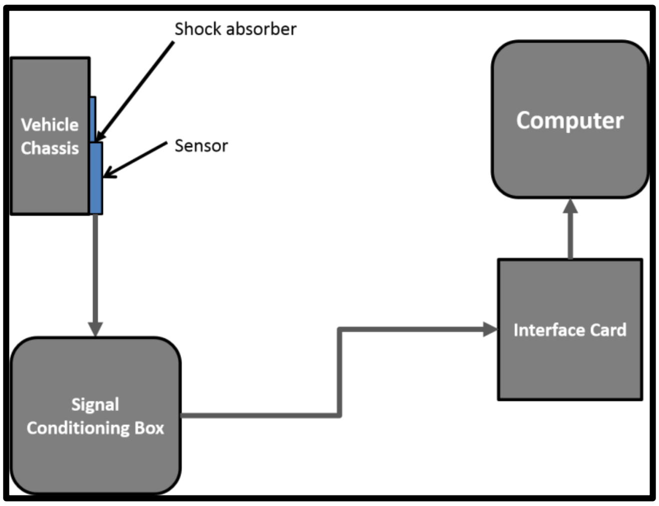


Figure 3.10 Shock absorber position measuring system on the experiment.

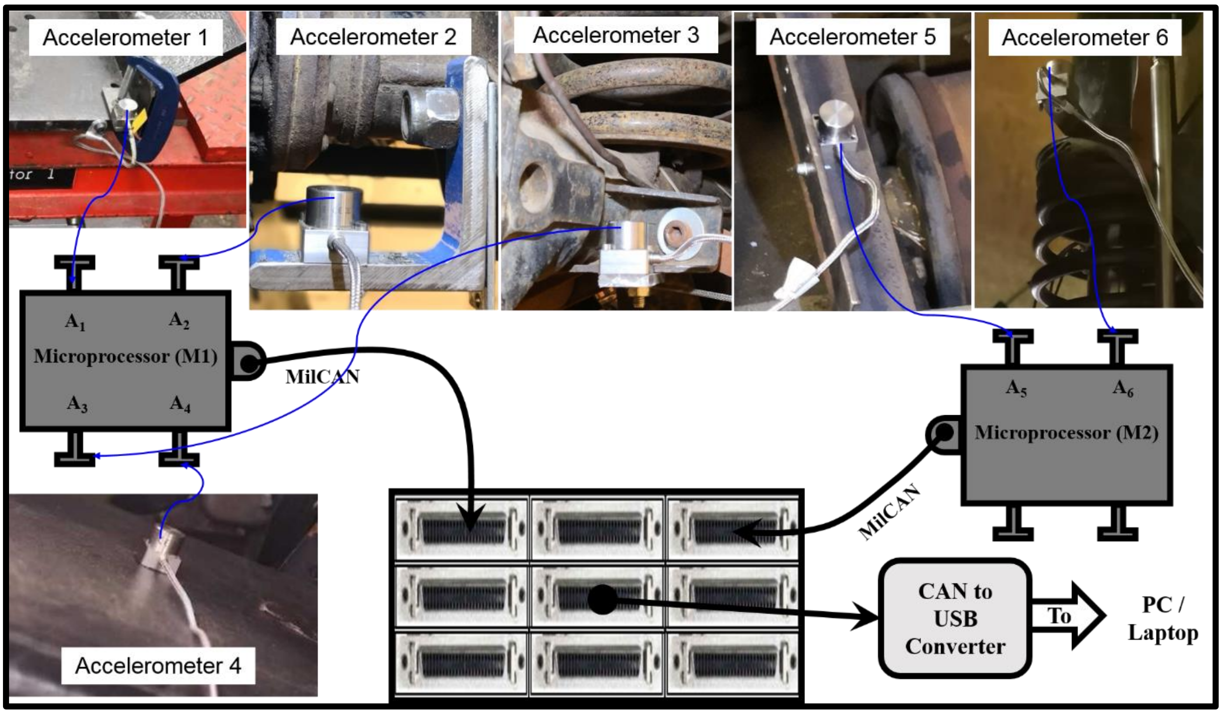


Figure 3.11 HUMS system for suspension system monitoring.

The sensor data processed by the two modules are then passed to the data hub using MilCAN connectors. The data from the data hub can then be passed to the computer/laptops using CAN-to-USB converter unit for further post-processing. This system is highly portable, easy to integrate, less intrusive to the vehicle systems and easily adaptable to other platforms. The test platform used in this research is a Land Rover 110 which is used as a light utility vehicle by military forces. Figure 3.2 shows the test platform vehicle with fully instrumented HUMS system for suspension health monitoring.

### 3.2.1.7 Controller Area Network (CAN)

The CAN based data acquisition system was designed and commissioned for the experiments. The multiple nodes integrate the different physical quantities of measurements like acceleration, temperature and the pressure. The data acquisition system provides a smart link between the analog sensors and the digital CAN-Bus. The A/D converter was used to digitalized the measured analog signals from different sensors. The digitalized data was then programmed to CAN protocol. The CAN protocol data was then sent through the CAN-Bus system and read and recorded using the specialized programme at the Matlab/Simulink interface.

### 3.2.1.8 Signal Conditioning Box

The signal conditioning box is essentially the heart of the data acquisition system, which was designed in-house. This box consists of a filter to remove noise in the sensor data, gain amplifier, analog to digital converter and the CAN Bus interface (See Figure 3.12). The digital output from the box is then converted in a readable form with the help Matlab/Simulink software. The box is powered with ±12 V DC for all circuits, micro modules and sensors. A separate power supply of floating 12 V DC is required for accelerometers; this also powers the thermocouple micro module.

Figure 3.12 Picture of Signal Conditioning Box.

### 3.2.1.9 Micro-Processor

Vehicle cooling data from various sensors are then passed to the micro-processor unit. The micro-processor units used in this experiment are taken from PIC18 family. This family consists of all the traditional advantages of microcontroller units including high computational performance, and this comes with an extremely competitive price. These features make the PIC18 family a logical choice for most high-performance applications, specifically when the price is a primary parameter. The PIC18 variant used in this research is PIC18F46K80, which is an 8-bit system with 64 MHz speed and comes with 44 pin in/out connection. Further details on this system can be found on [43,44]. Figure 3.13 shows a snapshot of the microprocessor unit used in the experiment.

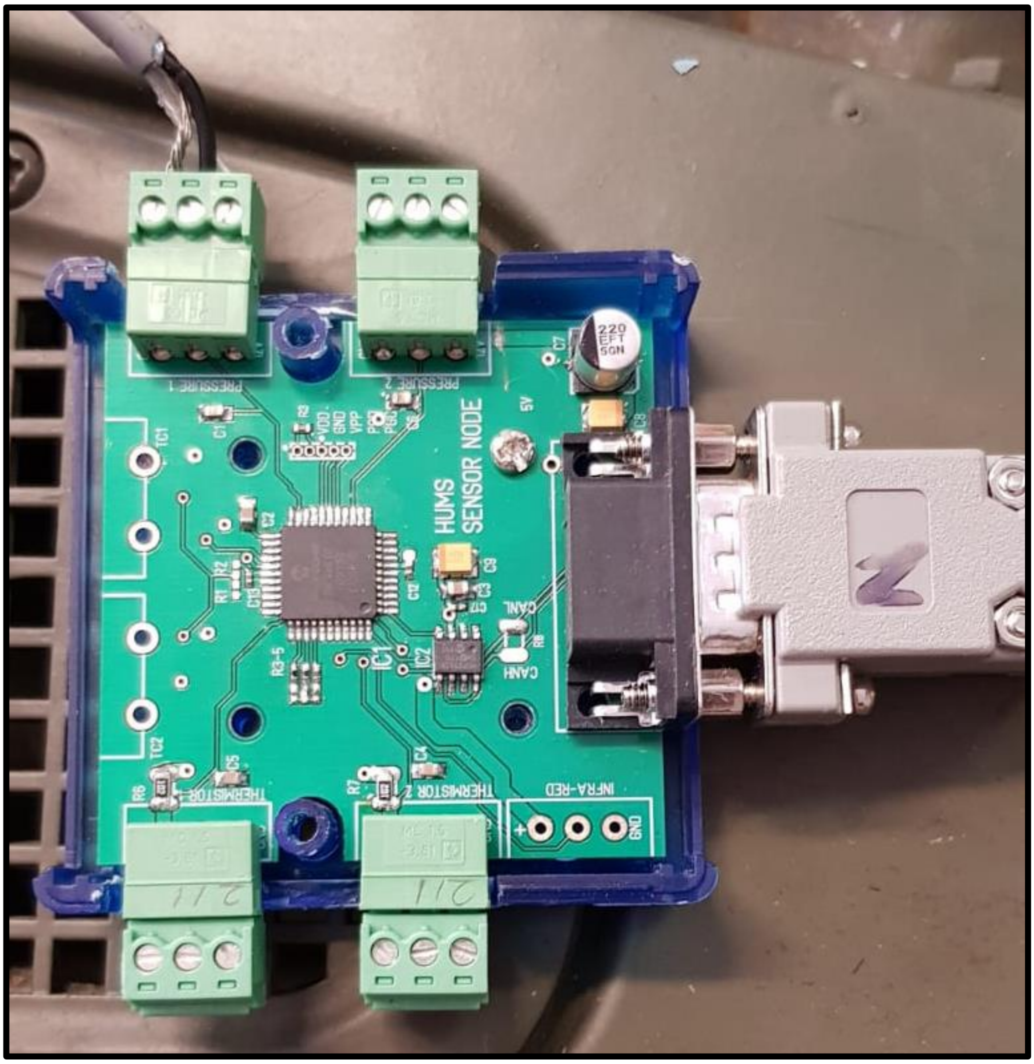


Figure 3.13 PIC18F46K80 Micro-Chip.

#### 3.2.1.10 Fault detection strategy

The locations of the accelerometers were chosen based on the suspension system position. The mounting points of the accelerometers were selected where the suspension travel is at the peak value. The industrial graded accelerometers with high sensitivity were used in this study to accurately measure the vibration at each points. The aluminium mountings were used to rigidly fasten the accelerometers to avoid any artefact in the data. The failure was introduced to each suspension units and the corresponding acceleration signal was analysed to detect the failure mechanism. As illustrated in the Figure 3.11, the output accelerations were measured at different locations in the suspension system. Firstly, failure was particularly introduced to the front damper by removing the oil from the tube. Secondly, the damper outer casing was crushed to cause the failure. These two failed dampers were fixed to the suspension system one by one and the result were compared with the healthy suspension system with the healthy dampers.

## 3.3 Engine sub systems Health monitoring

### 3.3.1 Cooling systems

The cooling system architecture has been designed to be highly modular and includes state-of-the-art hardware components, most of which are commercially available off-the-shelf. Due to the rapid miniaturization of digital electronic circuits in recent years, and the miniaturized components available at a significantly low prices, the highly modular unit designed and assembled in this research has a cost figure which is negligible compared to the platform cost. The main components of the HUMS for cooling system monitoring include a microprocessor unit, a CAN-to-USB converter or CAN-to-UART (Universal Asynchronous Receiver/Transmitter) converter, CAN Bus data connector, accelerometer, pressure transducers, temperature sensors and MEMS motion sensors. A schematic of the designed architecture is shown in Figure 3.14.

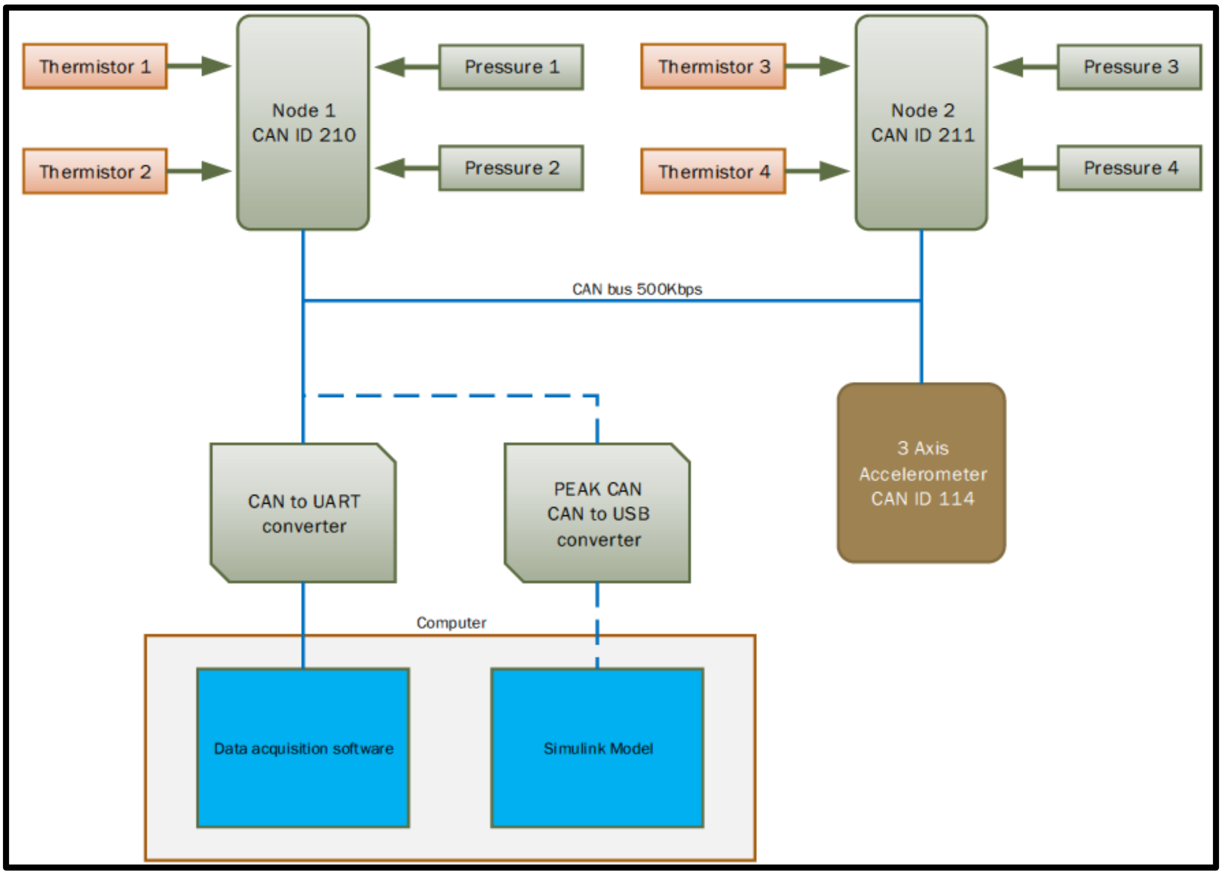


Figure 3.14 Essential components of the proposed HUMS system for cooling monitoring.

Based on the above designed, the necessary sensors are mounted in the key locations around the engine and are connected to the two modules or nodes. Figure 3.15 shows the picture of the engine with respective positions of the sensors along with the overall architecture. The key part of the HUMS system hardware consists of two micro-processor unit, M1 and M2 (nodes) with each able to take inputs from several sensors.

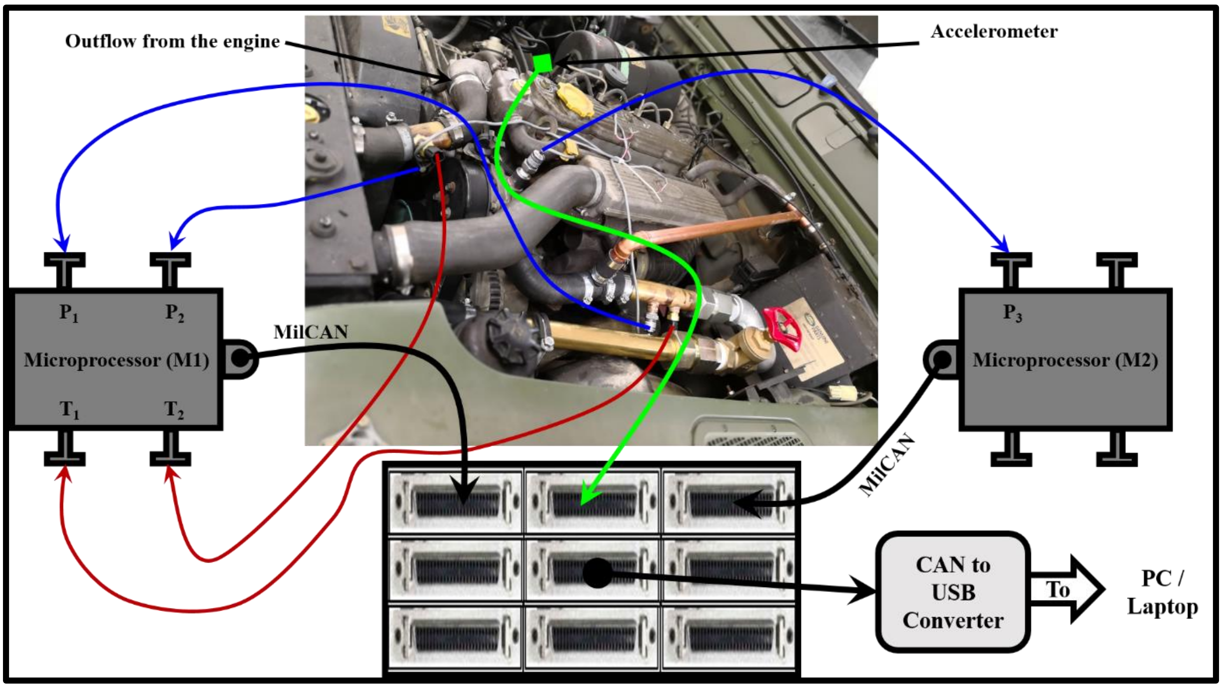


Figure 3.15 HUMS system for cooling system health monitoring.

The sensor data processed by the two modules are then passed to the data hub using MilCAN connectors. The data from the data hub can then be passed to the computer/laptops using CAN-to-USB converter unit for further post-processing. This system is highly portable, easy to integrate, less intrusive to the vehicle systems and easily adaptable to other platforms. To ensure the versatility and facilitate varying engine operating conditions e.g. increased/reduced load, speeds etc., various modifications were done to the engine while ensuring the vehicle remained road legal. One such modification involved addition of a cooling flow control valve to simulate the failure scenarios e.g. reduced cooling flow, cases involving leak or even flow blockage (Land Rover 110). Figure 3.16 shows the test platform vehicle with fully instrumented HUMS system for cooling health monitoring. Two temperature and three pressure points were selected in the cooling system flow path to monitor the changes in the temperature and the pressure at these points. The changes in the temperature and the pressure values are used to identify the different failure mechanism in the cooling system. The components of the cooling system health monitoring modules are explained next:

Figure 3.16 Land Rover110 test platform with instrumented cooling system HUMS.

### 3.3.2 Pressure Transducer

For the pressure measurement, the industrial graded MSP300 low cost pressure transducer by MEAS was used. These transducers are suitable for measuring both the liquid and gas pressures, and these are applicable even in difficult environments such as contaminated water, steam, and mildly corrosive fluids. The standard version of this commercially available transducer includes a threaded pipe section allowing a leak-proof, all metal sealed mounting with excellent durability. It is derived from micro-fused technology generally found in aerospace applications, and employs micro-machined silicon piezo-resistive strain gauges fused with high temperature glass on a stainless steel diaphragm. This sensor provides a highly accurate pressure measurement capability up to a threshold of 17kPsi (this way more than what is encountered in automotive cooling systems). Figure 3.17 shows an image of the pressure transducer; more details on the transducer is available from [45, 46].

Figure 3.17 MSP300 Pressure Transducer.

### 3.3.3 Temperature Sensor

For the temperature measurement, Low Temperature Passive Probes (LTP Series), were used. These sensors feature a durable, closed-tip design that provides a high degree of reliability even in harsh operating conditions. The sensor's thermistor sensing element effectively senses liquids and gases because of its enhanced sensitivity, accuracy and reliability. In addition, the threaded mounting that comes with the sensor provides easy and durable mounting in difficult and harsh environments. The sensor provides a good range for automotive cooling system applications, the range is typically -400C to 1500C with good response time for a water flow (less than 20 sec). A figure with LTP temperature sensor is shown in Figure 3.18, and the further details on these sensors can be found in [47].

Figure 3.18 LTP Temperature Sensor.

For the engine cooling system, temperature is the most important parameter which can indicate and monitor the system health. In order to monitor the health of a cooling system, a minimum of two temperature sensors are required. One sensor is mounted at the top of the radiator on the hot side of the thermostat to monitor the hot coolant entering the radiator, and the remaining one is to be mounted at the bottom of the radiator to measure the lower temperature of the coolant entering the engine. A third temperature sensor, which is a reference sensor, can be used to measure the ambient temperature. The temperature values, thus, measured from the sensors are then used to compare and establish the general status of the engine health. A schematic of a generic cooling system in a typical automotive platform is shown in Figure 3.19 along with the locations of the temperature sensors.

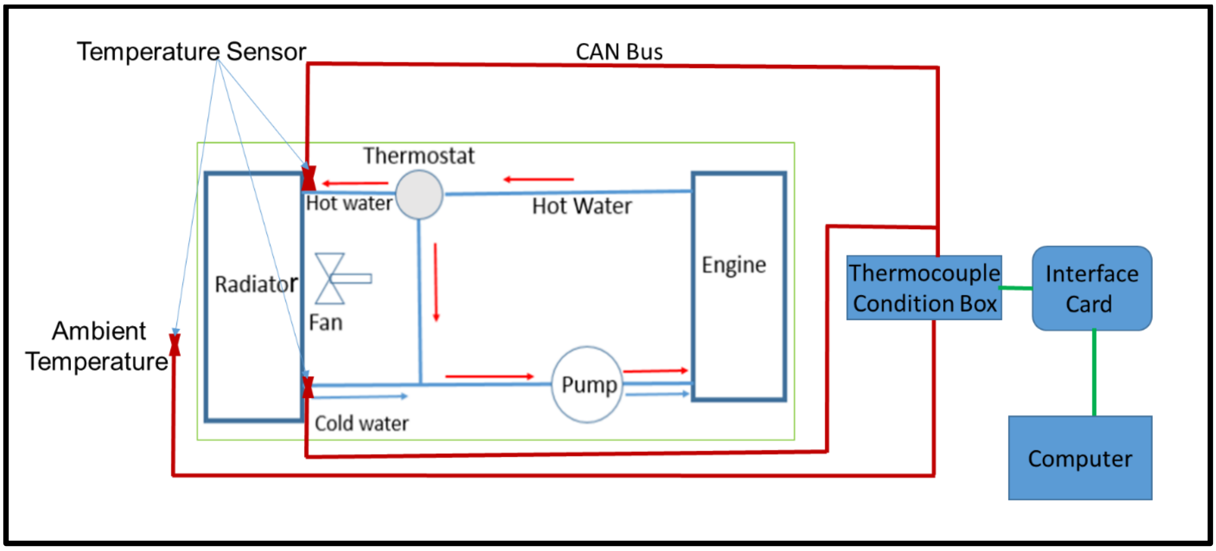


Figure 3.19 Typical temperature measuring system of cooling system.

### 3.3.4 Fault detection strategy for the engine cooling system

The Figure 3.20 shows the proposed experimental design for the fault detection in the cooling system in the vehicle. The different failure mechanisms were introduced to the cooling system by closing the inlet valve by half- and full- turn and then the belt of the pump was removed. The performance of the healthy and faulty cooling system was compared using the measured data.

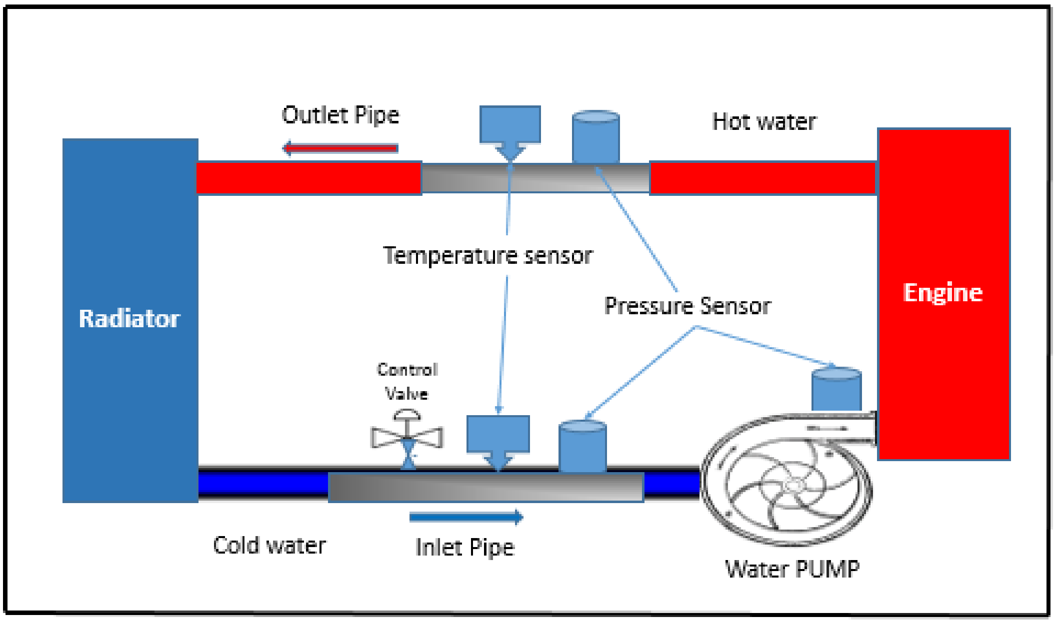


Figure 3.20 shows the experimental design for the cooling system.

In addition to the laboratory testing conditions, the same experiments were repeated while running the vehicle in-field to measure the test data to compare with the one obtained in the laboratory running conditions. Figure 3.21, shows the route path where the vehicle was taken for the test.

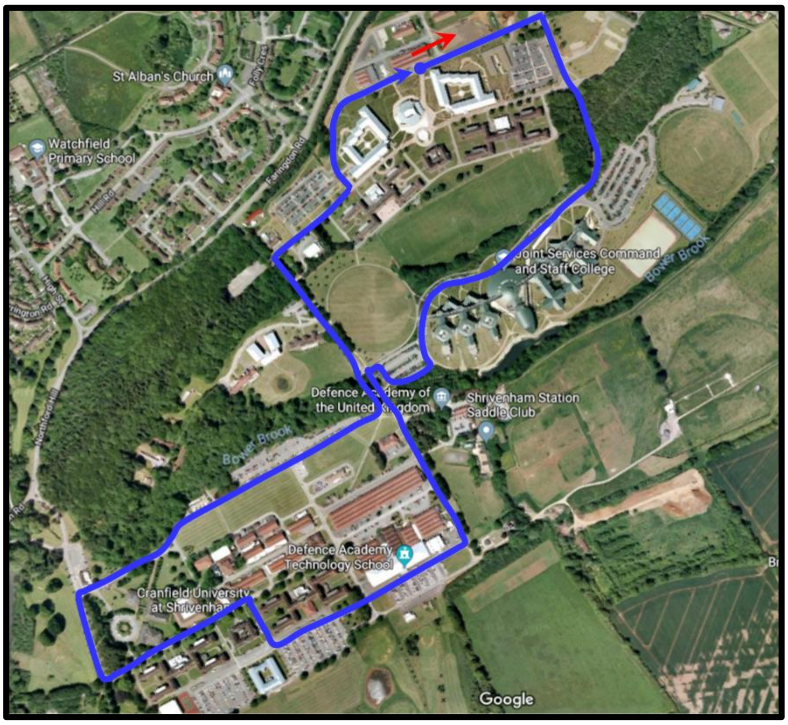


Figure 3.21 shows the route path for the vehicle in-field driving test.

Temperature sensor

The thermistor sensors were used to monitor the variation of the temperature in real time in different locations in the cooling system with different simulated failures. The first sensor was fixed at the outlet pipe to monitor the coolant temperature leaving the engine to the radiator. The second thermistor was fixed at the inlet pipe, its purpose being to monitor the coolant temperature just before its way to the engine.

Pressure sensor

Three pressure sensors were fixed in three different locations, the first one is just before the pump to indicate the pressure between the radiator and the pump. The second pressure sensor was fixed at end of the water pump, and its purpose to monitor the pressure of the coolant just before its way to engine. In order to keep the system working in redundancy, other pressure sensor was fixed at the outlet pipe to monitor the liquid pressure leaving the engine back to radiator. All the captured data from sensors were sent to the conditioning box through CAN bus system.

Control valve

This valve was fixed before the water pump to simulate failure to the water pump. The failures were formed/simulated in two cases(leakage/blockage), the first one to close the valve half turn, and then the second case was closed fully. In the two different cases data were collected and analysed by using MATLAB.

Water pump drive belt

Drive belt failure has a direct effect to the function and performance of the water pump. Two sensors were fixed to monitor the temperature and the pressure at two points, the one before the pump and the other one after the pump. The drive belt was removed fully to simulate the death of the water pump or the cut-off of the belt. The collected data was analysed and shown in the experimental result in Chapter 7.

## 3.4 Lubricant system

In addition to the cooling system, the lubrication system is considered the second most critical system for the efficient and safe operation of automotive engine, and a dysfunctional lubrication system can result in a catastrophic failure of the engine and powertrain. Hence, monitoring of the health status of the lubrication system can also help diagnose the overall engine health problems. Figure 3.22 shows the newly commissioned instrumented 4-cylinder diesel engine for the test.

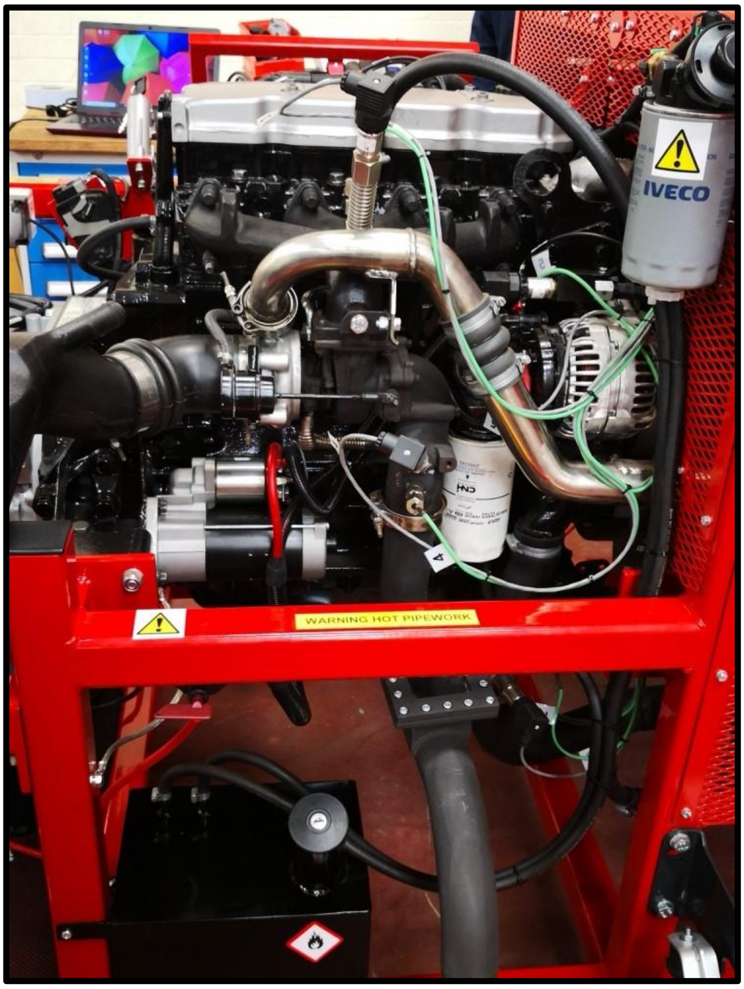


Figure 3.22 Photograph of a 4-cylinder diesel engine newly commissioned for the test.

The main parameters which can be employed to monitor the lubrication system health are the oil pressure and temperature, especially the temperature is crucial since the viscosity of the oil is temperature dependant. The pressure and the temperature sensors were instrumented in the engine cooling and lubricant system to measure the temperature and the pressure at different locations.

### 3.4.1 Fault detection strategy for the engine lubricant system

The temperature and the pressure at different locations were monitored and measured with different engine running conditions to see the changes in the measured parameters measured the lubrication flow path. No external failure mechanism was introduced to the lubrication system at this stage, however, this will be discussed in detail in the corresponding Chapter 8.

### 3.5 Summary

This chapter has described the methodology used in this research. This thesis consists of five technical chapters, Chapter 4, to 8. The chapter 4 is purely an analytical study focussing on cost modelling of HUMS implementation in the vehicles. The chapter 5 is focussing on the case study of used two different types of military vehicles used in Royal Army of the Sultanate of Oman. The rest of the three studies are experimental studies. The short description of the experimental procedure, apparatus used in those particular studies, description of the sensors used, description of the data capturing techniques and the description of the analysis used to interpret the data were explained and discussed in this methodology chapter.

# Chapter 4

# Cost Modelling

In this chapter, financial implications of HUMS/ALS integration in land vehicles are reviewed and scrutinised. A brief review of cost modelling approaches for the HUMS/ALS integrated vehicles and overall cost implications are assessed.

## 4.1 Overview

It is now well established that adaptation/integration (or retrofitting in legacy vehicle) of HUMS is increasing in an attempt to improve the safety, reduce maintenance cost, and eventually extend the life of existing vehicles [48]. In fact, many countries' defence departments have made it a compulsory requirement to have HUMS/ALS system integrated in all future vehicle acquisitions [49, 50]. To justify the acquisition of HUMS/ALS integrated system financially, it is important to prove the financial viability, and, to this effect, various cost benefit analysis (CBA) studies have been performed.

The evaluation of cost benefit, however, is not straight forward. This is because the majority of the benefits provided by HUMS are intangible and hence cannot always be equated to a monetary value. Therefore, the financial implication of integrating HUMS on land platforms are not merely the HUMS equipment procurement cost, there are a range of costs and also the benefits that must be identified and properly quantified to establish an accurate picture of overall financial cost. The cost of the platform itself, along with the HUMS equipment, is probably the most easily quantifiable among all the costs.

The platform cost generally consists of the costs associated with the various sensors mounted on the platform, the sensor connectivity architecture and the data acquisition & processing units. It is worth stressing here that the HUMS equipment on a typical land platform generally constitutes a very small percentage of the capital cost of the platform itself. Many of the sensors required by HUMS that will be found on COTS equipment are built in as standard to parameters they measure and as such it can be excluded while costing HUMS e.g. engine temperature sensors. With the continuous advancement on the sensor technologies, it is envisaged that the cost of integrating the HUMS equipment on land platforms will be significantly cheaper in the future. In addition, the continuous development will improve the reliability and operation range of the sensors improving the overall reliability.

Various approaches have been used to assess the financial implications of integrating HUMS [51, 52]. For example, the cost effectiveness of HUMS system on Apache and Blackhawk helicopters is determined using a modification of the RITA-HUMS CBA software

[51] The analysis used information such as: aircraft details along with its operational frequencies, maintenance, HUMS equipment and HUMS installation cost. The output from the analysis gave detailed indications on the benefit along with cost tables that showed impact of in-flight and mission abort for aircraft with and without HUMS, as well as an estimation of aircraft maintenance cost. In addition, the results from the analysis facilitated the formation of projections on the vehicle's future operating costs.

Giurgiutiu et al. [53] performed a comprehensive cost effectiveness analysis of Vibration Management Enhancement Program (VMEP) and HUMS for a helicopter fleet. Their analysis showed that the VMEP/HUMS implementation raised the initial acquisition cost when compared to a baseline system without VMEP/HUMS. After three and a half years, however, the VMEP/HUMS project was found to break-even; and from that point the VMEP/HUMS project cost fell below baseline system with sharp slope with time consequently resulting in significant saving. In fact, they quote the VMEP/HUMS system to have a present value of almost $149k when compared to baseline. Similarly, Australian Department of Defence (DoD) commissioned a task to conduct an analysis that would provide financial implications of implementing HUMS [52]. The task used Life Cycle Costing Analysis (LCCA) methodology to assess benefits and shortcomings in financial context. The outcome of the task showed that the financial and logistic impacts could be estimated with a high degree of confidence. It was also claimed that the benefit to the organization implementing HUMS may be identified and expressed subjectively. This could, in turn, enable the project staffs involved with the vehicle to adequately quantify the benefits of utilizing the HUMS system to a diverse stakeholder group.

## 4.2 Cost Analysis Technique for Land Platforms

At the present time, a range of cost modelling approaches exist with varying degrees of fidelity and complexity [51-54], however these methods mostly deal with air platforms. The approaches for the land platforms are very scarce. Although a number of models and tools have been developed over the years to financially support the decisions on the adoption of HUMS and CBM, there is no model on which to establish a robust business case for HUMS and CBM on military land vehicles. G. E. Gallasch [55] conducted a thorough review on the existing methods and assessed the methods, both qualitative and quantitative, for land vehicle cost analysis. In the analysis, each tool was considered against criteria regarding its features, capabilities, and applicability to land based platform. This analysis proposed a value proposition framework. However, the value proposition framework is still to be defined clearly. To overcome these ambiguities and simplify the costing process, in this chapter, a simple yet effective method is proposed which will provide a step-by-step approach to assess the cost implication of HUMS integration in land vehicles. The method is described as follow:

In this model, firstly a parameter called, Operational Availability (OA) for a land platform is defined as:

$$OA = \frac{\Lambda_{tt}}{\Lambda_{tt} + \Delta t} \tag{4.1}$$

Where $\Lambda_{tt}$ is total time the vehicle is in service. This parameter is composed of the vehicle's net task or mission time and the stand by time. The parameter, Δt, is down time of the vehicle. This value will be very different (significantly smaller) for a vehicle with integrated HUMS system when compared to a vehicle without HUMS which is sent to workshop after the fault development and had to wait for the spare parts to become available. Hence, the value of OA for the vehicle with HUMS will be larger than the vehicle without HUMS. This is because,

$$\Delta t_{\text{with HUMS}} << \Delta t_{\text{witthoutHUMS}} \tag{4.2}$$

The total cost of the land platform is, then, estimated to be:

$$\begin{aligned} \text{Total Cost}(\Gamma)_{\text{with HUMS}} &= \sum(\text{All the Costs}) \\ &= \Phi_{\text{PC}} + \delta + \Phi_{\text{CC}} + \Phi_{\text{SM}} + \Phi_{\text{RC}} + \beta + \Phi_{\text{HC}} \end{aligned} \tag{4.3}$$

and for the vehicle without HUMS,

$$\text{Total Cost}(\Gamma)_{\text{withoutHUMS}} = \Phi_{\text{PC}} + \delta + \Phi_{\text{CC}} + \Phi_{\text{SM}} + \Phi_{\text{RC}} + \beta\,. \tag{4.4}$$

Equations 4.3 and 4.4 above list all the cost components which have been considered in this research. Now each of the costs and the proposed method to estimate them will be presented below:

1. **Platform Cost ($\Phi_{PC}$):** Platform cost is a one-off cost and it is assumed to be same for both, the vehicle with HUMS, and the vehicle without HUMS.

2. **Out of Service Penalty (δ):** Out of service penalty is modelled to be a yearly cost, and it is solely dependent on the availability of the platform. It is calculated to be:

$$\delta = \frac{\Phi_{PC} \times (1\text{-}\mathrm{OA})}{\Lambda_{\mathrm{tt}}} \tag{4.5}$$

**3. Cost of Repair ($\Phi_{RC}$):** The cost of repair consists of two parts: repair cost for scheduled events and for unscheduled events. It is expected that the cost of repair will be significantly less for a vehicle with HUMS when compared to a vehicle without HUMS. ***Cost of Repair*** is approximated as follow:

$$\Phi_{\mathrm{RC}} = \Phi_{\mathrm{SR}} + \Phi_{\mathrm{UR}} \tag{4.6}$$

In this paper, the repair cost for scheduled events is approximated using the weighted function as follow:

$$\left(\Phi_{\mathrm{SR}}\right)_{\text{with HUMS}} = 0.5 \times \left(\Phi_{\mathrm{SR}}\right)_{\text{withoutHUMS}} \times \left(1 + \frac{\Lambda_{st}}{\Lambda_{tt}}\right) \tag{4.7}$$

Where,

$\Lambda_{st}$ = Time the vehicle is in service and,

$\Lambda_{tt}$ = Total time the vehicle is in service.

$\Phi_{CC}$ = Cost of Consumable
$\Delta t$ = Down Time
$\Phi_{HC}$ = HUMS cost
$\beta$ = Accidental allowance cost
$\delta$ = Out of Service Penalty
$\Phi_{PC}$ = Platform Cost
$\Phi_{RC}$ = Repair Cost
$\Phi_{SM}$ = Stock Management Cost
$\Phi_{SR}$ = Schedule Repair Cost
$\Gamma$ = Total Cost
$\Lambda_{st}$ = Time the vehicle is in service
$\Lambda_{tt}$ = Total time the vehicle is in service
$\Phi_{UR}$ = Unscheduled Repair Cost

The weighting function in Eq 4.7 is designed so that it causes a gradual increase in the scheduled repair cost of a vehicle with HUMS and will rise to a value same as that of vehicle without HUMS towards the end of the vehicle life. This is because when the vehicle is new, the repair will not be required as frequently as it will when the vehicle is old. The CBM in HUMS will only trigger maintenance action when it is necessary i.e. based on the actual health of the component or subsystem rather than in specific time interval as in the case of the vehicle without HUMS. Therefore, the key assumption which the authors have used, while devising this model, is the scheduled repair cost for the vehicle with HUMS is around half of the cost for vehicle without HUMS in the beginning of the service life [56], and it linearly increases to the cost equal to the vehicle without HUMS at the end of the service life. This is reasonable since at the start of the service life, the vehicle components are new and hence there will be very few repair requirements triggered by the on-board HUMS (the authors started by modelling cost to be half, but it may even be lower). Similarly, at the end of the service life, the components would have aged and the HUMS system will trigger the repair requirements more frequently such that the cost would be similar to the vehicle without HUMS.

Note that the *Scheduled* service time interval for a civilian car is about 1 year or after 12000 miles (this figure is a general rule of thumb and can vary slightly depending on the make and model of the vehicle) whereas for a Military vehicle it is about 2 years. Similarly, the model presented in this chapter uses following weighting function to estimate the repair cost for *unscheduled* events:

$$\left(\Phi_{\mathrm{UR}}\right)_{\text{with HUMS}} = \left(\Phi_{\mathrm{UR}}\right)_{\text{withoutHUMS}} \times \left(0.25 + 0.75\frac{\Lambda_{st}^2}{\Lambda_{tt}^2}\right) \tag{4.8}$$

The weighting function in Eq 4.8 is designed to have a relatively small unscheduled repair cost to start with when the vehicle is new, and the cost increases more rapidly (with a quadratic relation) when the vehicle gets older. While modelling unscheduled cost for vehicle with HUMS, it was assumed that the cost was significantly low at the start of the vehicles' service life (around one-fourth of the cost for Vehicle without HUMS) since the components and parts are all new; and hence the need for unscheduled repair would be minimal. Similarly, the cost was modelled to increase non-linearly as the vehicle was getting old. Specifically, the weighting is more biased in such a way that the unscheduled cost increases rapidly as the vehicle approaches the end of its service life. It is also intuitive in that, the unscheduled (or sudden and unexpected) failures are more likely to occur when the vehicle is old, and hence the higher cost when the vehicle is in the last quarter of its service life.

### Cost to allow unforeseen accidents (β)

In addition to scheduled and unscheduled costs, a yearly cost figure allowing for the accidental events in the vehicle's operational life is accounted for by a constant value. This constant amount will vary from vehicle to vehicle and also the operational environments.

### Cost of HUMS System ($\Phi_{HC}$)

Finally, the cost of HUMS equipment is modelled in two parts: hardware cost; and running cost (this consists of crew training, repair & maintenance components). The hardware cost is a constant value and may vary from platform to platform. The running cost in this research has been modelled by an exponential function. This is to model a trend which is high to start with, but decreases rapidly with vehicle's operational life. This is to account for the high start-up cost of the HUMS system initially, but the cost of HUMS decreases rapidly as the users become experienced at using it and hence repair & maintenance cost keeps decreasing. The HUMS cost is modelled by the following equation:

$$\Phi_{\mathrm{HC}} = C_0 \times e^{-\alpha \Lambda_s} \tag{4.9}$$

where,

$C_0 = \text{Initial startup cost of HUMS system}$

$\Lambda_s = \text{The length of time the vehicle has been in service (in years)}$

$\alpha = \text{Constant factor taken to be } 0.5.$

### Present Value of Costs ($\Phi_{PV}$)

The time varying components of the costs presented above need to be accounted for the time value of money to calculate the net present value. The method to evaluate the present value is described in detail by Boardman et al. [57]. Generally, when there are projects that have impacts over several years, it is necessary to aggregate the benefits and costs that arise in different years. In CBA, the costs that occur in future are discounted relative to the present costs in order to obtain their present values ($\Phi_{PV}$). Discounting has nothing to do with inflation directly, but inflation must be taken into account while applying the discount. For example, if a cost occurs in year t, it is converted to its present value by dividing it by $(1+\gamma)^t$, where $\gamma$ is the discount rate. Therefore, if a project has a life of n years and $\Phi_t$ is the cost in year t, then, the present value of the cost, $\Phi_{PV}$, can be calculated as [57]:

$$\Phi_{\mathrm{PV}} = \sum_{\mathrm{t}=0}^{\mathrm{n}} \frac{\Phi_{\mathrm{t}}}{(1+\gamma)^{\mathrm{t}}} \tag{4.10}$$

## 4.3 Cost Modelling Validation Cases

### 4.3.1 Light Personnel Carrier (4X4 Land Vehicle)

The proposed method above is tested and validated using the data available in the work of Lee [58]. Lee [58]'s work presented a HUMS cost and benefit model for a general purpose wheeled land vehicle (a typical 4×4 land vehicle), which was based on the Defence Science and Technology Organization (DSTO)'s HUMSSAVE 4 program (Beta Release 1) [59]. In the validation presented here, only the vehicle data from [58] were used. The data is used to compare a 4×4 land vehicle basic platform (without HUMS system) with the same vehicle consisting of an integrated HUMS system. The basic platform costs, yearly repair costs, stock management cost and the cost of consumables are taken from [58] and is presented in Table 4.1. The out of service penalty is calculated using the Equation 4.5 above. All the component costs associated with the operation of the vehicle is calculated as described above, and it is plotted in Figure 4.1. From the figure, the total cost of the vehicle is initially high, but decreases with time until the vehicle is half way through its service life. The cost increases again as the vehicle nears its end of service. It is also noted here that the costs presented in this paper was arrived at by applying the discount factor to account the time value of money (see [57] for details). Interestingly, this variation in the cost of the vehicle was found to be in close resemblance with the bath-tub curve, which is widely used in reliability engineering [60].

Table 4.1: Capital and yearly costs (all costs are in Aus. Dollars $)

| **Capital Costs** | | |
|---|---|---|
| | **Vehicle without HUMS** | **Vehicle with HUMS** |
| Basic platform cost | 60000 | 60000 |
| Total cost of HUMS System Hardware | 0 | 3000 |
| Total platform cost | 60000 | 63000 |
| Operational availability | 60% | 65% |
| **Yearly Costs** | | |
| Cost of Stock Management | 5500 | 3850 |
| HUMS repair, upgrade & running cost | 0 | 4950 |
| Cost of Consumable | 880 | 774 |
| Scheduled Event Cost of Repair | 2640 | - |
| Unscheduled Event Cost of Repair | 2750 | - |
| Out of Service Penalty | 1200 | 1102 |

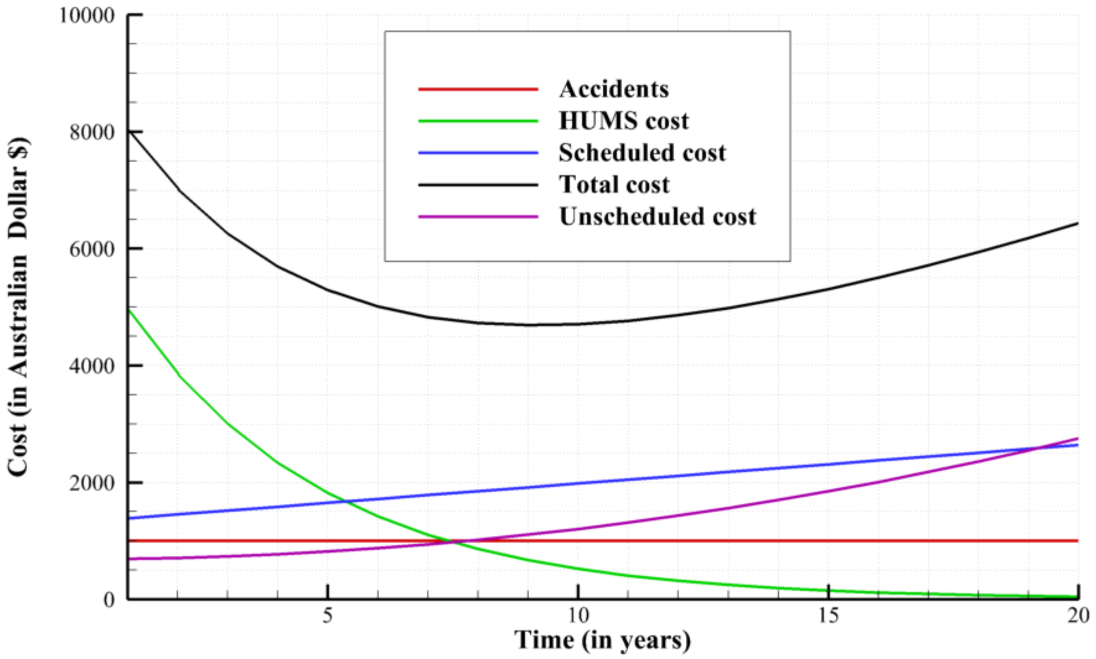


Figure 4.1 Plot of various cost components over time for the vehicle with HUMS.

The initial capital costs and the yearly cost along with the out of service penalty figures (this is also an annual cost) are then used to create a yearly accumulated account of the total costs for both the platforms. The yearly cost which accumulates over time is created for a period of 20 years (this is the expected service life of the vehicle as stated in [58]) and is presented in Table 4.2. Trend of this variation is then plotted in Figure 4.2 for both the platforms.

Table 4.2: Accumulated overall cost against time (in years)

| Year | Vehicle without HUMS | Vehicle with HUMS |
|---:|---:|---:|
| 1 | 68290 | 70326 |
| 2 | 76299 | 76954 |
| 3 | 84038 | 83044 |
| 4 | 91515 | 88720 |
| 5 | 98739 | 94073 |
| 6 | 105719 | 99177 |
| 7 | 112463 | 104085 |
| 8 | 118979 | 108841 |
| 9 | 125274 | 113477 |
| 10 | 131356 | 118018 |
| 11 | 137233 | 122484 |
| 12 | 142911 | 126891 |
| 13 | 148397 | 131250 |
| 14 | 153698 | 135572 |
| 15 | 158819 | 139863 |
| 16 | 163768 | 144129 |

| | | |
|---|---|---|
| 17 | 168548 | 148375 |
| 18 | 173167 | 152604 |
| 19 | 177630 | 156820 |
| 20 | 181942 | 161025 |

It is clearly evident from Table 4.2 (also in Figure 4.2) that the cost of the HUMS integrated system breaks even in just over two years' time when compared to the system without HUMS. The plot in Figure 4.2 also shows a much shallower slope of overall cost rise for the HUMS integrated vehicle when compared to the vehicle without HUMS. This results in a relatively short period (just over 2 years) to break even in terms of cost. This finding from the proposed cost model is consistent with the cost model proposed in the past literatures [53, 58]. Lee's work [58] evaluated the break-even to occur after around 2.76 years (almost 3 years) which is slightly later than that calculated by the model presented here. Despite being a simplified model, this model allows for a discount factor to reflect on the discounted cash flow i.e. considering the time-value of money (the model in [58] also accounts for the time value of money).

In overall, the result presented in Table 4.2 demonstrates that despite the simplicity in comparison to the model in [53,58], the current model can perform a quick and effective study to assess the financial feasibility of employing HUMS in military vehicles. In addition to these tangible benefits, HUMS can also give all sorts of intangible benefits, whist real, are difficult to quantify. For example, it can give a competitive advantage to a mission by guaranteeing a higher availability of the platform. This will also result in the morale boost of the soldiers involved in the mission. Another example is the increase in safety this can result, by providing the operating crew with prior information on the specific nature of a minor technical problem so that they are aware of it and they can focus on their mission objectives without deviating their attention to diagnose it themselves. However, since it is not possible to assign an economic value to these benefits, they cannot be included in the cost modelling.

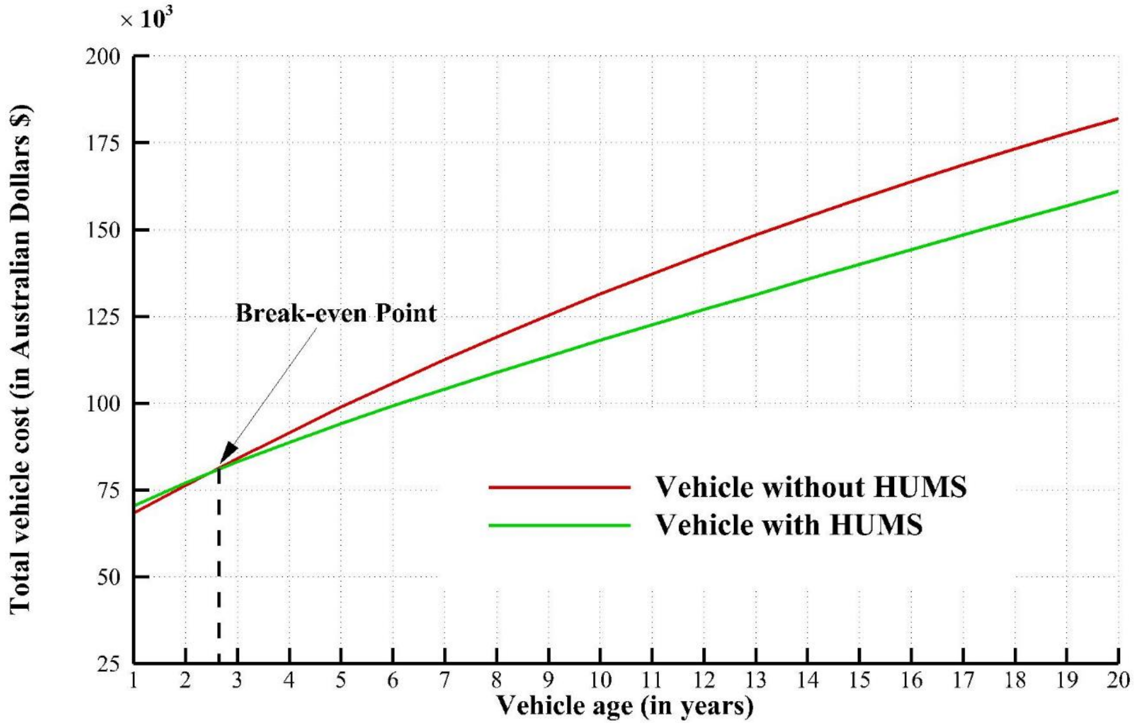
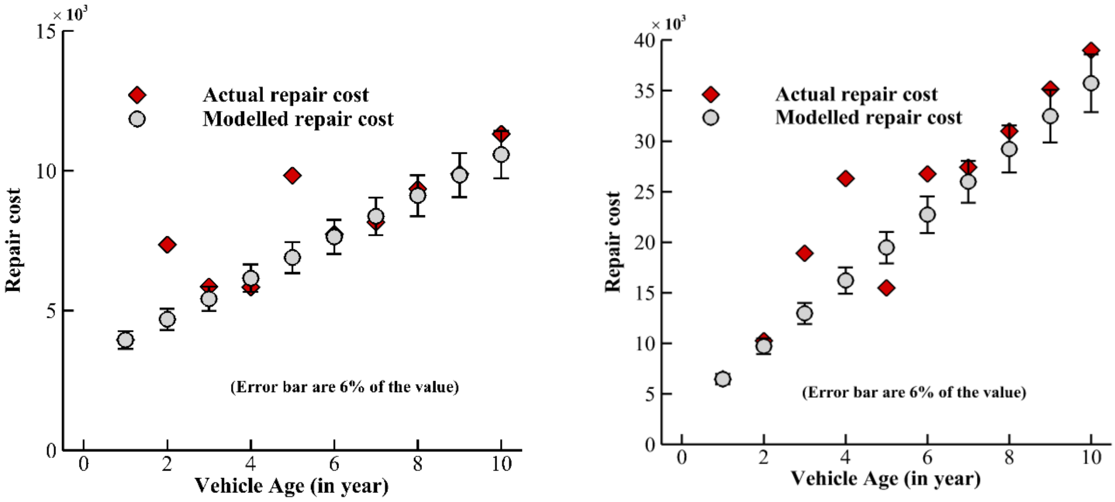


Figure 4.2 Plot of accumulated cost over time for vehicle with and without HUMS.

### 4.3.2 Armoured Personnel Carrier: Piranha and Main Battle Tank: Challenger

After validating the model with the available data in the literature, it was used to assess the financial viability of employing HUMS in two distinct classes of military vehicles: an armoured personnel carrier (APC), Piranha and a main battle tank (MBT), Challenger 2. Piranha is a light armoured vehicle which is designed for the main purpose of rapid reconnaissance functions, and is a highly mobile personnel carrier with effective attack capability. The Challenger 2 on the other hand is a MBT to provide a front line attack role. The data for both of these vehicles were collected by the author from Royal Army of the Sultanate of Oman. The Omani army has a large fleet of Piranha (approximately 175), and a relatively smaller Challenger 2 fleet (approximately 45). They are keen to assess the financial implications of integrating HUMS on these platforms to improve the reliability and safety.

The data provided include the in-service repair data for each fleet spanning over a period of 10 years. Hence at first instant, these data were processed further to conduct a sanity check of the proposed model. Specifically, the repair costs sampled from these in-service usages were compared with the modelled cost. The in-service repair cost was then compared with the modelled cost for both the vehicle types: Piranha and Challenger 2. The actual repair cost data were averaged over the sample size and plotted against time (here time is the vehicle age in service). The comparative plots are presented in Figures 4.3(a) and 4.3(b) for the APC and MBT classes respectively.



(a) Piranha (b) Challenger 2

Figure 4.3 Repair cost comparison for Piranha & Challenger 2 (all costs in Omani Rials).

From the figures, it is clear that actual data agree well with the modelled cost. Some discrepancies, however, are also evident, especially for the Challenger 2. This is because in the event of the major system failures on Challenger 2, the systems (e.g. engine, gearbox) were out of service due to prolonged spare acquisition time. Such anomalies can generally be excluded from data evaluation to avoid result skewing.

The initial capital costs and the yearly cost along with the out of service penalty figures (this is also an annual cost) were again used to create a yearly accumulated account of the total costs for both vehicle types. Table 4.3 and 4.4 present the numerical data from the cost analysis using the model for Piranha (also plotted in Figure 4.5). It is also noted here that the 'unscheduled repair cost of the vehicle without HUMS' required in Eq. 4.8 for this analysis is calculated by averaging the real vehicle usage data. From the results, the HUMS integrated Piranha platform is found to break-even just after 5 years. Considering the unit platform cost and the complexities involved with this type of vehicle, the HUMS integration will result in a significant cost saving in the long term.

Figure 4.4 Piranha which is in service in Royal Army of Oman.

Table 4.3 Capital and yearly costs (all costs are in Omani Rials RO)

| Capital Costs | | |
|---|---|---|
| | **Vehicle without HUMS** | **Vehicle with HUMS** |
| Basic platform cost | 541914 | 541914 |
| Total cost of HUMS System Hardware | 0 | 3500 |
| Total platform cost | 541914 | 551914 |
| Operational availability | 68.5% | 75% |
| **Yearly Costs** | | |
| Cost of Stock Management (based on a fleet of 173 vehicles) | 65 per vehicle | 93 per vehicle |
| Cost of Consumable | 530 | 467 |
| Scheduled Event Cost of Repair (per year) | 500 | - |
| Unscheduled Event Cost of Repair | 852 | - |
| Out of Service Penalty | 8535 | 6899 |

Table 4.4 Accumulated overall cost against time (in years)

| Year | Vehicle without HUMS | Vehicle with HUMS |
|---|---|---|
| 1 | 552069 | 556840 |
| 2 | 561537 | 566081 |
| 3 | 570353 | 573790 |
| 4 | 578551 | 580415 |
| 5 | 586162 | 586259 |
| 6 | 593215 | 591528 |
| 7 | 599742 | 596357 |
| 8 | 605768 | 600837 |
| 9 | 611320 | 605030 |
| 10 | 616424 | 608975 |
| 11 | 621104 | 612699 |
| 12 | 625382 | 616221 |
| 13 | 629279 | 619552 |
| 14 | 632818 | 622703 |
| 15 | 636018 | 625681 |
| 16 | 638897 | 628493 |
| 17 | 641474 | 631146 |
| 18 | 643765 | 633645 |
| 19 | 645788 | 635996 |
| 20 | 752123 | 638205 |

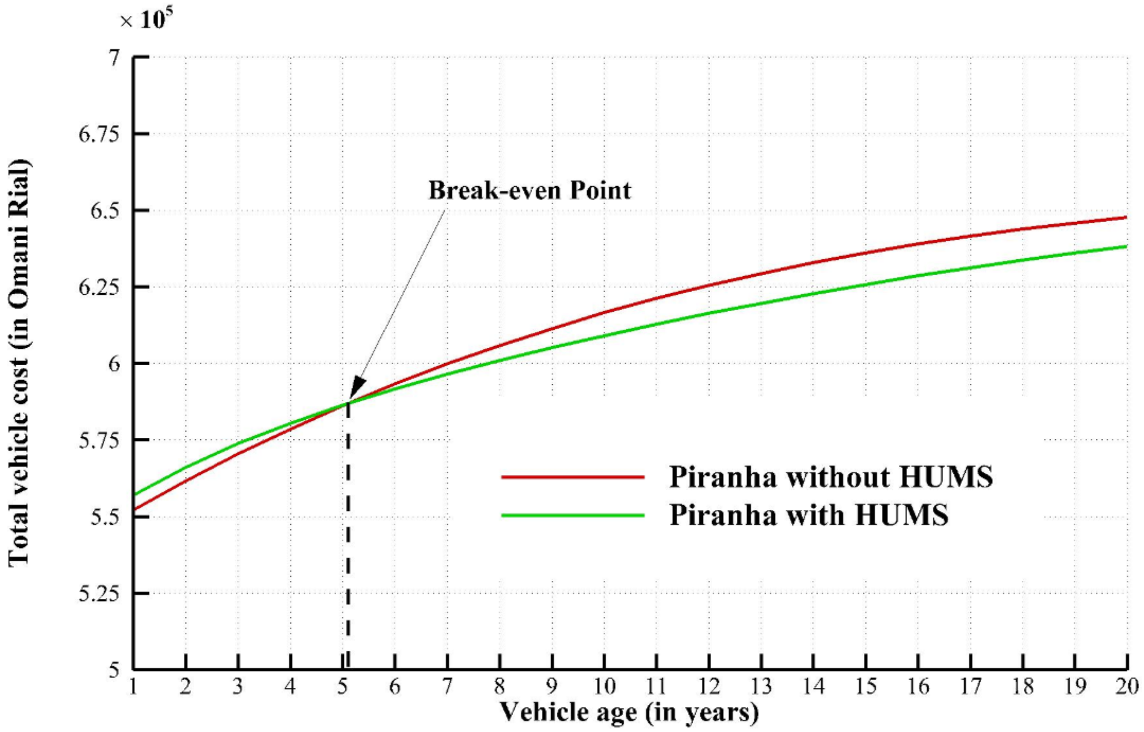


Figure 4.5 Plot of accumulated cost over time for Piranha with and without HUMS.

Similarly, the results from the cost analysis on the Challenger 2 platform (see Figure 4.6) are presented in Tables 4.5 and 4.6. The trend of the accumulated cost variation is also plotted in Figure 4.7, which shows that the cost rise does not vary linearly, it is seen to plateau gradually with time due to the discount rate to account for the time value of money. Again, the results show that the MBT platform will break even within 3 years, this is even sooner than the Piranha fleet. However, it is worth noting here that the unit cost of MBT is so high that the HUMS integration cost is only a negligible fraction of the base platform cost. Hence, there exists even more substantial financial benefits of integrating HUMS in the MBT platform.

Figure 4.6 Challenger2 currently in service with Royal Army of Oman.

Table 4.5 Capital and yearly costs (all costs are in Omani Rials RO)

| **Capital Costs** | | |
|---|---|---|
| | **Vehicle without HUMS** | **Vehicle with HUMS** |
| Basic platform cost | 2678000 | 2678000 |
| Total cost of HUMS System Hardware | 0 | 7600 |
| Total platform cost | 2678000 | 2778000 |
| Operational availability | 68.5% | 75% |
| **Yearly Costs** | | |
| Cost of Stock Management (based on a fleet of 43 vehicles) | 171 | 120 |
| Cost of Consumable | 990 | 871 |
| Scheduled Event Cost of Repair | 550 | - |
| Unscheduled Event Cost of Repair | 1519 | - |
| Out of Service Penalty | 42179 | 33570 |

Table 4.6 Accumulated overall cost against time (in years)

| **Year** | **Vehicle without HUMS** | **Vehicle with HUMS** |
|---|---|---|
| 1 | 2721873 | 2727515 |
| 2 | 2762778 | 2763498 |
| 3 | 2800867 | 2795029 |
| 4 | 2836283 | 2823134 |
| 5 | 2869163 | 2848527 |
| 6 | 2899638 | 2871702 |
| 7 | 2927834 | 2893006 |
| 8 | 2953869 | 2912684 |
| 9 | 2977857 | 2930912 |
| 10 | 2999908 | 2947820 |
| 11 | 3020124 | 2963508 |
| 12 | 3038605 | 2978053 |
| 13 | 3055445 | 2991524 |
| 14 | 3070734 | 3003975 |
| 15 | 3084557 | 3015460 |
| 16 | 3096996 | 3026026 |
| 17 | 3108128 | 3035717 |
| 18 | 3118029 | 3044577 |
| 19 | 3126768 | 3052647 |
| 20 | 3134413 | 3059967 |

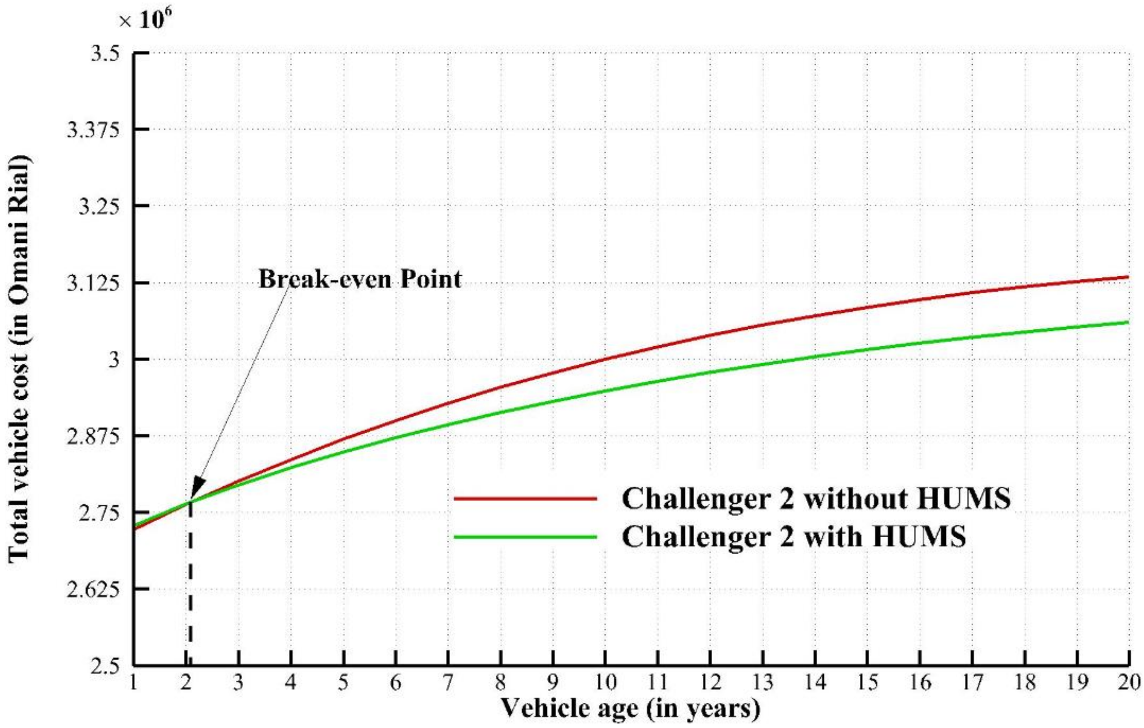


Figure 4.7 Plot of accumulated cost over time for Challenger 2 with and without HUMS.

### 4.4.4 Chapter Summary

This chapter presented a simple and effective method to analyse the financial implication of integrating HUMS system was proposed for military land vehicles. The model provides logical steps to estimate the yearly repair costs, operational availability and the overall costs to understand the financial implication of HUMS integration over the whole service life. The method was validated by using the available vehicle data from previously published literatures, and it was found to predict similar break-even time. The model was also used to assess the financial viability of integrating HUMS in other military platforms e.g. light armoured vehicle, Piranha and Main Battle Tank, Challenger 2. In both the cases, the analysis showed significant financial savings in the long term.

# Chapter 5

# Case study on history of military vehicle (Piranha and Challenger 2 usage in the Royal Army of Oman

## 5.1 Introduction

The system of Health and Usage Monitoring Systems (HUMS) on military land vehicles often suffer from the lack of data. The data represent the history of failure mechanism of vehicle's components are limited. The data contain failure mechanism is a prerequisite for improved HUMS design but missing in the literature. This study intends to analyse such data as case studies to identify the main components which are prone to cause regular failure, thus to monitor by the HUMS system.

The author of the dissertation visited the Royal Army of Oman, in the Sultanate of Oman to get a close look at the critical parts that are worthy to be monitored and to diagnose the faults long enough before they affect other parts or damage the vehicle at a critical time during operation or training and make them non-operational. Access to early information about the failure of the parts can also provide many benefits, including low cost of yearly repair, presence or availability of spare parts, as the warning of the part signal of failure is always diagnosed before its final failure. The HUMS system is making the presence of those who work in the maintenance and repair facility ready to carry out the repair in a certain time.

The data for two types of vehicles were collected. The first vehicle was a Challenger 2, main battle tank. This MBT is made in the United Kingdom, and is considered a heavy and vital piece of equipment. The number of vehicles were covered in this study 20 tanks. Emphasis was placed on the data on certain parts, which are very important in this vehicle and from the work experience of the author in different Electrical and Mechanical Engineering units. These parts are always failing repeatedly. These parts are as follows:

- The engine
- Drive line
- Electrical system
- Suspension system
- Other parts (e.g. Gun system, Turret and Chassis and Optronic system)

The second selected type of vehicle was the Piranha, armoured personnel carrier. The data were collected for 40 vehicles. The study covered the same parts which were in the case of the Challenger 2.

The data collection was for 10 years for the both vehicles, in order to provide a standard indicator of the common repairs or most serious faults suffered by these vehicles during that period. As the data included the types of faults and their causes, the date of entry of the workshop and the date of departure. The data also included the prices of spare parts with the labour to estimate the costs resulting from these faults, especially because the reason is a partial breakdown or small parts were behind that costly failure.

The intended study is to analyse and identify which parts of these two military vehicles fail frequently and estimate the total cost and the time for the repair for the failure. Based on the findings, the main components of the vehicles will be selected for the future study of the developments of HUMS system.

## 5.2 Data collection method

The data for this case study was collected from the Royal Army Units, The Sultanate of Oman. The military vehicles of 20 Challenger and 40 Piranha were used in this case study for analyzing the history of the characteristics of fault mechanism. These two vehicles represent, one heavy vehicle ‘MBT’ and other light vehicle ‘APC’. The data contains the details of the reported faults, reason for the fault, cost for the repair and the duration for the repair. The collected data contains vehicle fault history for 10 years. The different parts of the vehicles were considered to analyse the fault mechanism which includes engine, driveline, electrical system, suspension and other parts. The number of vehicle was selected based on the availability of military vehicle data from the Oman Army. The maximum numbers were selected to provide enough statistical energy in the analysis.

## 5.3 Data description

This section describes the draw data of the two selected military vehicles, Challenger 2 and Piranha. The 20 different Challenger 2 were selected in this study and the Table 5.1 contains the details of the failure of the individual parts of the 20 vehicles over 10 years. The individual parts of the Challenger 2 include, engine, driveline, electric system, suspension system and other parts. For the Piranha, 40 different vehicles were selected and Table 5.2 contains the details of the failure mechanism of the individual parts of the vehicle. The individual parts include, engine, driveline, electrical system, suspension system and other parts.

Table 5.1 The details of the failure history of the individual parts of the 20 Challenger 2 for 10 years.

| Challenger 2 | Engine In 10 years | Drive-line In 10 years | Elect in 10 years | Suspension In 10 years | Other parts In 10 years | Service Once a year |
|---|---|---|---|---|---|---|
| 1 | 8 | 5 | 2 | 7 | 6 | Once a year |
| 2 | 5 | 4 | 2 | 3 | 8 | ,, |
| 3 | 7 | 1 | 3 | 5 | 6 | ,, |
| 4 | 4 | 2 | 3 | 4 | 5 | ,, |
| 5 | 4 | 3 | 3 | 5 | 7 | ,, |
| 6 | 8 | 2 | 4 | 5 | 6 | ,, |
| 7 | 4 | 2 | 2 | 3 | 8 | ,, |
| 8 | 5 | 4 | 5 | 3 | 12 | ,, |
| 9 | 9 | 3 | 5 | 3 | 13 | ,, |
| 10 | 7 | 6 | 4 | 5 | 20 | ,, |
| 11 | 9 | 10 | 3 | 4 | 13 | ,, |
| 12 | 11 | 5 | 1 | 4 | 10 | ,, |
| 13 | 9 | 3 | 5 | 5 | 9 | ,, |
| 14 | 5 | 1 | 2 | 3 | 11 | ,,, |
| 15 | 6 | 3 | 2 | 3 | 12 | ,, |
| 16 | 7 | 7 | 2 | 3 | 11 | ,, |
| 17 | 11 | 5 | 2 | 3 | 13 | ,, |
| 18 | 6 | 5 | 2 | 4 | 18 | ,, |
| 19 | 13 | 2 | 4 | 3 | 12 | ,, |
| 20 | 5 | 7 | 2 | 4 | 18 | ,, |
| *Total* | 143 | 80 | 58 | 79 | 218 | |

Table 5.2 The details of the failure history of the individual parts of the 40 Piranha for 10 years.

| Piranha | Engine faults in 10 years | Drive- line faults in 10 years | Elect Faults In 10 years | Suspension Faults in 10 years | Other parts fault in 10 years | Service once a year |
|---|---|---|---|---|---|---|
| 01 | 15 | 13 | 5 | 2 | 1 | ,, |
| 02 | 14 | 11 | 3 | 2 | 2 | ,, |
| 03 | 19 | 6 | 1 | 5 | 0 | ,, |
| 04 | 9 | 6 | 1 | 3 | 1 | ,, |
| 05 | 11 | 9 | 0 | 1 | 1 | ‘’ |
| 06 | 12 | 9 | 1 | 3 | 0 | ‘’ |
| 07 | 11 | 4 | 1 | 3 | 0 | ‘’ |
| 08 | 15 | 11 | 2 | 1 | 0 | ‘’ |
| 09 | 12 | 7 | 1 | 3 | 0 | ‘’ |
| 10 | 12 | 7 | 1 | 5 | 0 | ‘’ |
| 11 | 15 | 5 | 3 | 5 | 2 | ‘’ |
| 12 | 5 | 10 | 3 | 3 | 4 | ‘’ |

| | | | | | | |
|---|---|---|---|---|---|---|
| 13 | 13 | 6 | 3 | 0 | 2 | ‘’ |
| 14 | 11 | 9 | 4 | 3 | 3 | ‘’ |
| 15 | 12 | 7 | 4 | 2 | 3 | ‘’ |
| 16 | 8 | 5 | 5 | 1 | 0 | ‘’ |
| 17 | 8 | 8 | 6 | 2 | 2 | ‘’ |
| 18 | 14 | 9 | 4 | 2 | 1 | ‘’ |
| 19 | 16 | 10 | 4 | 2 | 3 | ‘’ |
| 20 | 15 | 7 | 6 | 3 | 1 | ‘’ |
| 21 | 13 | 6 | 7 | 1 | 1 | ‘’ |
| 22 | 12 | 9 | 4 | 3 | 1 | ‘’ |
| 23 | 19 | 8 | 7 | 3 | 5 | ‘’ |
| 24 | 13 | 7 | 6 | 2 | 2 | ‘’ |
| 25 | 22 | 11 | 5 | 1 | 4 | ‘’ |
| 26 | 9 | 7 | 2 | 2 | 4 | ‘’ |
| 27 | 15 | 3 | 3 | 3 | 3 | ‘’ |
| 28 | 12 | 5 | 1 | 0 | 5 | ‘’ |
| 29 | 6 | 5 | 5 | 5 | 6 | ‘’ |
| 30 | 7 | 6 | 2 | 1 | 4 | ‘’ |
| 31 | 6 | 5 | 3 | 2 | 2 | ‘’ |
| 32 | 14 | 1 | 2 | 0 | 7 | ‘’ |
| 33 | 7 | 5 | 4 | 2 | 3 | ‘’ |
| 34 | 8 | 1 | 4 | 2 | 4 | ‘’ |
| 35 | 12 | 3 | 1 | 2 | 2 | ‘’ |
| 36 | 13 | 6 | 4 | 0 | 2 | ‘’ |
| 37 | 11 | 5 | 5 | 3 | 5 | ‘’ |
| 38 | 10 | 9 | 3 | 2 | 1 | ‘’ |
| 39 | 11 | 7 | 4 | 2 | 2 | ‘’ |
| 40 | 17 | 6 | 1 | 4 | 2 | ‘’ |
| Total | 484 | 273 | 131 | 90 | 91 | |

## 5.4 Analysis

The individual parts of each vehicle were further divided into several subsystems to analyse the detailed description of the failure mechanism. All the failure mechanisms were analysed on a yearly and quarterly basis in order to find out the parts which are more prone to failure in ten years and the cause of their failure. The data were analysed in Excel and the histogram were used to show the statistics of the failure of each component of the vehicle.

## 5.5 Results

### 5.5.1 Challenger 2

#### 5.5.1.1 Engine

In the first quarter of the year, it seemed that there are more failures in the engine which is not expected as the new vehicle (Figure 5.1). However, there could be some possible reasons for this such as harsh environmental operating conditions and the lack of training provided for the crew members at the initial stage of the service of the vehicle. The failures which appeared in rest of the periods are due to the heavy usage of the vehicle during the exercise.

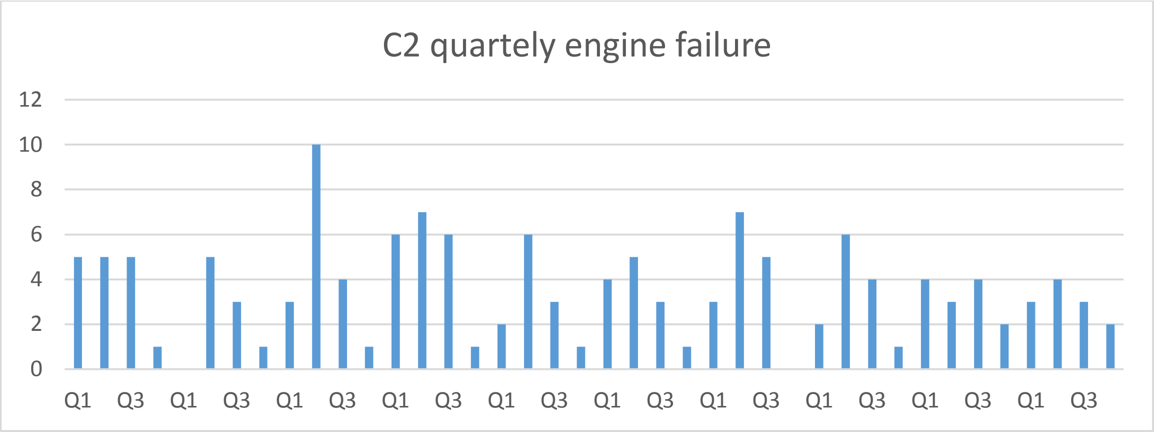


Figure 5.1 Histogram describes the quarterly engine failure of the C2.

#### 5.5.1.2 Driveline

The failure appeared in the gear boxes of the vehicles due to problems with the oil heat exchanger and the problem in the humidity separator system (Figure 5.2). These failure modes occur mainly by the problems with the heat exchanger and / or humidity system.

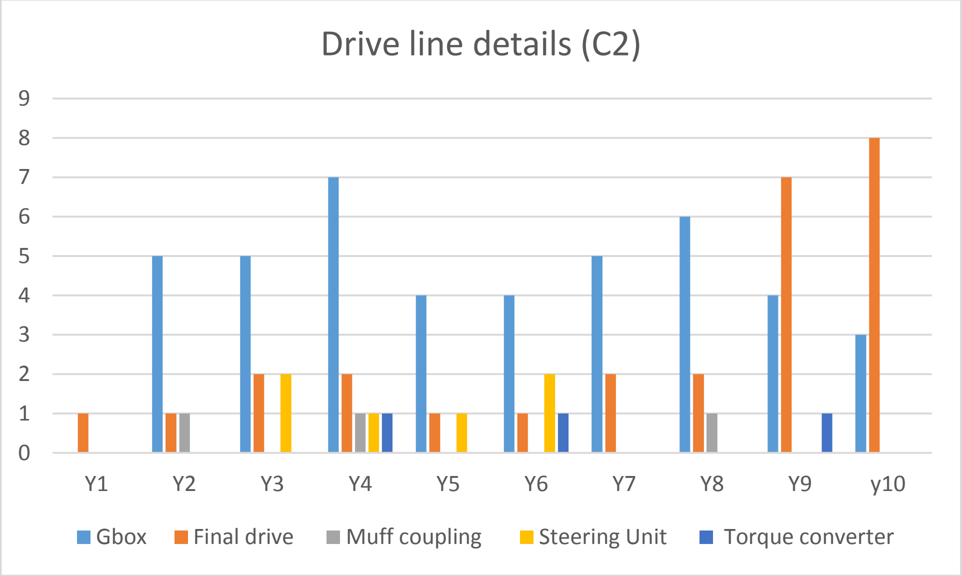


Figure 5.2 Histogram describes the yearly driveline failure of the C2.

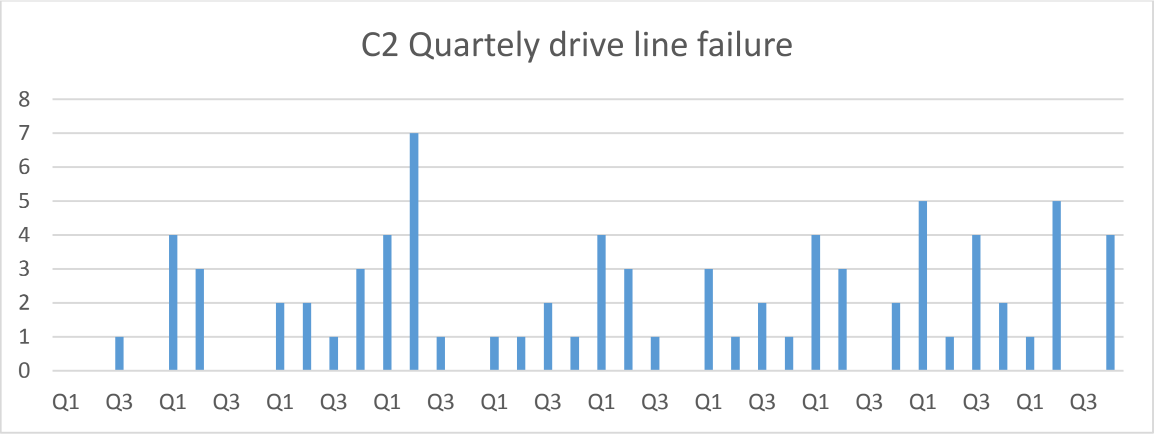


Figure 5.3 Histogram describes the quarterly driveline failure of the C2.

### 5.5.1.3 Lubricant system

The failure in the lubricant system seemed to be not normally distributed. There are more failures in the oil pump than other sub-units. This lubricant system is attributed in the further study for developing the HUMS management system.

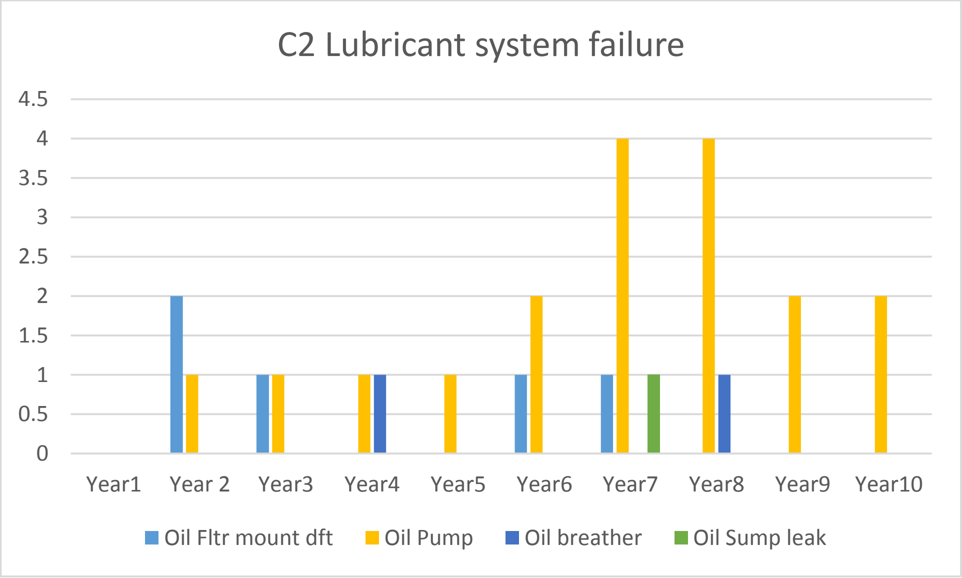


Figure 5.4 Histogram describes the yearly lubricant system failure of the C2.

The failure in the cooling system is not normally distributed. There seemed to be more failures in the water pump than other sub-units, the failure skewed towards the water pump. This suggests that health monitoring is less important for this element than the preventive maintenance. The main cause for the higher frequency of failure is that the vehicle is operating in the hot and dust environment for longer period of time.

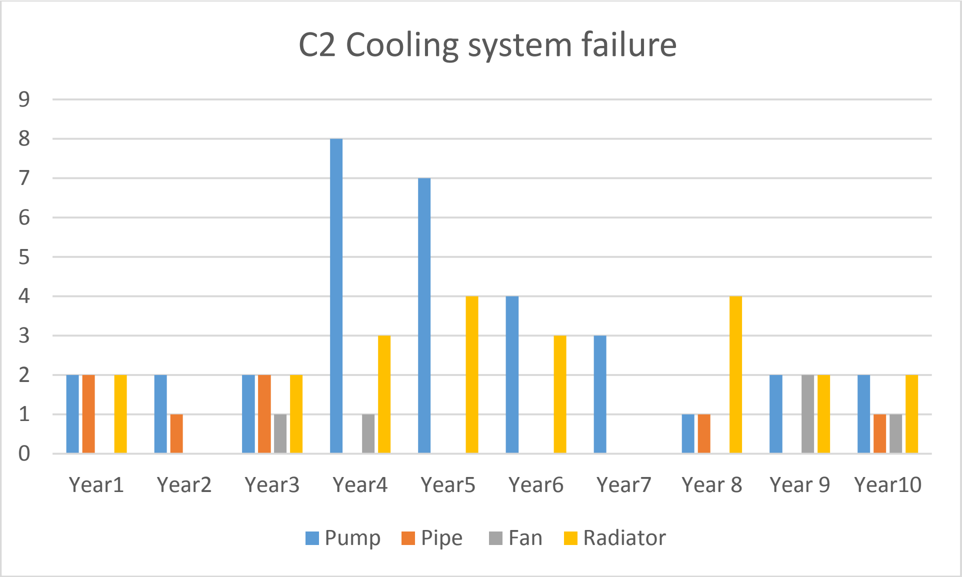


Figure 5.5 Histogram describes the yearly cooling system failure of the C2.

The failure in the fuel system is not normally distributed. There are more failures in the fuel system because this unit has collection of several small units together (e.g. fuel pipes).

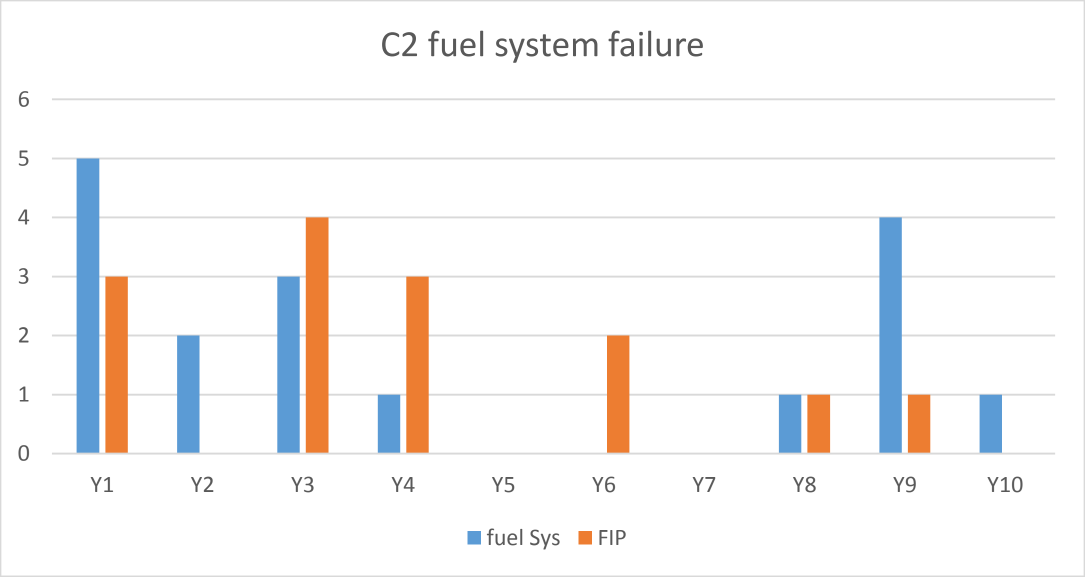


Figure 5.6 Histogram describes the yearly fuel system failure of the C2.

#### 5.5.1.4 Electric system

The failures in the electrical system seemed to be normally distributed as expected (Figure 5.7). However, there seemed to be more failures in the AC unit compared with other sub-units. This is due to the fact that the heavy usage of the AC unit, because the operating environmental temperature of these vehicle is very high (e.g. 50 ºC - desert and hot environment with dusty nature) and the usage of the AC units are mandatory all the time. Also some of the sensitive electronics items require the operating AC environment all the time.

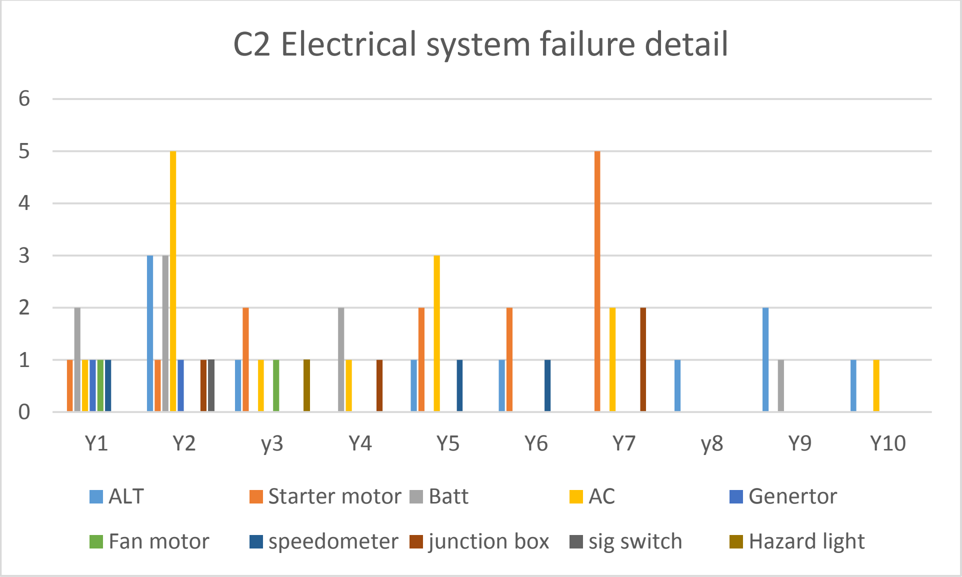


Figure 5.7 Histogram describes the yearly electric failure of the C2.

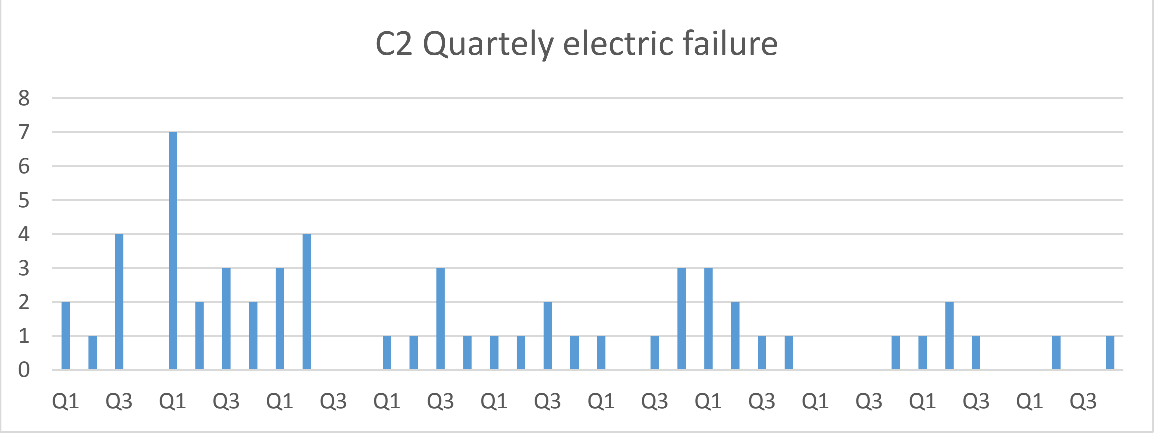


Figure 5.8 Histogram describes the quarterly electric failure of the C2.

### 5.5.1.5 Suspension system

The failures in the suspension system of the vehicle seemed to be very high. This is due to the nature of the hydro-gas suspension system having the common leakage in the gas line. This common failure is attributed in this study for further development of the HUMS management system and this will be discussed in details in the next Chapter, Chapter 6.

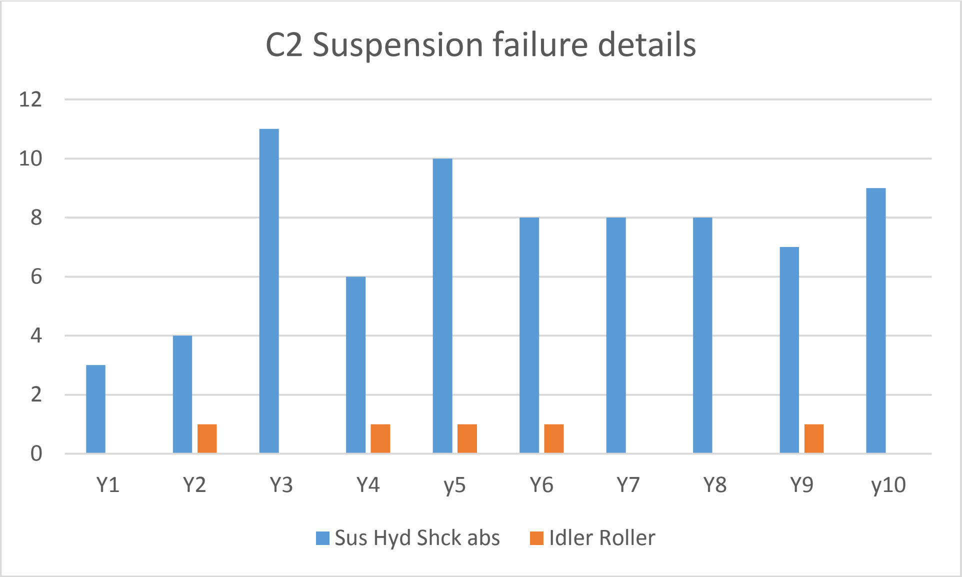


Figure 5.9 Histogram describes the yearly suspension failure of the C2.

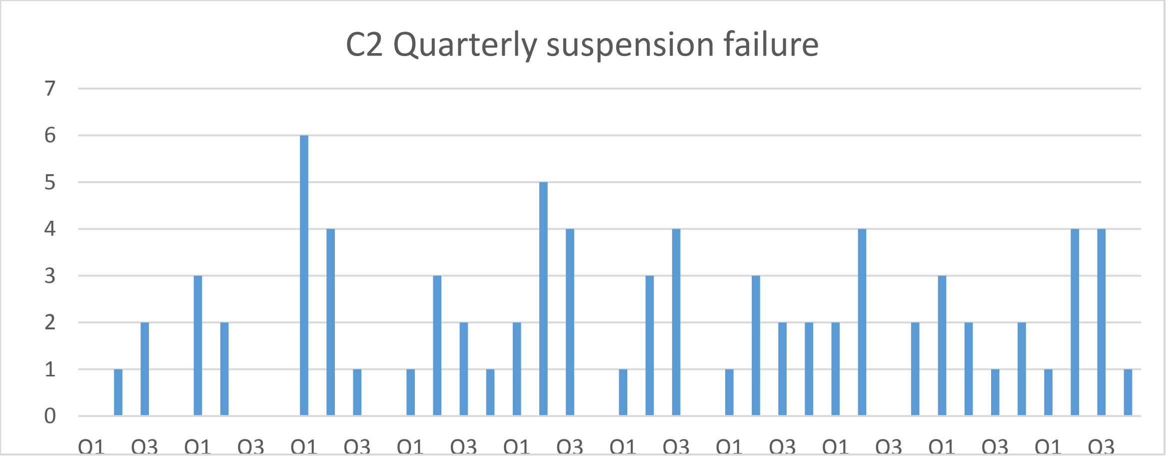


Figure 5.10 Histogram describes the quarterly suspension failure of the C2.

### 5.5.1.6 Other parts

The failure appeared in the other parts seemed to be normally distributed as expected. The electronics system seemed to have more failure compared with the gun system and the chassis but this is very less compared with other systems failures.

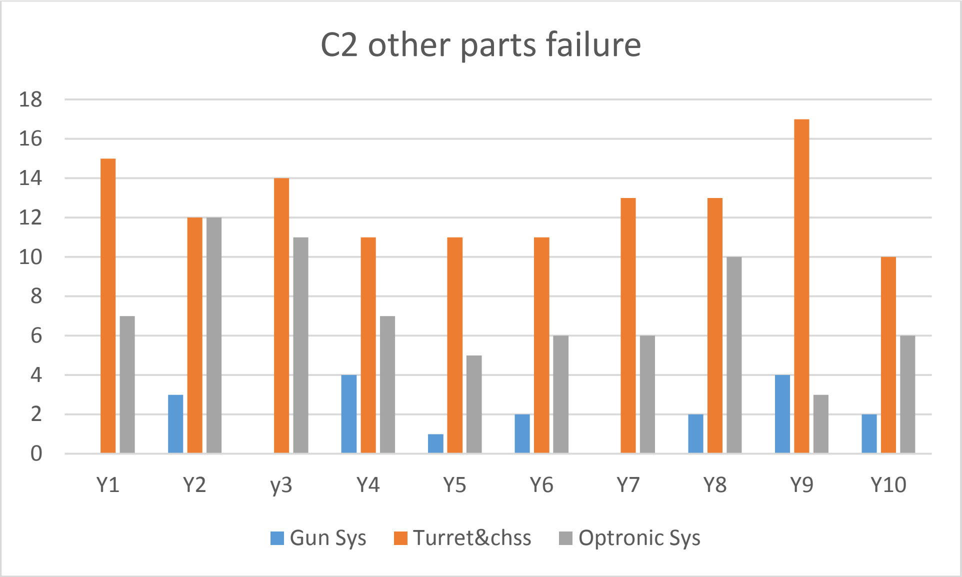


Figure 5.11 Histogram describes the yearly other parts failure of the C2.

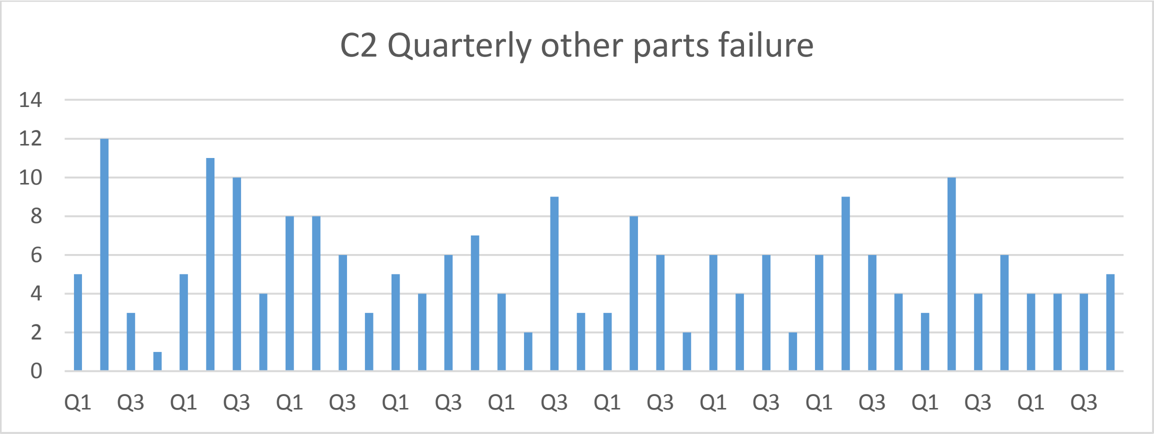


Figure 5.12 Histogram describes the quarterly other parts failure of the C2.

### 5.5.2 Piranha

#### 5.5.2.1 Engine

In the first quarter of the year, it seemed that there are more failures in the engine of the Piranha which is not expected as the new vehicle (Figure 5.15). However, there could be some possible reasons for this such as harsh environmental operating conditions and the lack of training provided for the crew members at the initial stage of the service of the vehicle. The failures appeared in rest of the periods are due to the heavy usage of the vehicle during the exercise and the usage of the Piranha vehicle is more compared with the Challenger 2.

The failure in the fuel system seemed to be normally distributed (Figure 5.13). However, there are some higher failure due to the failure of the fuel pump and other sub-system (e.g. leakage).

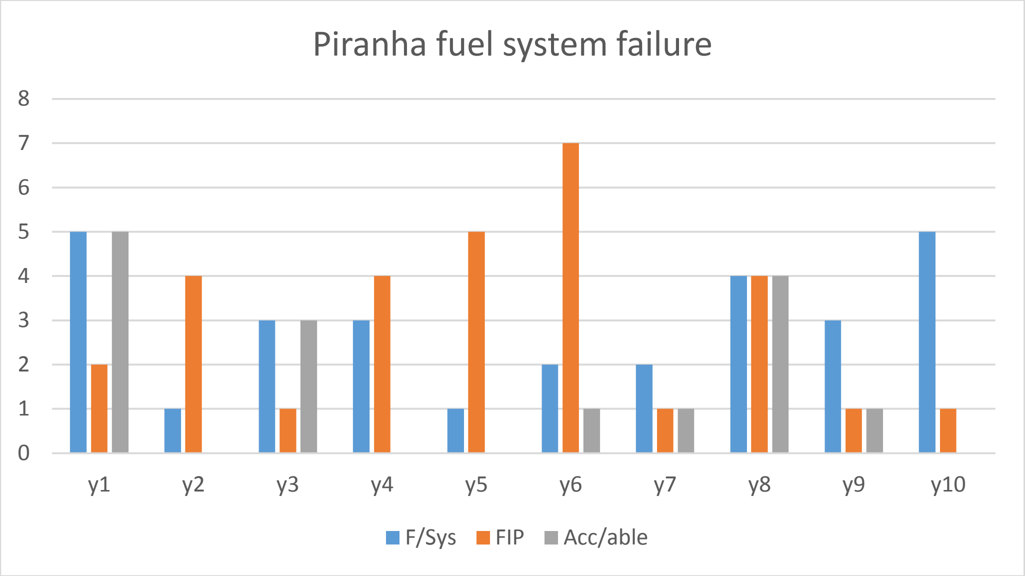


Figure 5.13 Histogram describes the yearly fuel system failure of the Piranha.

The failure in the cooling system seemed to not normally distributed. However, there seemed to be more failure in the water pump as expected than other sub-units. Failure in the cooling system result in complete failure of the engine in most of the cases. Thus the cooling system is selected as one of the main system for the further study for developing HUMS management system in the Chapter 7.

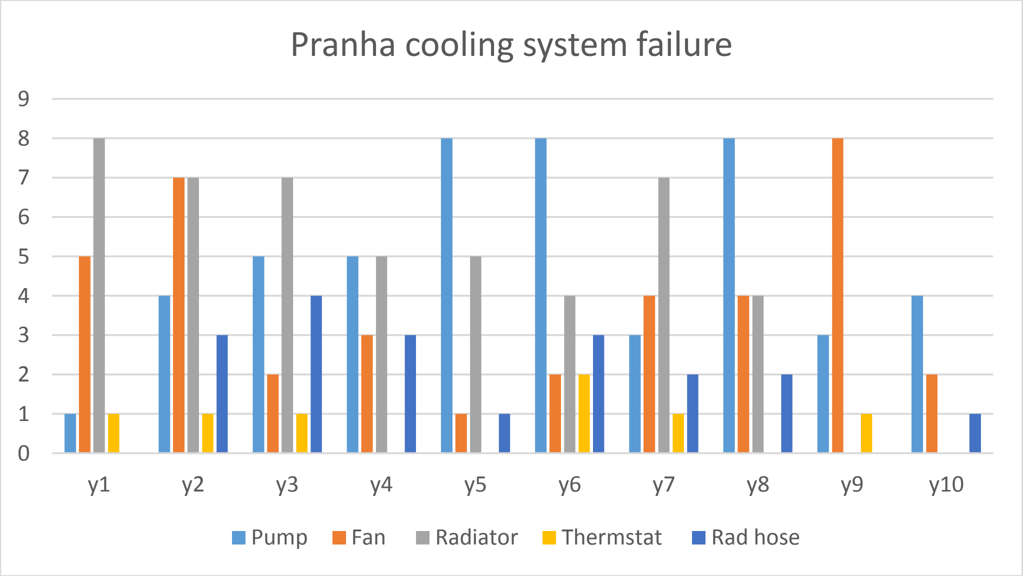


Figure 5.14 Histogram describes the yearly cooling system failure of the Piranha.

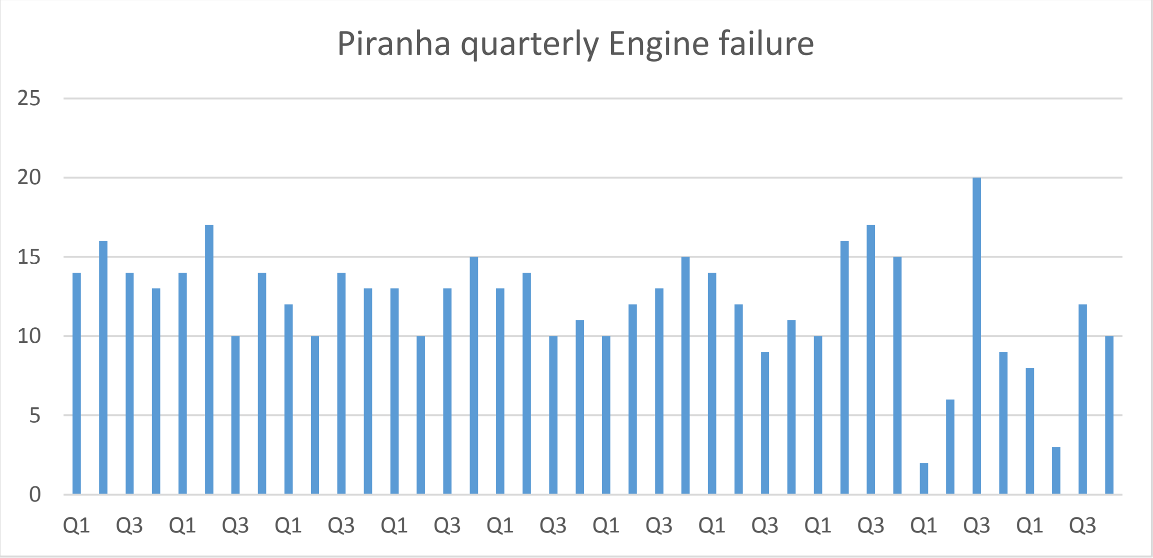


Figure 5.15 Histogram describes the quarterly engine failure of the Piranha.

### 5.5.2.2 Driveline

The failure appeared in the driveline seemed to be normally distributed as expected. However, there are some more failure in some of the sub-units (Steering system) due to the heavy usage during the exercise. And also the leakage in the hydraulic units caused more failures in the sub-units of the driveline.

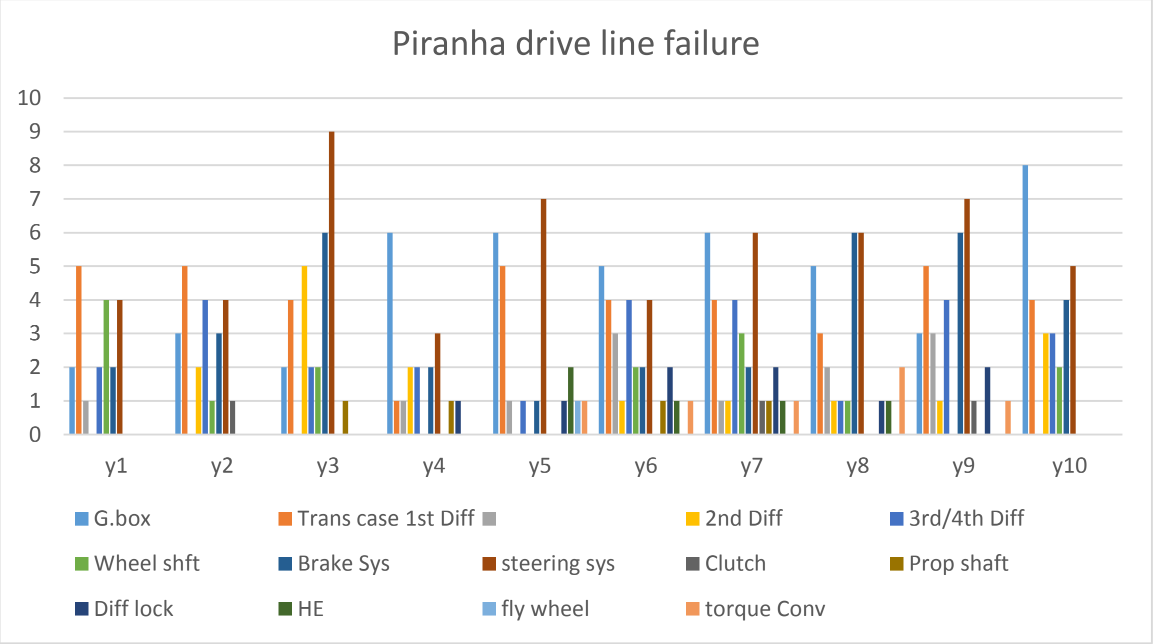


Figure 5.16 Histogram describes the yearly driveline failure of the Piranha.

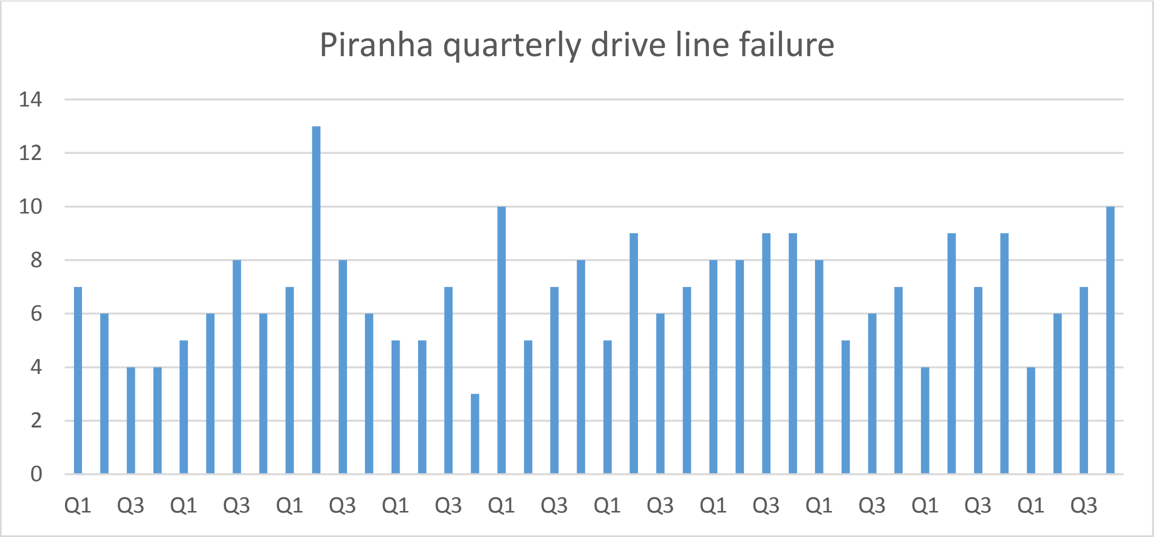


Figure 5.17 Histogram describes the quarterly driveline failure of the Piranha.

### 5.5.2.3 Lubricant system

The failure in the lubricant system seemed to be not normally distributed. The oil pump seemed to have more failure than other sub-units.

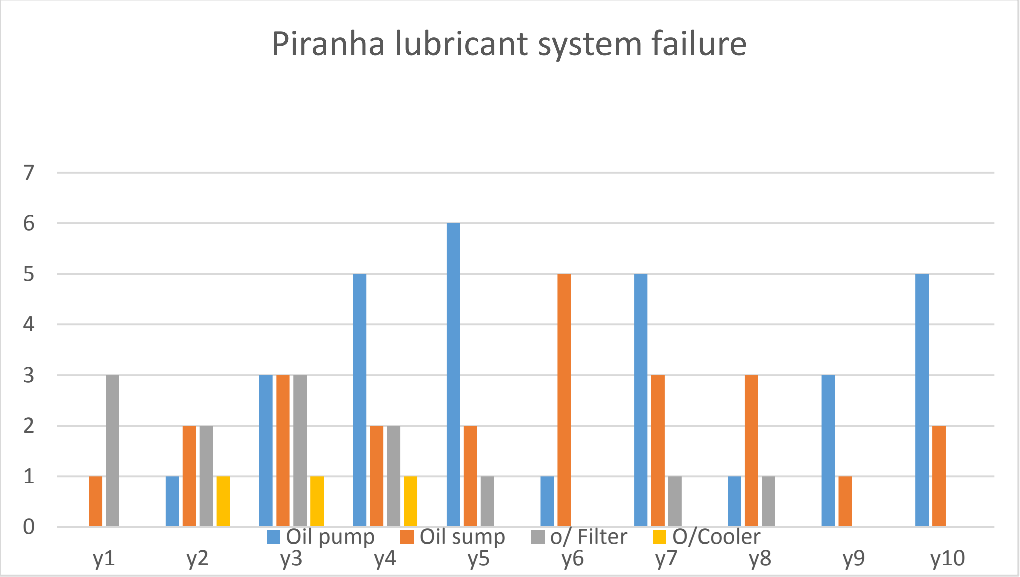


Figure 5.18 Histogram describes the yearly lubricant failure of the Piranha.

Table 5.3 Water pump and oil pump failure history

| No | Vehicle | 2013 | | 2014 | | 2015 | |
|---|---|---|---|---|---|---|---|
| | | water pump | oil pump | water pump | oil pump | water pump | oil pump |
| 1 | MAN | 28 | 47 | 33 | 41 | 43 | 52 |
| 2 | SCORPION | / | / | / | / | / | / |
| 3 | MANTRA | 25 | 19 | 33 | 17 | 28 | 32 |
| 4 | NISSAN | 61 | 23 | 56 | 11 | 72 | 44 |
| 5 | PANHARD | 16 | 5 | 22 | 6 | 19 | 11 |
| 6 | G6 | 2 | 1 | 1 | 1 | 5 | 2 |
| 7 | M60 | **without water pump** | 11 | **without water pump** | 15 | **without water pump** | 21 |

Table 5.3 shows the history of failures in the water and oil pumps for the different military vehicles.

### 5.5.2.4 Electric system

The failure in the electric system seemed to be normally distributed as expected. The AC unit seemed to have more failures compared with other sub-units due to the heavy usage.

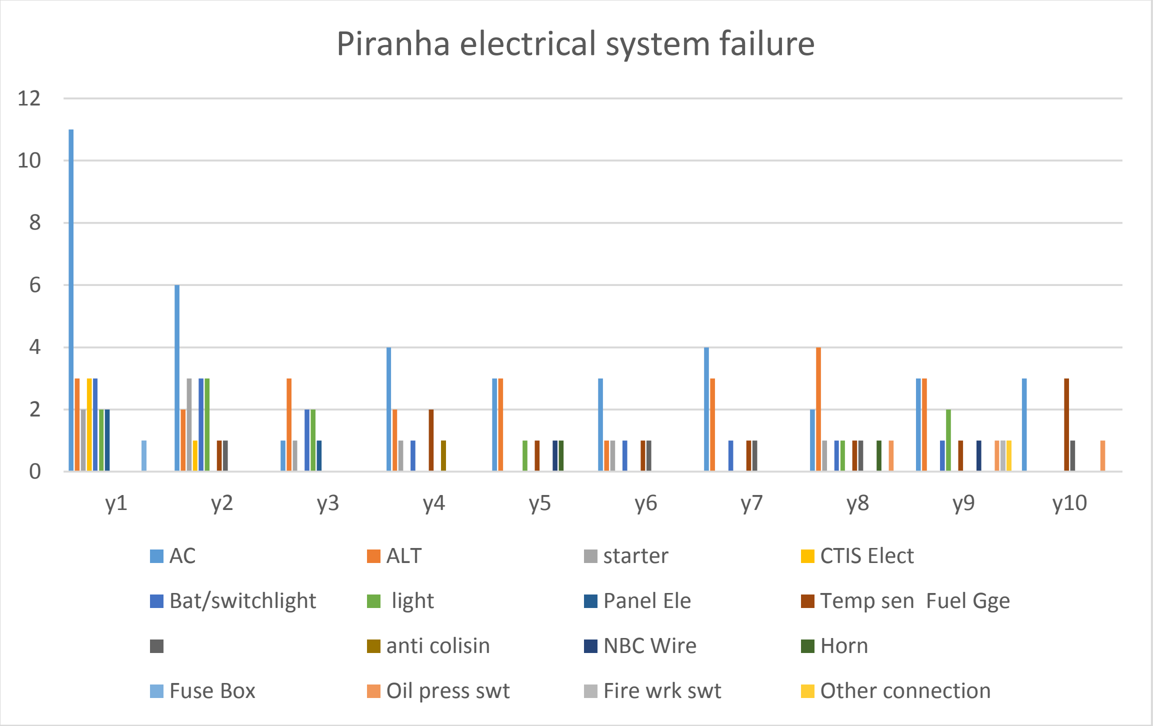


Figure 5.19 Histogram describes the yearly electric failure of the Piranha.

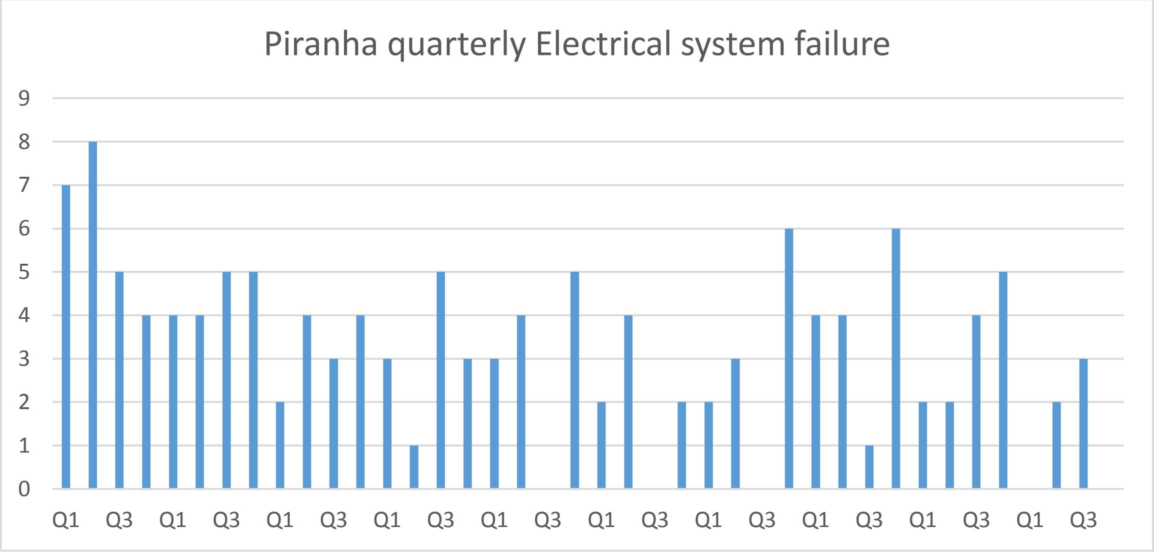


Figure 5.20 Histogram describes the quarterly electric failure of the Piranha.

#### 5.5.2.5 Suspension system

The failure appeared in the suspension system seemed to be not normally distributed as expected. Some sub-units seemed to have more failure than other (Figure 5.21).

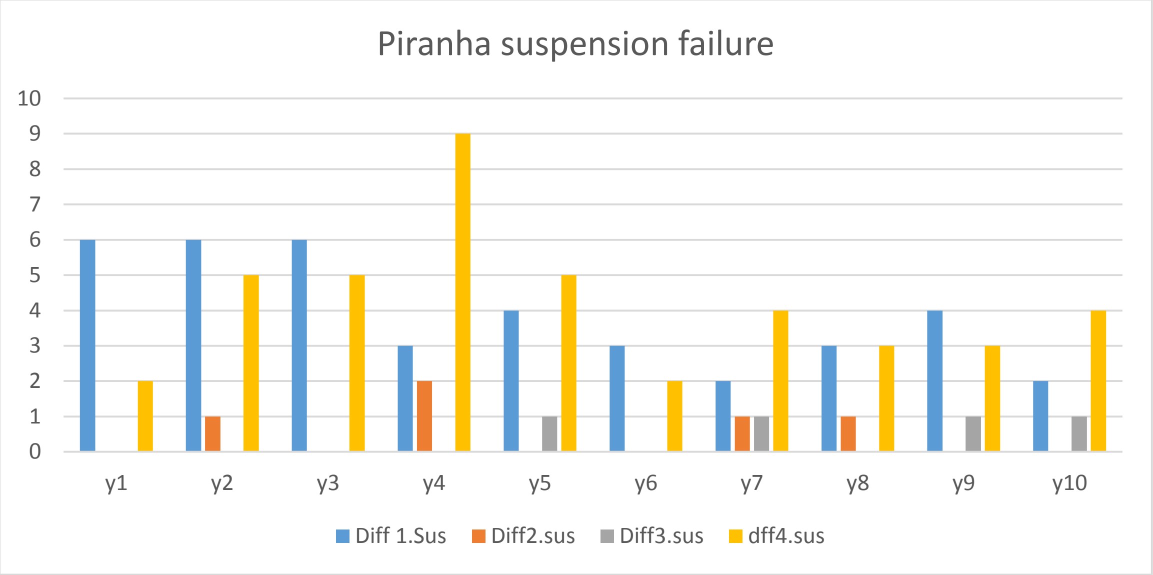


Figure 5.21 Histogram describes the yearly suspension failure of the Piranha.

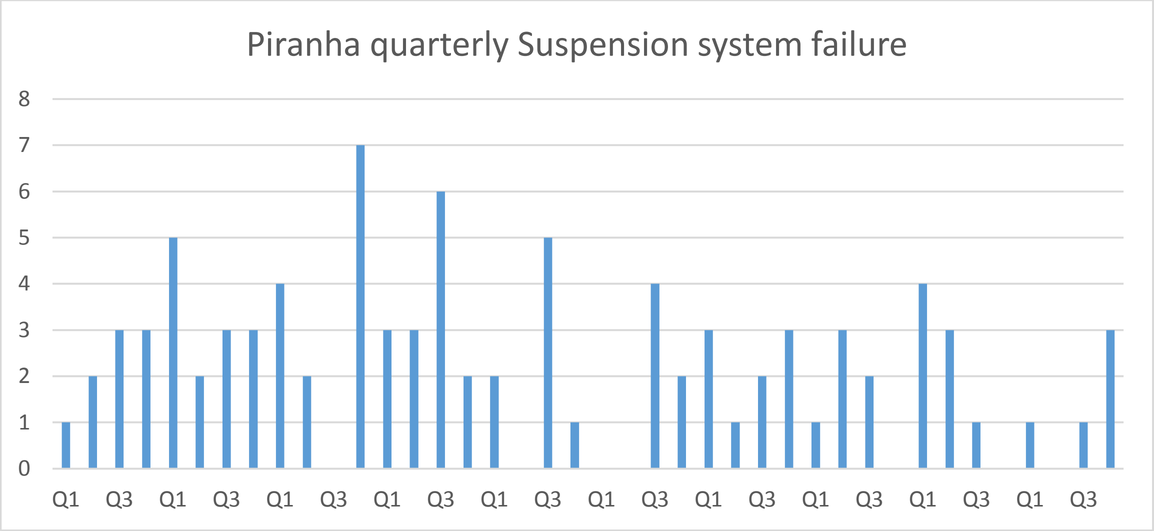


Figure 5.22 Histogram describes the quarterly suspension failure of the Piranha.

### 5.5.2.6 Other parts

The failures in the other parts seemed to be normally distributed. However, there are some more failures in the different small sub-units (Figure 5.23).

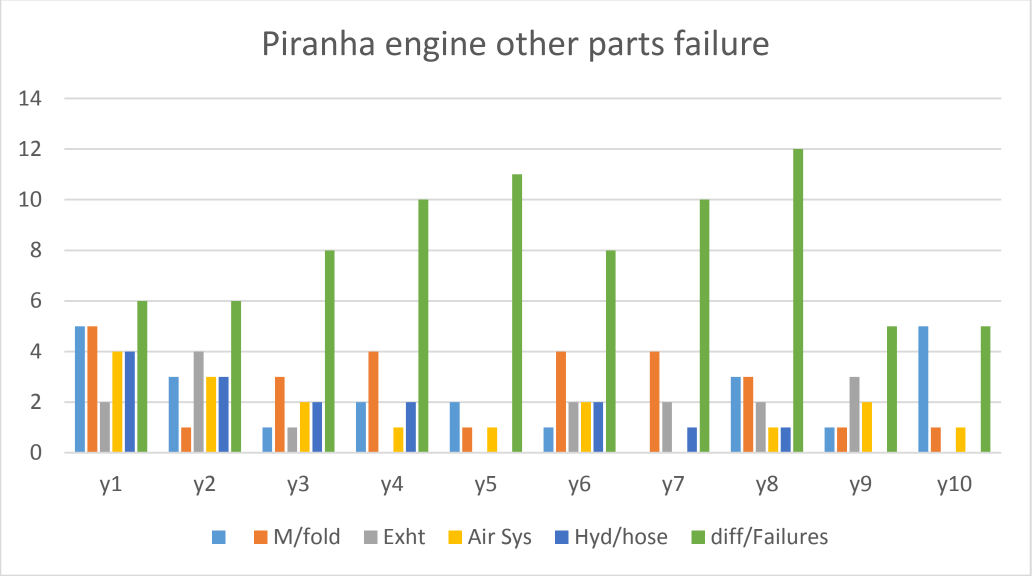


Figure 5.23 Histogram describes the yearly other parts failure of the Piranha.

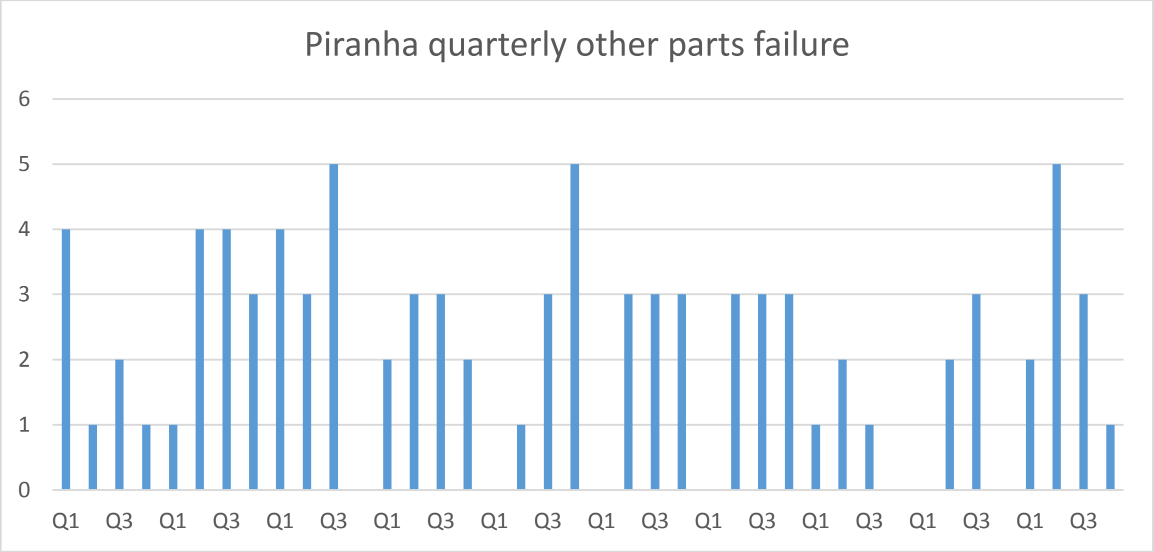


Figure 5.24 Histogram describes the quarterly other parts failure of the Piranha.

### 5.5.3 Operation availability of the vehicles

The operational availability (OA) of the Challenger 2 is calculated using the total time of the vehicle in service divided by the total time (Table 5.4).

Table 5.4 Operational availability of the Challenger 2.

| Tank number | Total period( 10 yrs.)(TS) | Service time in days(TS-DT) | DT in days ( From data table) | OA%(Service time/total period) | DT% | Number of failure | Mean DT |
|---|---|---|---|---|---|---|---|
| 01 | 3650 days | 1849 | 1801 | 51% | 49% | 34 | 53 |
| 02 | 3650 | 1430 | 2220 | 39% | 61% | 28 | 79 |
| 03 | 3650 | 2869 | 781 | 79% | 21% | 32 | 24 |
| 04 | 3650 | 2823 | 827 | 77% | 23% | 27 | 31 |
| 05 | 3650 | 2675 | 975 | 73% | 27% | 31 | 31 |
| 06 | 3650 | 3126 | 524 | 86% | 14% | 32 | 16 |
| 07 | 3650 | 2974 | 676 | 81% | 19% | 28 | 24 |
| 08 | 3650 | 1234 | 2416 | 34% | 66% | 39 | 62 |
| 09 | 3650 | 3087 | 563 | 85% | 15% | 34 | 17 |
| 10 | 3650 | 1631 | 2019 | 45% | 55% | 52 | 39 |
| 11 | 3650 | 2779 | 871 | 76% | 24% | 47 | 19 |
| 12 | 3650 | 2655 | 995 | 73% | 27% | 38 | 26 |
| 13 | 3650 | 2324 | 1326 | 64% | 36% | 41 | 32 |
| 14 | 3650 | 2910 | 740 | 80% | 20% | 33 | 22 |
| 15 | 3650 | 1793 | 1857 | 49% | 51% | 34 | 55 |
| 16 | 3650 | 2302 | 1348 | 63% | 37% | 41 | 33 |
| 17 | 3650 | 2667 | 983 | 73% | 27% | 44 | 22 |
| 18 | 3650 | 2128 | 1522 | 58% | 42% | 45 | 34 |
| 19 | 3650 | 2416 | 1234 | 66% | 34% | 45 | 27 |
| 20 | 3650 | 1879 | 1771 | 51% | 49% | 43 | 39 |

The operational availability (OA) of the Piranha is calculated using the total time of the vehicle in service divided by the total time (Table 5.5).

Table 5.5 Operational availability of the Piranha.

| Vehicle number | Total period 10 years(T) | Service Time in days(T-DT) | DT in days | OA% | DT% |
|---|---|---|---|---|---|
| 01 | 3650 | 3034 | 616 | 83% | 17% |
| 02 | 3650 | 3041 | 609 | 85% | 15% |
| 03 | 3650 | 2823 | 827 | 77% | 23% |
| 04 | 3650 | 3096 | 554 | 85% | 15% |
| 05 | 3650 | 3035 | 615 | 83% | 17% |
| 06 | 3650 | 2902 | 748 | 80% | 20% |
| 07 | 3650 | 3248 | 402 | 89% | 11% |
| 08 | 3650 | 3030 | 620 | 83% | 17% |
| 09 | 3650 | 2971 | 679 | 81% | 19% |
| 10 | 3650 | 3032 | 618 | 83% | 17% |

| | | | | | |
|---|---|---|---|---|---|
| 11 | 3650 | 2788 | 862 | 76% | 24% |
| 12 | 3650 | 2861 | 789 | 78.3% | 21.7% |
| 13 | 3650 | 2854 | 796 | 78% | 22% |
| 14 | 3650 | 2935 | 715 | 80% | 20% |
| 15 | 3650 | 2811 | 839 | 77% | 23% |
| 16 | 3650 | 3106 | 544 | 85% | 15% |
| 17 | 3650 | 2905 | 745 | 79% | 21% |
| 18 | 3650 | 2848 | 802 | 78% | 22% |
| 19 | 3650 | 3002 | 648 | 82% | 18% |
| 20 | 3650 | 2856 | 794 | 78% | 22% |
| 21 | 3650 | 2768 | 882 | 76% | 24% |
| 22 | 3650 | 2758 | 892 | 75% | 25% |
| 23 | 3650 | 2577 | 1073 | 71% | 29% |
| 24 | 3650 | 2923 | 727 | 80% | 20% |
| 25 | 3650 | 2719 | 931 | 74% | 26% |
| 26 | 3650 | 3150 | 500 | 86% | 14% |
| 27 | 3650 | 3036 | 614 | 83% | 17% |
| 28 | 3650 | 3196 | 454 | 87% | 13% |
| 29 | 3650 | 3013 | 637 | 82% | 18% |
| 30 | 3650 | 3131 | 519 | 85% | 15% |
| 31 | 3650 | 3113 | 537 | 85% | 15% |
| 32 | 3650 | 3143 | 507 | 86% | 14% |
| 33 | 3650 | 3177 | 473 | 87% | 13% |
| 34 | 3650 | 3082 | 568 | 84% | 16% |
| 35 | 3650 | 3170 | 480 | 86% | 14% |
| 36 | 3650 | 3105 | 545 | 85% | 15% |
| 37 | 3650 | 2802 | 848 | 76% | 24% |
| 38 | 3650 | 2985 | 665 | 81% | 19% |
| 39 | 3650 | 3006 | 644 | 82% | 18% |
| 40 | 3650 | 2951 | 699 | 80% | 20% |

## 5.6 Discussion

### 5.6.1 The most affected part in Challenger 2

The results from the case study of the history of failure mechanism in Challenger 2 showed that cooling system, lubrication system and suspension systems are the most affected systems in Challenger 2 during the operation and training. The cause for these failure is speculated using several factors such as adverse environmental condition, heavy usage during training and the lack of skilled technicians. Consequences of these sub-system failure results in the failure of engine as a whole and lead to a massive repairing cost and delaying time as described in Table 5.6.

Table 5.6 Main failure repairing time and the cost details

| Part | Cost(£)/ unit | Repair Time |
|---|---|---|
| Engine | 85000 | At least 1 year (UK) |
| Water Pump | 2640 | 10- 20 days |
| Oil pump | 9000 | 4-10 days |
| Radiator repair | 180 | 3-5 days |
| Radiator hose | 490 | About 13 days waiting and repair |

The failure of water pump, oil pump, radiator and radiator hose would not cause higher price for repairing or replace, however, these failures lead to the catastrophic failure of the engine due to the over-heat and thus cost high price. If the failure in these sub-units can be prevented, then failure of the engine also will be prevented and the high cost for the repairing or replacement of the engine can be prevented. Table 5.7. The electrical system and driveline are less affected system compared with other sub-systems mentioned above.

Table 5.7 The Tank challenger 2 items sent to the UK for overhauling in a period of 10 years.

| NO | Component | Total Component | Time needs to return to Oman(day) | Total cost (£) |
|---|---|---|---|---|
| 1 | Engine | 5 | 210-300 | 286000 |
| 2 | Gear box | 8 | 180-300 | 7500,502,000 |
| 3 | GRLF | 9 | 210- 270 | 159,000 |
| 4 | LRF | 1 | 270 | 85,000 |
| 5 | CDU | 2 | 210 | 39,000 |
| 6 | Thermal imager | 6 | 150-270 | 104,4000 |
| 7 | Telescope CPS | 1 | 180 | 17,500 |
| 8 | GPS+CPS | 2 | 180-300 | 47,500 |
| 9 | Navigation system | 1 | 210 | 14,000 |
| 10 | Steering Unit | 1 | 230 | 35,000 |

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### 5.6.2 The most affected part in Piranha

The results from the case study of the history of failure mechanism in Piranha showed that cooling system, lubrication system and suspension systems are the most affected systems in Piranha during the operation and training. The cause for these failures are speculated using several factors such as adverse environmental condition, heavy usage during training and the lack of skilled technicians. Consequences of these sub-system failures result in the failure of engine as a whole and lead to a massive repairing cost and delaying in time.

### 5.6.3 Effect of cost and time for repairing the failure parts

The cost and time for repairing the sub systems are very low, though they have a frequent failure. However, the careless handling of these failures lead to a catastrophic engine failure and hence result in massive repairing cost and the time delay**.**

### 5.6.4 Comparison of failure between Challenger 2 and Piranha

The failure mechanisms in both vehicles showed similar pattern where the similar sub-systems were failed frequently in both vehicles. However, the failures occurred in the Piranha are less frequent compared with Challenger 2.

## 5.7 Conclusion

The study showed that most affected parts in Challenger 2 and Piranha are cooling system, lubrication system and the suspension system. The failure to monitor these systems leads to a catastrophic failure of engine and hence cause massive cost and the time delay. Based on these findings, the cooling system, lubrication system and the suspension system are selected as the model systems to design and develop a HUMS system to diagnose the failures in the military vehicles, e.g. Land Rover 110.

# Chapter 6

# Investigation of effective lab testing mechanism to identify the failure of military vehicle suspension system

## 6.1 Introduction

The vehicle suspension systems have been designed to maintain contact between a vehicle's tyres and the road, and to isolate the frame of the vehicle from the harmful vibration that comes from the road to keep the vehicle and the crew safe. The suspension systems work by incorporating with other sub-systems of the vehicle such as tyres, wheels, braking system, steering systems to provide the safety and ride comfort. The main functions of the suspension systems include, support the weight of the vehicle, wheel alignment, keep the tyres in firm contact with the road, provide comfortable ride and etc.

Shock absorbers parallel with springs are widely used to damp out the oscillation that comes from the road by absorbing the energy. A shock absorber is one of the most important elements in a vehicle suspension system. The shock absorbers provide better handling, comfort, and safety while driving a vehicle by controlling the damping of the relative movement between the wheel and the vehicle body. The shock absorbers are designed to ensure the durability of other parts of the vehicle body. The shock absorbers are the crucial elements in the vehicle to provide the ride comfort of the crew to ensure the health and the safety of the crew.

In the context of the military vehicle, the performance of the military crew inside the vehicle is important as it has specified tasks, hence the isolation of vibration coming from the road to the vehicle body is crucial which can only be achieved by applying efficient suspension system to the vehicle. The failure of suspension system causes catastrophic damage to the crew and the weapon systems installed in the vehicle. The speed of the vehicle proportionally increases the error in the accuracy of the target point of the weapon systems used in the vehicle, because if the suspension system fails to damp out the excessive vibration coming from the high speed operating military vehicle which then cause the weapons and crew to vibrate. Thus the accurate operation of the weapons mounted on the military vehicle and the health of the crew are obtained only via healthy suspension systems.

## 6.2 Methodology

The experimental study is conducted on the Land Rover Defender 110 military truck using a four-poster hydraulic shaker system to examine the dynamic behaviour of the suspension system pertinent to failure. Band limited random excitation with two different excitation magnitudes was applied on the four shaker tables in the vertical (z-axis) direction of the vehicle and response accelerations on the vertical direction (z-axis) on top of the shaker table, on the axle, on top of the suspension system, on the centre of gravity of the vehicle and on top of the vehicle seat were measured. The two types of dampers, healthy and faulty, were tested with the vehicle to examine the effect of failure on the frequency response of the suspension systems. The measured time histories, i.e. the base excitation acceleration and the resultant in-line accelerations measured on top of the axle, suspension system, centre of gravity and the seat were processed and transformed into frequency response functions (FRFs), transmissibility.

### 6.2.1 Apparatus

The Land Rover Defender 110 military truck was instrumented with the accelerometers and put on top of the four-poster hydraulic shaker system (see Figure 6.1). The vertical motion is produced using four hydraulic shakers. The specifications of the hydraulic shakers, accelerometers and other experimental equipment were described in Sections 3.2.1.1 to 3.2.1.9 in Chapter 3.

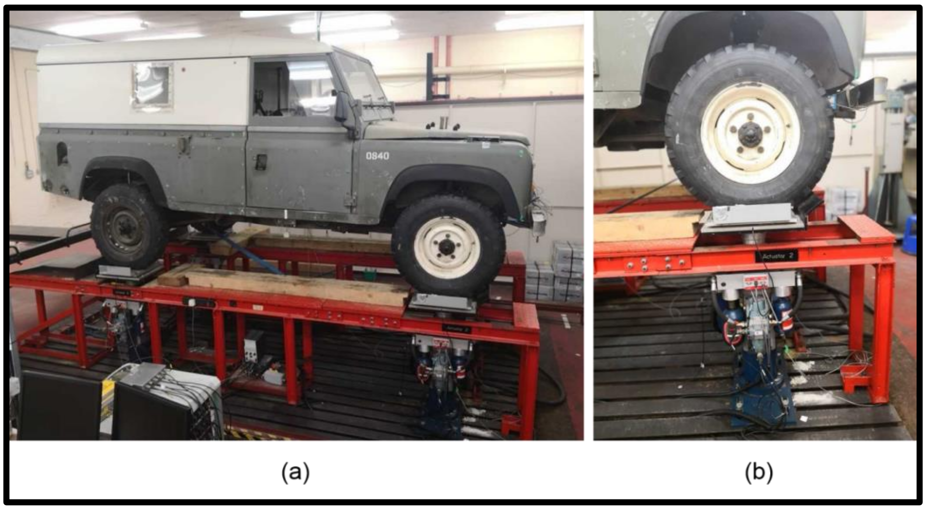

Figure 6.1 Photographic representation of the experimental setup: equipment and setup showing the Land Rover 110 military truck sits on top of the four-poster hydraulic shaker system (a) and the view of single wheel station (b).

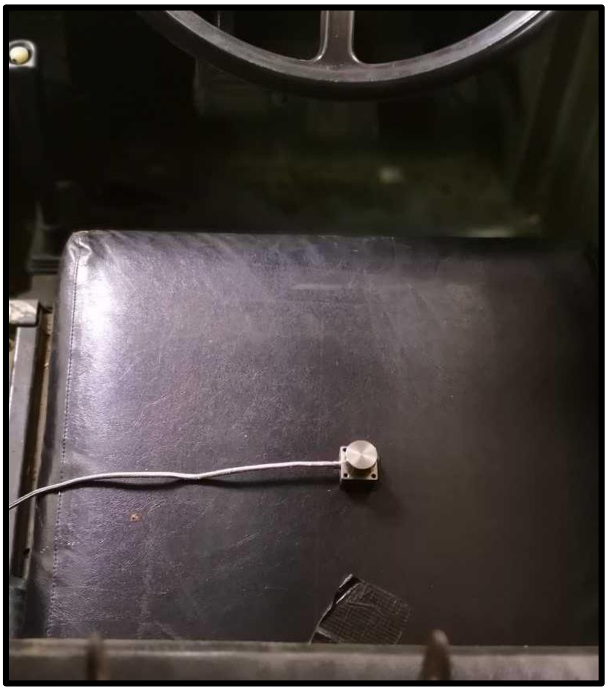

Figure 6.2 Photograph of the mounted accelerometer on the driver seat to measure the acceleration at the driver seat.

An accelerometer was rigidly mounted on top of the driver seat to measure the acceleration transmitted to the seat from the base input. The measured acceleration was used to evaluate the human vibration health and comfort exposure limits – the detail discussion around this evaluation is given in the Section 6.4. The ISO 2631 standard procedure was followed for this measurement and analysis [61, 62].

### 6.2.2 Stimuli

The instrumented Land Rover 110 military truck was exposed to vertical (z-axis) band limited random vibration at 0.5 to 20 Hz, at two vibration magnitudes. (Figure 6.3). The time history of the input base acceleration and the response accelerations on top of the axle, suspension system, centre of gravity and the seat have same duration of 43 seconds. The time histories of input in z- axis and response in z- axis accelerations are shown as an example in Figure 6.3 - two magnitudes were chosen to show respective time histories.

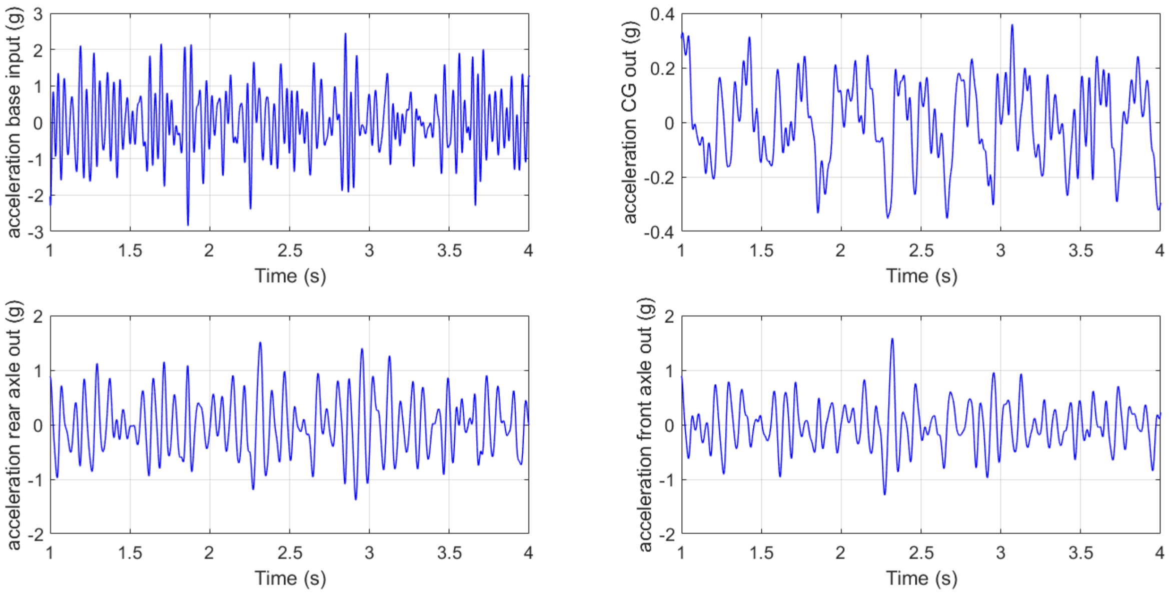

Figure 6.3 Example time histories of the input base excitation acceleration and the output accelerations on top of the front- and rear-axle and centre of gravity – healthy damper was used in the test.

The power spectral density functions (PSDs) of above shown time histories were calculated and shown Figure 6.4.

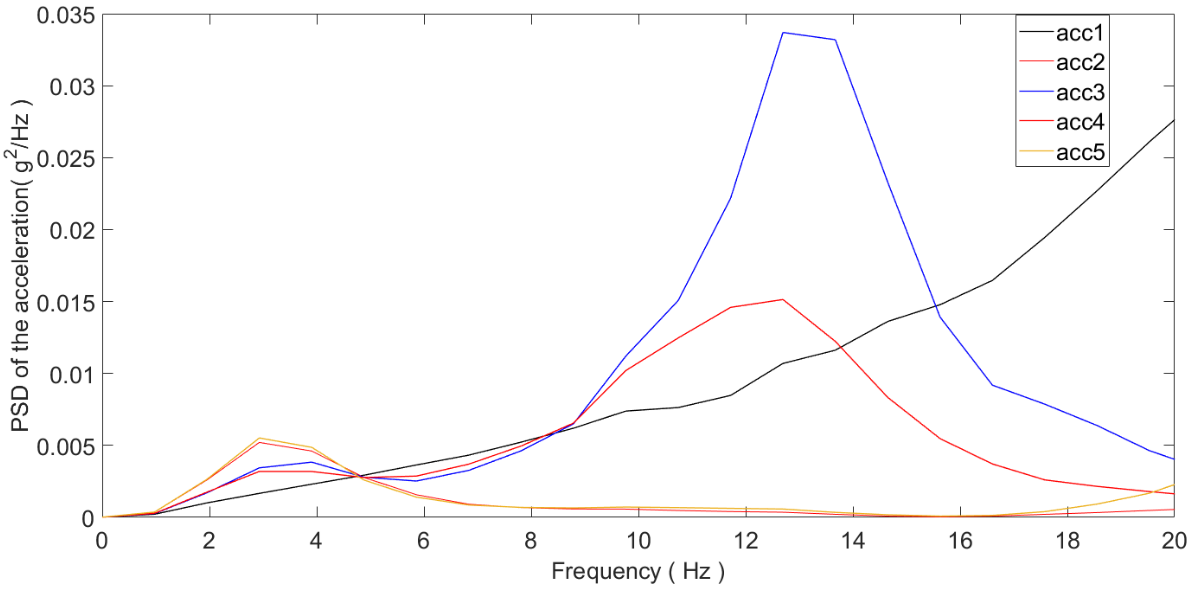

Figure 6.4 Example PSDs (Power Spectral Density) of the above shown time histories: acc1- PSD of the acceleration at the base, acc2- PSD of the acceleration at the CG, acc3- PSD of the acceleration at the rear axle, acc4- PSD of the acceleration at the front axle and acc5- PSD of the acceleration at the seat.

The time histories of sinusoidal sweep input excitation in z- axis and response in z-axis accelerations are shown as an example in Figure 6.5. The power spectral density functions (PSDs) of the following time histories were calculated and shown Figure 6.6.

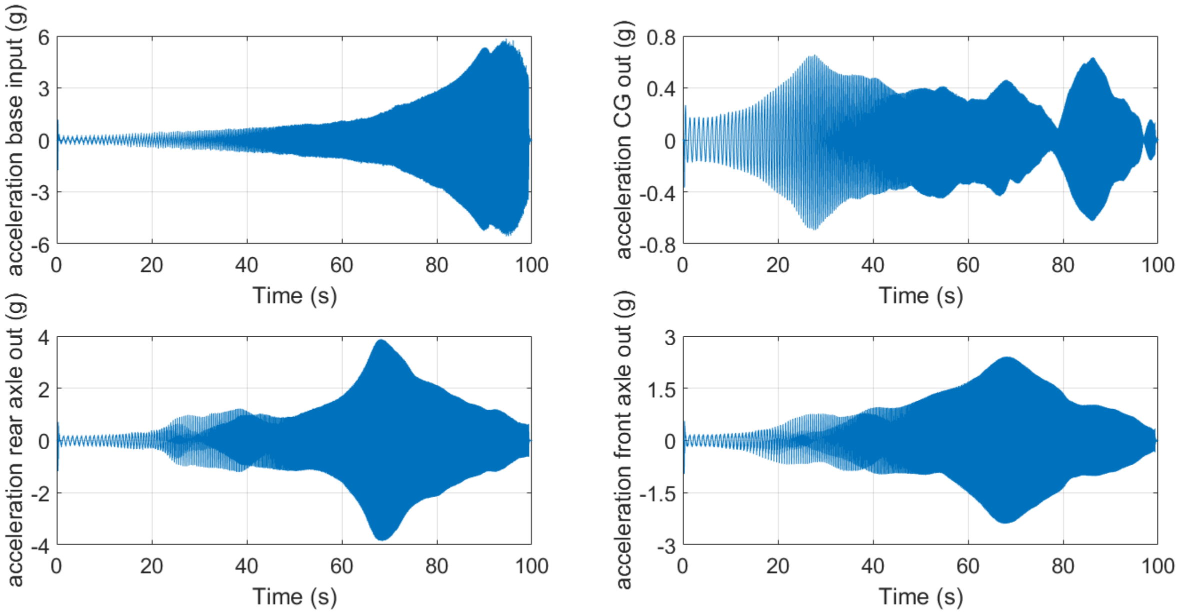

Figure 6.5 Example time histories (sinusoidal sweep) of the input base excitation acceleration and the output accelerations on top of the front- and rear-axle, and centre of gravity (CG) and the seat - healthy damper was used in the test.

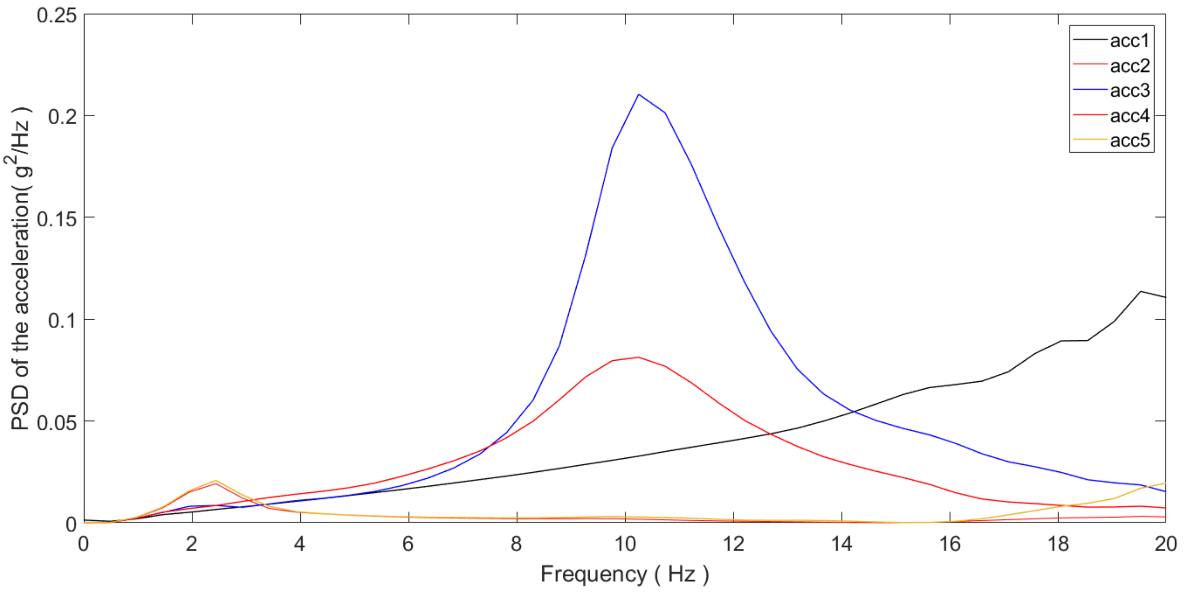

Figure 6.6 Example PSDs (Power Spectral Density) of the above shown time histories: acc1- PSD of the acceleration at the base, acc2- PSD of the acceleration at the CG, acc3- PSD of the acceleration at the rear axle, acc4- PSD of the acceleration at the front axle and acc5- PSD of the acceleration at the seat.

### 6.2.3 Analysis

The five channels of accelerations, one-input and four-output, time histories were sampled simultaneously at 1000 Hz with duration of 43 seconds with a working frequency range of 0.5 to 20 Hz. The time histories were then transformed to cross spectral density functions (CSDs), power spectral density functions (PSDs) and ordinary FRFs by applying a Fast Fourier Transform (FFT). The CSDs and PSDs were estimated via Welch's method at frequencies between 0.5 and 20 Hz. The FRFs for each of 43-seconds continuous random signals used a FFT windowing length of 1024 samples, a Hamming window with 50% overlap, a sampling rate of 1000 Hz and an ensuing frequency resolution of 0.9 Hz (Table 6.1). The 0.9-Hz procedure was used to give a higher confidence level with 168 degrees of freedom at each frequency.

Table 6.1 Signal processing procedure used to calculate the transmissibility between base and on top of the axle and suspension system.

| Excitation frequency (Hz) | Duration (s) | Sample per second | FFT length | Degrees of freedom | Windowing overlap | Frequency resolution (Hz) |
|---|---|---|---|---|---|---|
| 0.5 to 20 | 43 | 1000 | 1024 | 168 | Hamming<br>50% | 0.9 |

The complex transmissibility was first computed from the time histories using CSD method:

$$H_T(f) = G_{\ddot{Z}\ddot{Z}_0}(f) \ / \ G_{\ddot{Z}_0\ddot{Z}_0}(f) \qquad (6.1)$$

where $H_T(f)$ is the transmissibility, $f$ is the excitation frequency in Hz, $G_{\ddot{Z}\ddot{Z}_0}(f)$ is the CSD between the resultant acceleration of axle and suspension system ($\ddot{Z}$) in m/s$^2$ and the input base excitation acceleration ($\ddot{Z}_0$) in m/s$^2$, $G_{\ddot{Z}_0\ddot{Z}_0}(f)$ is the PSD of the input base excitation acceleration.

The properties of the frequency response function (i.e. resonance frequency and the magnitude) were used to identify the dynamic behaviour of the faulty damper.

## 6.3 Results

The two dampers, one healthy and the other faulty, were fixed to the Land Rover vehicle one by one and the corresponding frequency response function were measured. First, the suspension system with healthy damper was tested with two different excitation magnitudes for the evaluation of the frequency response function – two magnitudes of excitation were used to evaluate the effect of vibration magnitude on the frequency response function. Then, the suspension system with faulty damper was tested with two different excitation magnitudes for the evaluation of the frequency response function – two magnitudes of excitation were used to evaluate the effect of vibration magnitude on the frequency response function. The properties of the frequency response function (i.e. resonance frequency and the magnitude) were used in the analysis to evaluate the fault detection in the suspension system. The following sections explain the result and provides the constructive discussion and the conclusion of this work.

### 6.3.1 Frequency response of the healthy suspension system

The frequency response function, transmissibility (modulus and phase), of the healthy suspension system, between the base and the centre of gravity (T1), between the base and the front axle (T2), between the base and the rear axle (T3), and between the base and the seat (T4), were calculated to evaluate the frequency response of the vehicle suspension system.

Firstly, the frequency response of the healthy damper was examined. The key resonance frequencies, body mode around 2.5 Hz and the axle mode at around 11 Hz were observed (see Figure 6.7). The random vibration excitation with two different excitation magnitude were used, one with low (see Figure 6.7) and other with high (see Figure 6.8).

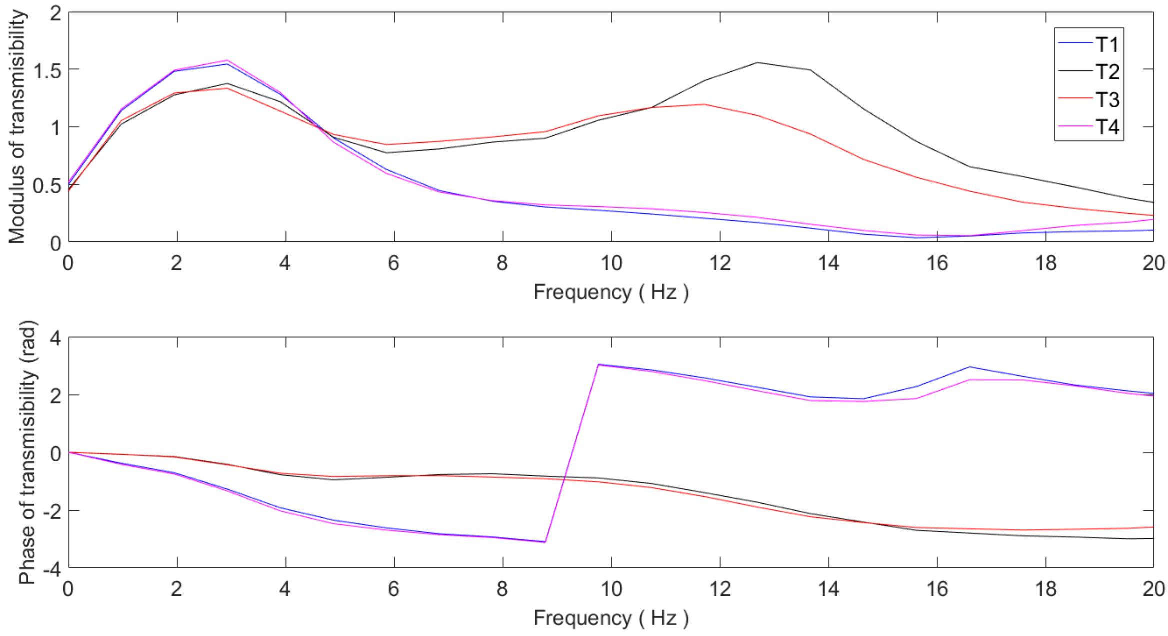

Figure 6.7 Modulus (top) and phase (bottom) of the transmissibility of the healthy suspension system with random input excitation with low vibration magnitude: Transmissibility between the base and the centre of gravity (T1), between the base and the front axle (T2), between the base and the rear axle (T3), and between the base and the seat (T4).

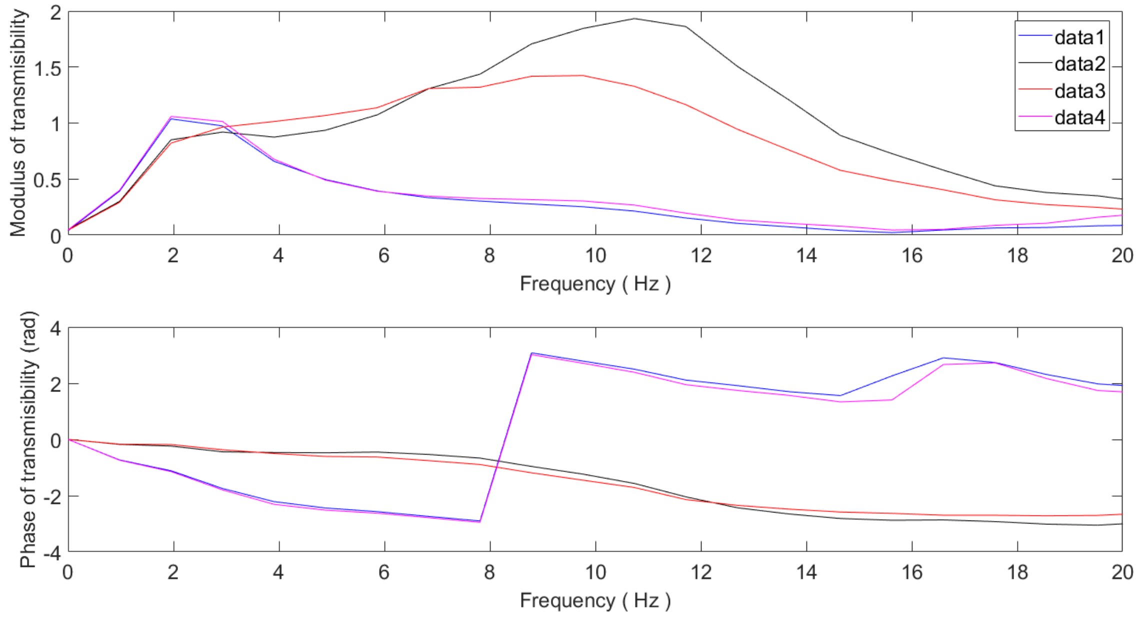

Figure 6.8 Modulus (top) and phase (bottom) of the transmissibility of the healthy suspension system with random input excitation with high vibration magnitude: Transmissibility between the base and the centre of gravity (data1), between the base and the front axle (data2), between the base and the rear axle (data3), and between the base and the seat (data4).

Secondly, the healthy damper was exposed to sinusoidal sweep excitation to examine the frequency response (see Figure 6.9). The key resonance frequencies of the vehicle remain same with the sinusoidal sweep excitation.

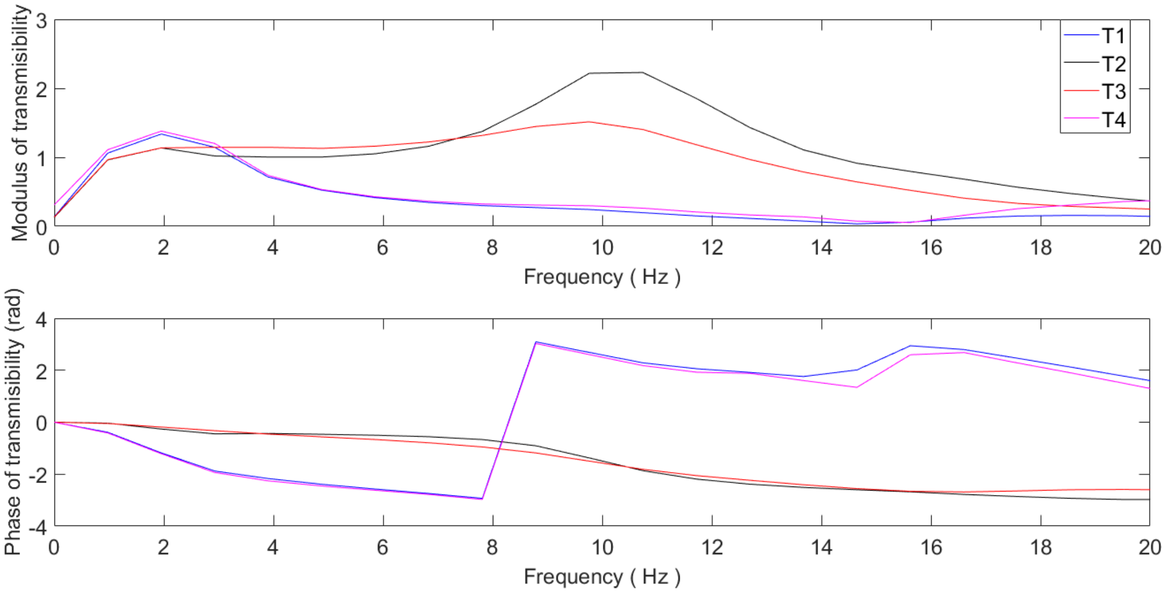

Figure 6.9 Modulus (top) and phase (bottom) of the transmissibility of the healthy suspension system with sinusoidal sweep input excitation: Transmissibility between the base and the centre of gravity (T1), between the base and the front axle (T2), between the base and the rear axle (T3), and between the base and the seat (T4).

### 6.3.2 Frequency response of the faulty suspension system

The frequency response of the faulty damper was examined. Firstly, the faulty damper was fixed to the front suspension system of the vehicle and the frequency response was examined using the random excitation with three different vibration magnitudes. The key resonance frequencies, body mode around 2.4 Hz and the axle mode at around 10 Hz were observed (see Figure 6.10). There is small reduction in the resonance frequency when the faulty damper was fixed to the vehicle, however the reduction was not very significant. The random vibration excitation with three different excitation magnitude were used, one with low (see Figure 6.10), one with medium (see Figure 6.11) and other with high (see Figure 6.12).

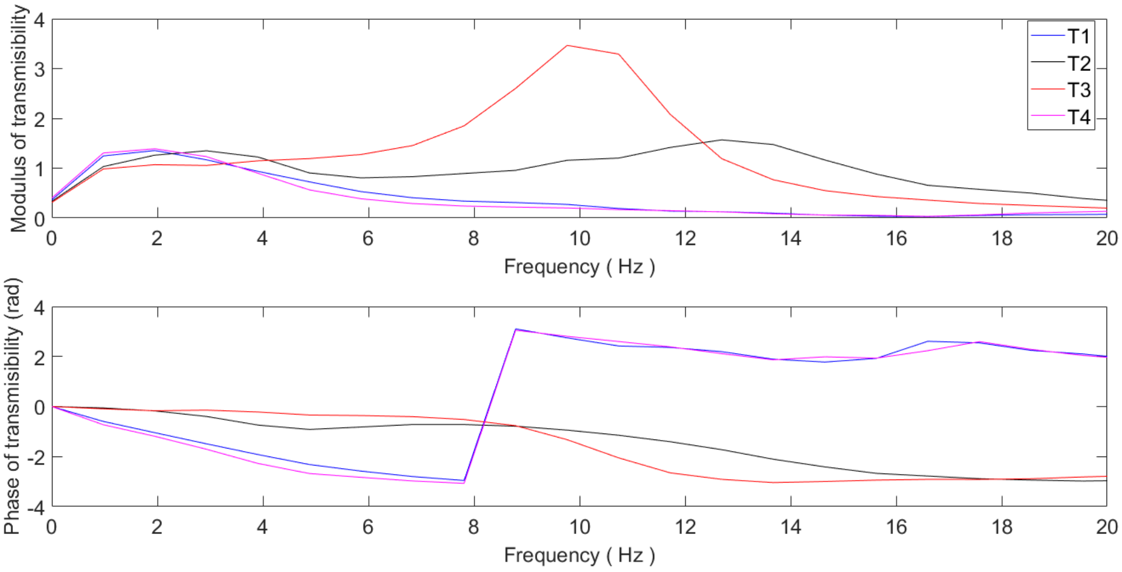

Figure 6.10 Modulus (top) and phase (bottom) of the transmissibility of the faulty suspension system with random input excitation with low vibration magnitude: Transmissibility between the base and the centre of gravity (T1), between the base and the front axle (T2), between the base and the rear axle (T3), and between the base and the seat (T4).

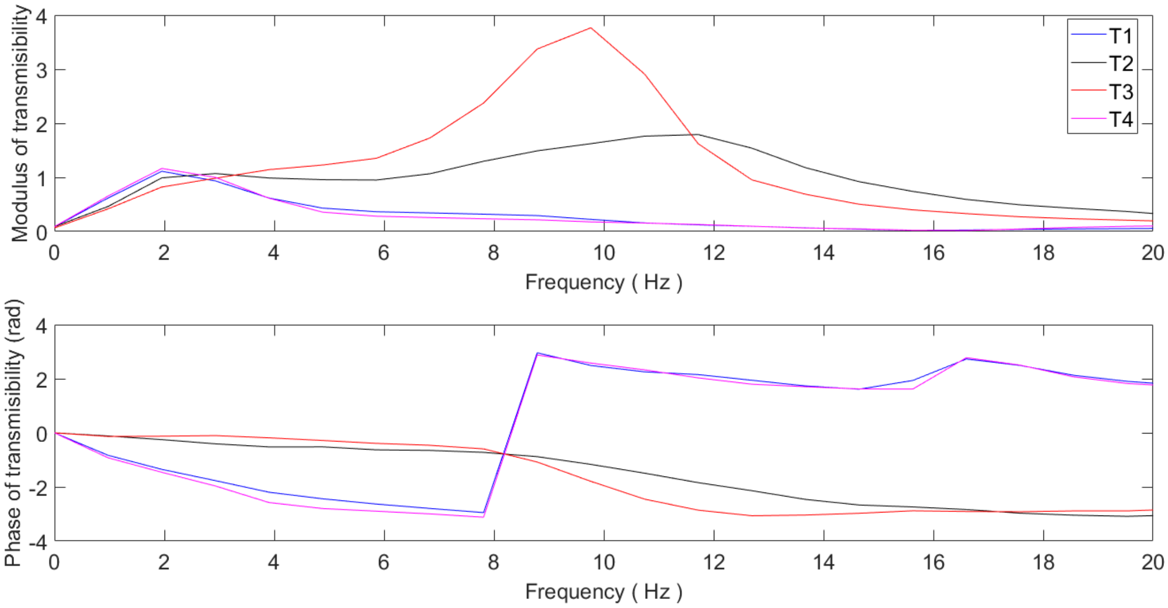

Figure 6.11 Modulus (top) and phase (bottom) of the transmissibility of the faulty suspension system with random input excitation with medium vibration magnitude: Transmissibility between the base and the centre of gravity (T1), between the base and the front axle (T2), between the base and the rear axle (T3), and between the base and the seat (T4).

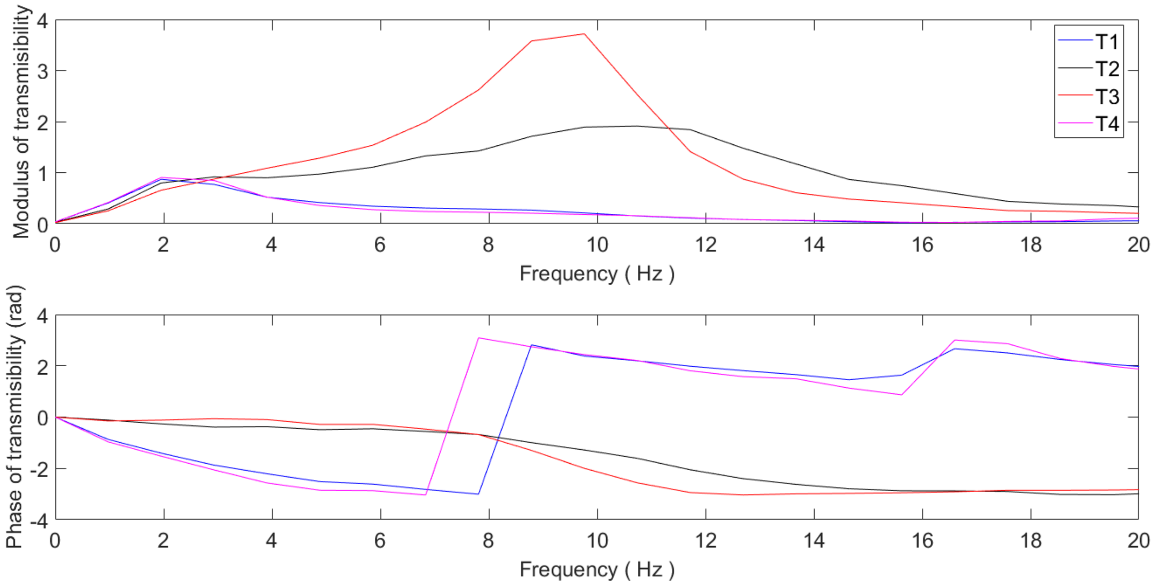

Figure 6.12 Modulus (top) and phase (bottom) of the transmissibility of the faulty suspension system with random input excitation with high vibration magnitude: Transmissibility between the base and the centre of gravity (T1), between the base and the front axle (T2), between the base and the rear axle (T3), and between the base and the seat (T4).

Secondly, the faulty damper was exposed to sinusoidal sweep excitation to examine the frequency response (see Figure 6.13). The key resonance frequencies of the vehicle remain almost same with the sinusoidal sweep excitation.

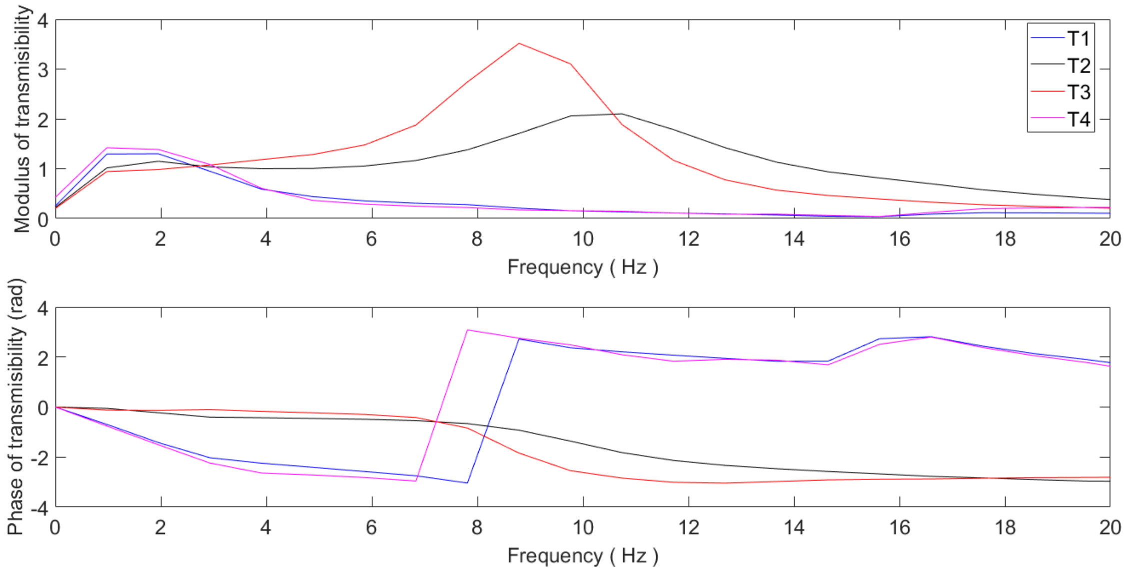

Figure 6.13 Modulus (top) and phase (bottom) of the transmissibility of the faulty suspension system with sinusoidal sweep input excitation (faulty damper is fixed to the front axle): Transmissibility between the base and the centre of gravity (T1), between the base and the front axle (T2), between the base and the rear axle (T3), and between the base and the seat (T4).

### 6.3.3 Effect of magnitude of excitation

The frequency response of the suspension system with different vibration magnitudes were examined to evaluate the effect of vibration magnitude.

Firstly, the healthy damper was fixed to the suspension system and the frequency response function was measured using the random excitation with two different vibration excitation (see Figure 6.14). As expected, there is no reduction in the resonance frequency when the healthy damper was fixed to the vehicle.

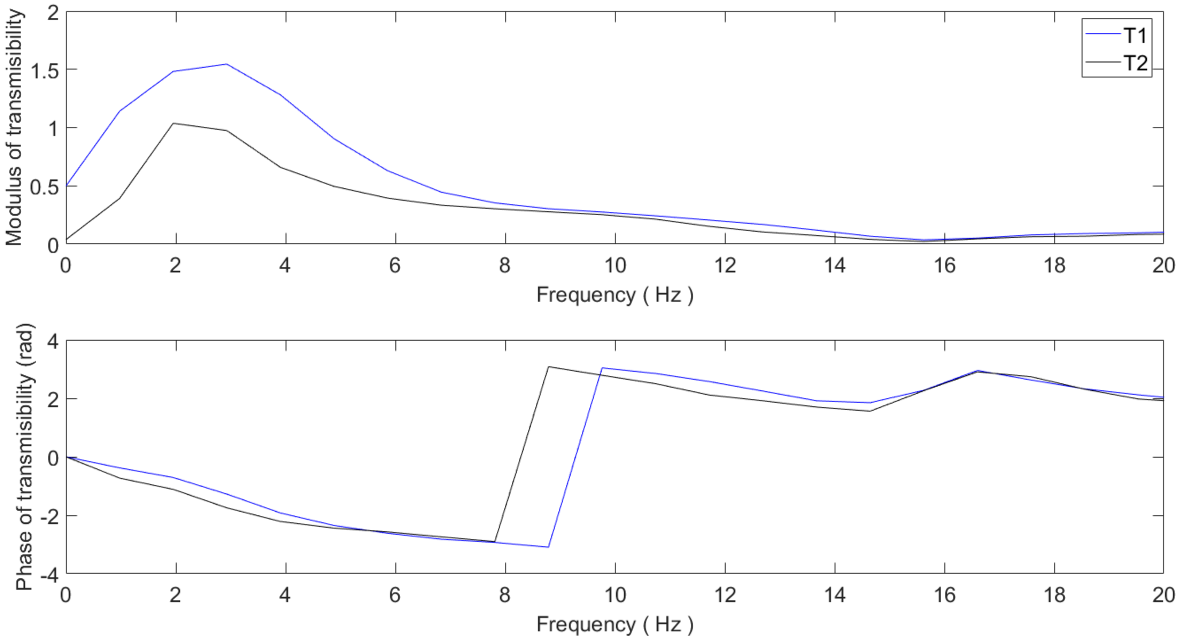

Figure 6.14 Modulus (top) and phase (bottom) of the transmissibility between the base and the CG for the suspension system with healthy damper exposed to random input excitation with two different magnitudes: excitation with low vibration magnitude (T2 and excitation with high vibration magnitude T1).

Secondly, the faulty damper was fixed to the front suspension system and the frequency response function was measured using the random excitation with three different vibration excitation (see Figure 6.15). There is no reduction in the resonance frequency when the healthy damper was fixed to the vehicle. However, as expected, magnitude of the transmissibility increases with the increase in the excitation magnitude.

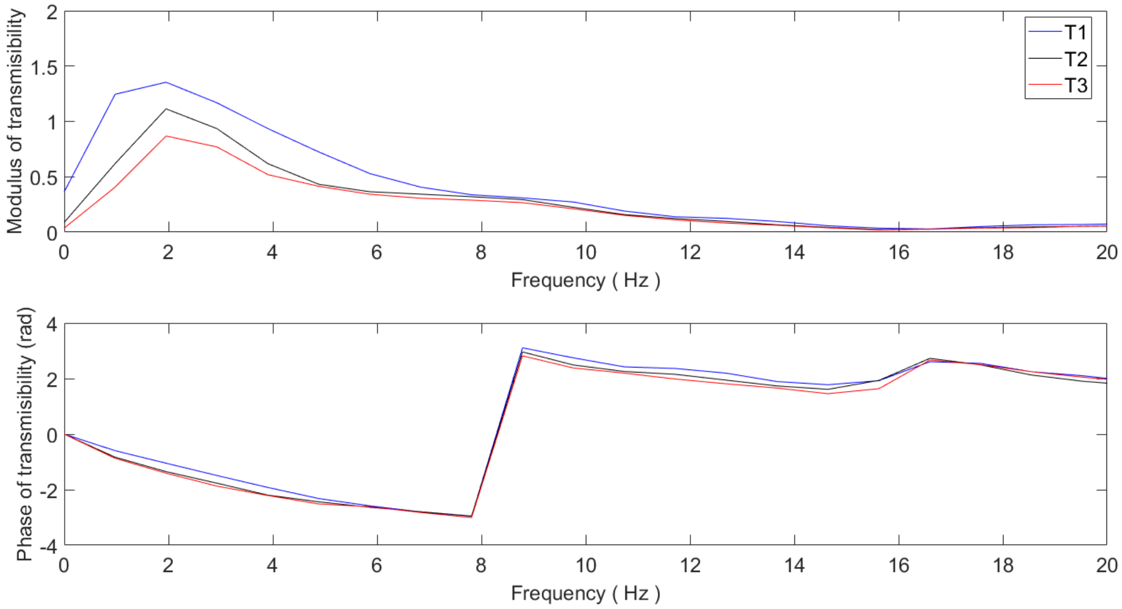

Figure 6.15 Modulus (top) and phase (bottom) of the transmissibility between the base and the CG for the suspension system with the faulty damper exposed to random input excitation with three different magnitudes: excitation with low vibration magnitude (T3), medium vibration magnitude (T2) and with high vibration magnitude (T1).

### 6.3.4 Effect of signal types of excitation

The frequency response of the suspension system with different excitation waveform were examined to evaluate the effect of excitation waveform.

Firstly, the healthy damper was fixed to the front suspension system and the frequency response function was measured using the random and sinusoidal sweep excitation (see Figure 6.16). As expected, there is no reduction in the resonance frequency when the healthy damper was fixed to the front suspension system of vehicle.

Secondly, the faulty damper was fixed to the suspension system and the frequency response function was measured using the random (with three different vibration excitation) and sinusoidal excitation (see Figure 6.17). There is no clear reduction in the resonance frequency when the faulty damper was fixed to the vehicle. However, as expected, magnitude of the transmissibility increases with the increase in the excitation magnitude of the random excitation.

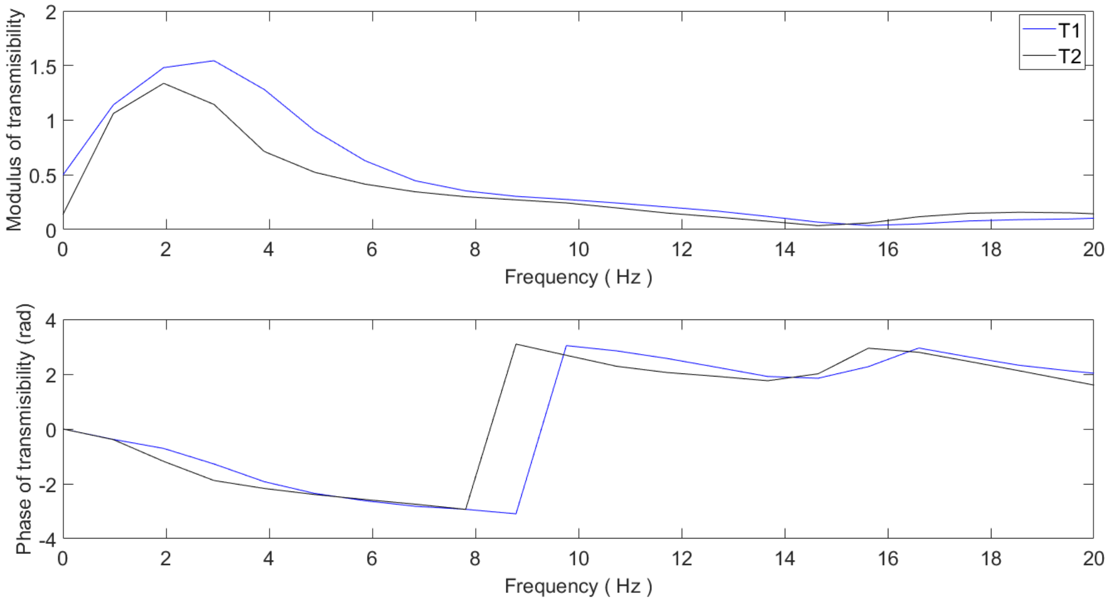

Figure 6.16 Modulus (top) and phase (bottom) of the transmissibility of the healthy suspension system exposed to two different excitations random and sinusoidal sweep: Excitation with random input (T1) and with sinusoidal input (T2).

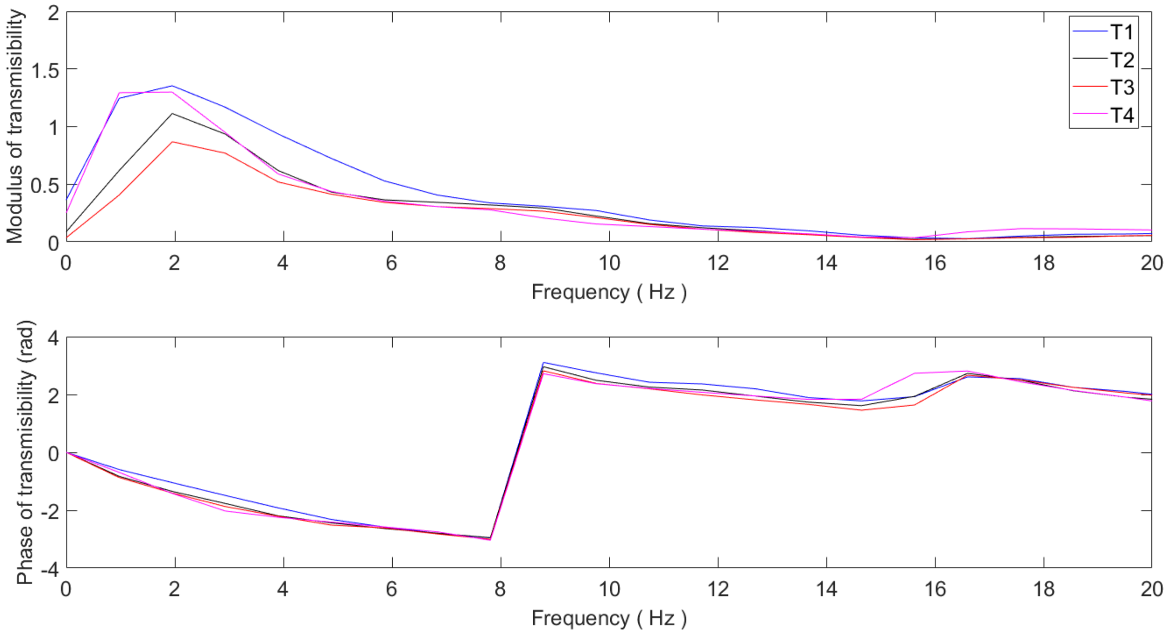

Figure 6.17 Modulus (top) and phase (bottom) of the transmissibility of the faulty suspension system exposed to two different excitations random (T1, T2 and T3) and sinusoidal sweep (T4): excitation with low vibration magnitude (T3), medium vibration magnitude (T2) and with high vibration magnitude (T1).

## 6.4 Discussion

The health monitoring of suspension system has been investigated in this study. There is no systematic approach available so far to monitoring the failure mechanism of the suspension system. The suspension system plays a vital role in the military vehicle, thus it is desired to have an integrated monitoring system to monitor the health of the suspension system.

This study has particularly focus on the failure of damper in Land Rover 110 military vehicle. At first, the healthy damper was tested to identify the frequency response behaviour. Then, the damper was introduced to some failure and tested again with same experimental conditions to evaluate the changes in the frequency response function between the healthy and the faulty damper. The four-poster hydraulic shaker system was used to excite the instrumented Land Rover vehicle and input and output were measured to estimate the frequency response function.

The effect of different vibration magnitudes and the excitation waveforms were tested to evaluate the failure detection mechanism. When the excitation magnitude was increased, there is little changes observed on the dominant resonance frequencies of the vehicle. The behaviour of unchanged resonance frequency with increasing vibration magnitude could be because, the evaluated excitation magnitudes were within the narrow band ranges (0.813 – 1.586g r.m.s). This study was designed as a preliminary study focusing on developing the experimental procedure to identify the failure mechanism of the suspension system. Due to the limited scope and the time, this study didn't use wide ranges of excitation magnitudes. The next step would be examining the damper with wide range of magnitudes.

The effect of different wave forms of the excitation signals was examined using the random and sinusoidal sweep excitations. The both excitation signals produced similar frequency response functions for the healthy and the faulty dampers as expected. This study reports that effect of excitation wave forms is negligible.

The amount of motion transmitted to the vehicle seat was measured using the accelerometer mounted on the driver seat (Figure 6.2). The human exposure limits were examined using the procedure described in ISO2631 [60,61]. The vibration exposure limit and the exposure action value is shown in the Figure 6.18.

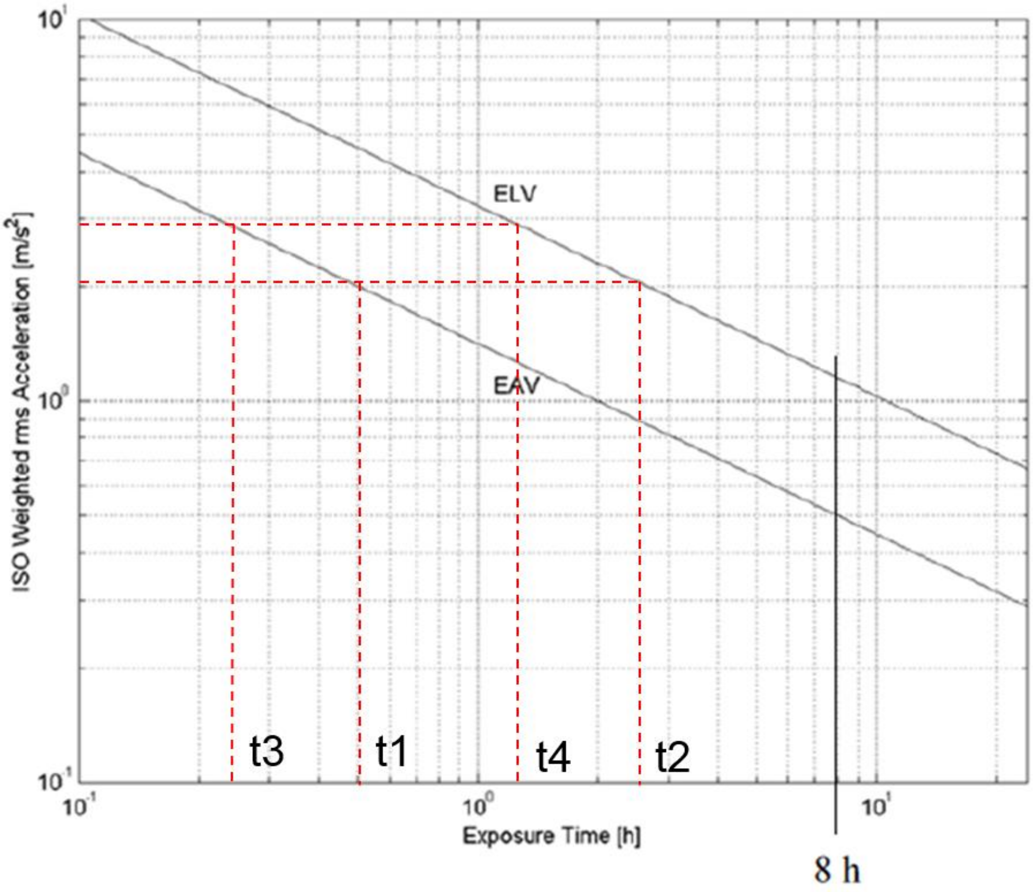

Figure 6.18 Graph shows the vibration exposure action value and the exposure limit value (adapted from ISO 2631 [61]).

The frequency weighted accelerations at the seat were calculated and the Figure 6.19 shows the weighted acceleration time histories measured at the seat using faulty dampers mounted on to the front suspension system. As expected when the faulty damper was fixed on to the vehicle, the weighted acceleration exceeds the exposure limit for the human at the low and high vibration excitations (weighted accelerations are 2.02 ms$^{-2}$ r.m.s. for the low excitation and 3.74 ms$^{-2}$ r.m.s. for the high excitation). The times t1 and t2 represent the vibration exposure action value and the exposure limit value for the 2.02 ms$^{-2}$ r.m.s. exposure respectively (Figure 6.18). The times t3 and t4 represent the vibration exposure action value and the exposure limit value for the 3.74 ms$^{-2}$ r.m.s. vibration exposure respectively (Figure 6.18).

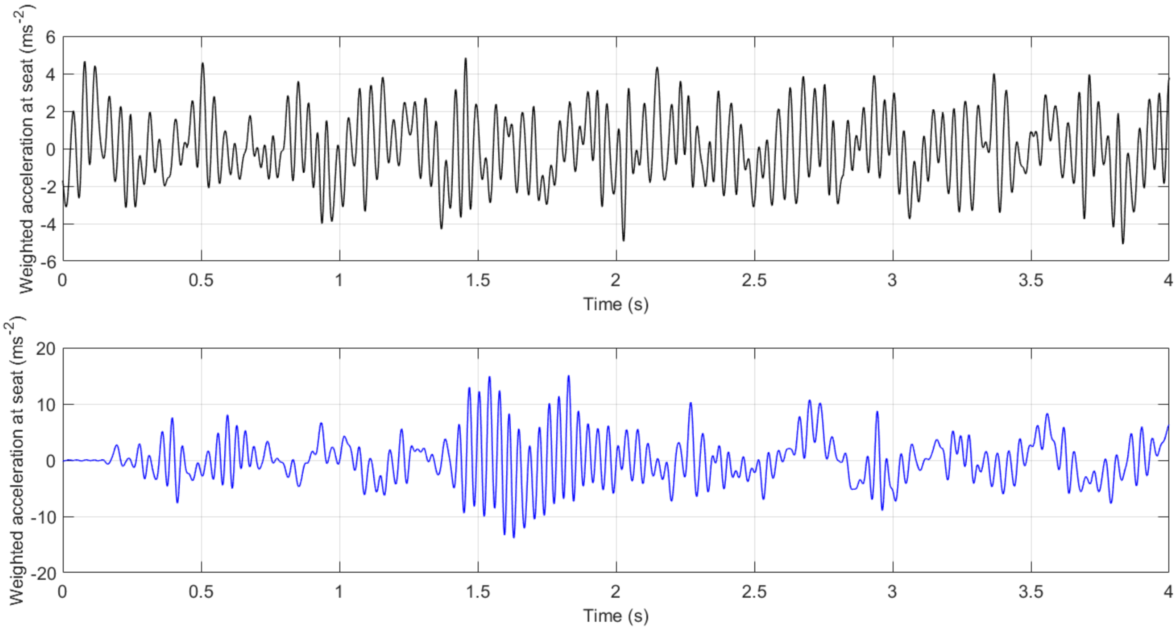

Figure 6.19 Weighted acceleration measured at the seat using faulty damper mounted on to the front suspension system – random vibration excitation with two different excitation magnitudes were used (low magnitude – top and high magnitude - bottom).

## 6.5 Conclusions

An experimental protocol was developed to examine the failure detection technique for the suspension system of the military vehicle. The frequency response function was used to evaluate the effectiveness of identifying the failure in the suspension system. The key resonance frequencies corresponding to the axle- and the body-mode were identified for the suspension system with the healthy damper (i.e. body mode 2.5 Hz and axle mode 11 Hz). Although the resonance frequency of the body- and the axle-mode were similar for the healthy and faulty damper, the small changes were observed when the excitation magnitude was increased. This nonlinear behaviour, changes in the resonance frequency with increasing excitation magnitude, primarily comes from the faulty damper. The strong conclusion on this finding couldn’t be made as the narrow band (0.813 – 1.586g r.m.s) of excitation magnitudes was used. Effect of vibration waveform is negligible. However, the small changes in the resonance frequencies using different magnitudes of base excitation seems to suggest the excitation magnitude has the potential to identify the failure based on the frequency response function. Additionally, the effect of vibration exposure for the crew inside the vehicle was evaluated using the healthy and the faulty dampers. The higher vibration exposure at the seat when faulty damper was fixed to the vehicle seems to suggest that failure in the suspension system causes health risk to the crew inside the vehicle.

# Chapter 7

## Investigation of effective lab testing mechanism to identify the failure of military vehicle cooling system

### 7.1 Introduction

A cooling system is used in the vehicle to prevent the components of the engine from overheating. There are some other advantages of an effective cooling system such as reducing the fuel consumption, retaining the strength of the components, prevents wear caused by friction between piston and cylinder, prevents high-temperature corrosions and reduces exhaust emission.

The cooling system is also responsible for the heating of the passenger space in a vehicle during operation in cold environments. Almost all the vehicles produced today are equipped with liquid cooling systems. In the past, the vehicles were commonly used with air cooled engines. The air cooled engines are not common in the recent years due to the high power output engines, and therefore increased heat energy. The heat produced in a liquid cooled engine is transferred to the air, whereas in an air cooled engine the heat is transferred to the air indirectly.

The failure detection or the health monitoring of the military vehicles is not a well-developed topic though some advanced vehicle systems have some embedded mechanisms to detect some particular health issues in the cooling systems. The operating conditions of the cooling system are normally used to evaluate the health issues in the cooling systems components. The novel health monitoring system which integrates all different operating systems of the military vehicle to monitor the state of the operating condition and to provide information for preventive maintenance in real time would be desirable. However, there is no such novel health monitoring systems available in the literature up to date.

The majority of parts of the cooling system wear out slowly, and with proper maintenance and periodic inspection they can be expected to experience only small, incremental problems. However, occasionally a cooling system will fail suddenly and dramatically and the vehicle engine will in effect fall. This sort of sudden failure results when a cooling system dramatically fails, the engine will cease automatically and results in entire vehicle failure. (Appendix B).

The sudden failure of the cooling system causes dramatic damage to the engine and its sub-systems and thus potentially leads to entire collapse of the vehicle and ultimately loss of life of the crew. Proper structured health and usage monitoring system (HUMS) usually helps to identify or send the signal of failure before it starts to collapse entirely. However, such universal systems are very sparse in the military vehicles – thus this begs or highly demands the need for such universal HUMS system for the cooling system in military vehicles.

This chapter explores effective lab testing mechanisms to identify the failure mechanism in the cooling system in the military vehicles.

## 7.2 Methodology

The experimental study is conducted on the Land Rover Defender (110) military vehicle engine using instrumented sensors and CAN Bus data acquisition system. The temperature and pressure sensors were instrumented in the engine cooling system and the corresponding data was captured with different engine operating conditions to identify the possible failure mechanisms.

Two temperature sensors were, one inlet pipe to the engine (T1) and the other outlet pipe to the engine (T2), mounted for the temperature measurements. Three pressure sensors were, one in the inlet before the pump (P1) and the other after the pump (P3) and the last one on the outlet of the engine (P2), mounted to capture the pressure measurements. In addition, one accelerometer was mounted on top of the engine to monitor the vibration exposure during the entire test.

At first, the engine was switched off and measurements were taken to evaluate the surrounding noises captured by the sensors. And then, the engine was started, and three different engine running conditions were used in the test, one with engine running speed 650 rpm (idle) and other with 850 rpm and the last one was infield driven condition. During this test, the engine was considered as running in healthy manner in the first place and the three different possible failure mechanism were introduced, half closed valve before the pump (leakage/semi blockage), then fully closed the valve (leakage/ fully blockage) and at last the fan belt was removed (indicating belt cut-off or water pump failure). The data (temperature, pressure and the acceleration) were measured during the test and transferred to the different computer for analysis. The home built CAN Bus data acquisition system was used to capture the data. The home built refers that the CAN Bus data acquisition systems (hardware) and the software interface in MATLAB were designed and built in the Engineering Dynamic Centre (EDC) laboratory at the Cranfield University as part of this PhD study.

### 7.2.1 Apparatus

The Land Rover Defender (110) military truck engine cooling system was instrumented with the temperature and pressure sensors along with an accelerometer. CAN Bus data acquisition system was incorporated with the afore mentioned sensors to enable data capture (see Figure 7.1). Three different engine running conditions were used for the test. The specifications of the temperature and pressure sensors, accelerometer, CAN Bus system and other experimental equipment were described in Sections 3.3.1 to 3.3.3 in Chapter 3.

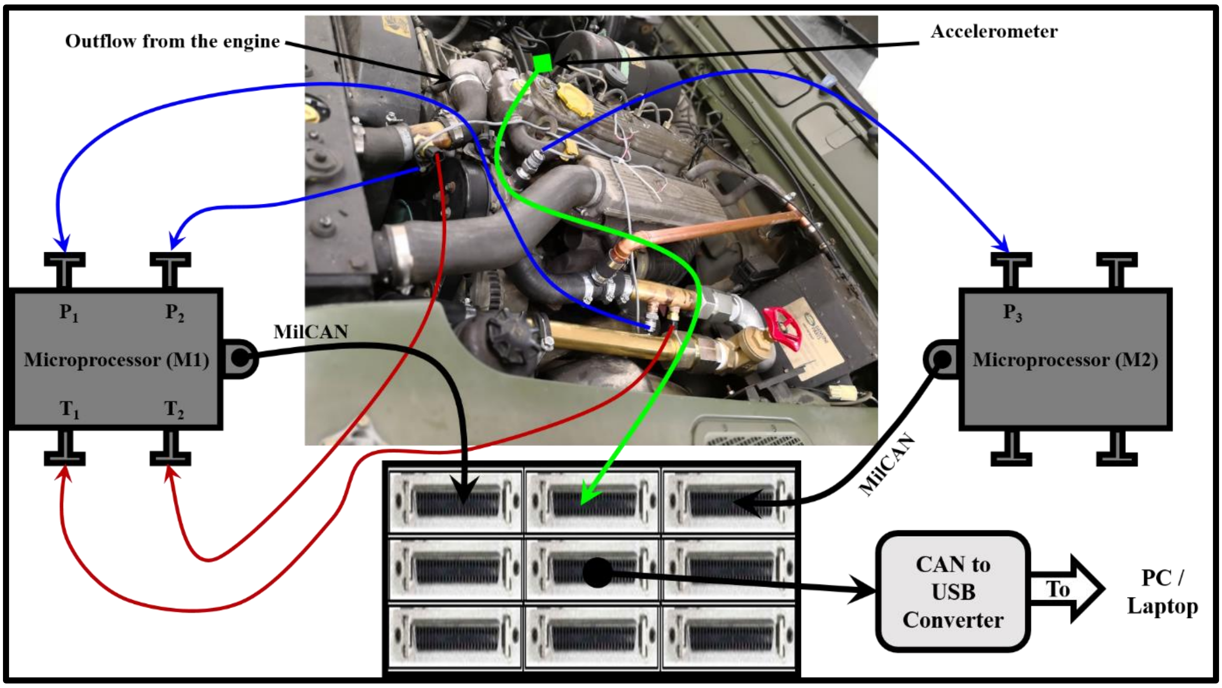

Figure 7.1 Photographic representation of the experimental setup: equipment and setup showing the Land Rover (110) military truck engine instrumented with the temperature and pressure sensors and an accelerometer with the CAN Bus system.

### 7.2.2 Analysis

The six channels of measured output data, one-output acceleration, two temperatures, three pressures, time histories were sampled simultaneously at 100 Hz with duration of 240 seconds.

## 7.3 Results

The two engine running conditions, one healthy and the other faulty, were used to capture the output measurements during the test. Firstly, the engine was run in healthy mode (normal operational mode) and two different engine speeds along with infield driving conditions were introduced to the engine. Secondly for the faulty operations, three different failure mechanisms were introduced to the engine by controlling the flow of the engine coolant by a regulator valve based on valve position, namely, half closed valve, fully closed valve, and finally the cooling pump belt removed. All the tests were repeated on the faulty engine running conditions. The measured output data were used to evaluate the effect of failure on the cooling system.

### 7.3.1 Temperature and pressure response of the healthy cooling system

Temperature and pressure at different locations in the cooling system were measured and monitored during the test. Different engine running conditions were used for the test.

The following notations describe the measurement details:

T1 – Temperature measured at the inlet to the engine

T2 – Temperature measured at the outlet coming from the engine

P1 – Pressure measured at the inlet to the engine (before the pump)

P2 – Pressure measured at the outlet coming from the engine

P3 – Pressure measured at the inlet between pump and the engine (after the pump)

#### 7.3.1.1 Temperature and pressure response of the healthy cooling system with different engine running condition simulated at the lab

***<u>No engine run</u>***

The experimental campaign was started with analysing the noise level in the system. Temperature and the pressure measurements were carried out at the designated locations on the cooling systems with ignition on condition (while the engine was switched off). As seen in the Figure 7.2, the temperature and the pressure were constant at all locations of the measurement indicating minimum fluctuation. The temperature was around 20 ºC and the pressure was around 20 psi in all the locations of the measurement. This is clearly indicating that the engine pressure and temperature reach a constant operating level during the healthy operation; and the cooling systems maintains at these constant level throughout the operations. In other words, there are the characteristics of healthy engine operation.

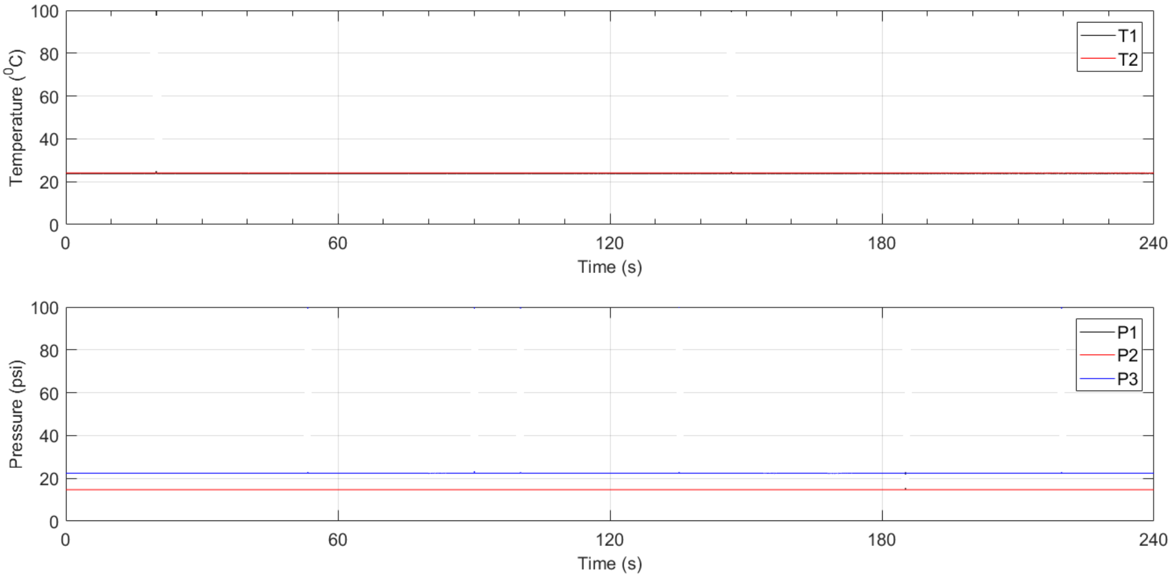

Figure 7.2 Temperature (top) and pressure (bottom) variation during ignition on condition.

***Idle run***

The healthy running condition of the cooling system was simulated at the lab, with idle engine running condition, to evaluate the variation in the temperature and the pressure measured at different locations of the cooling system. The Figure 7.3 shows that there was no significant variation in the temperature and pressure measured at all designated locations. The temperature was about 80 ºC and the pressure was about 20 psi throughout the measurement period of 4 minutes. As discussed above, the healthy operation is evident by the constant temperature and pressure levels.

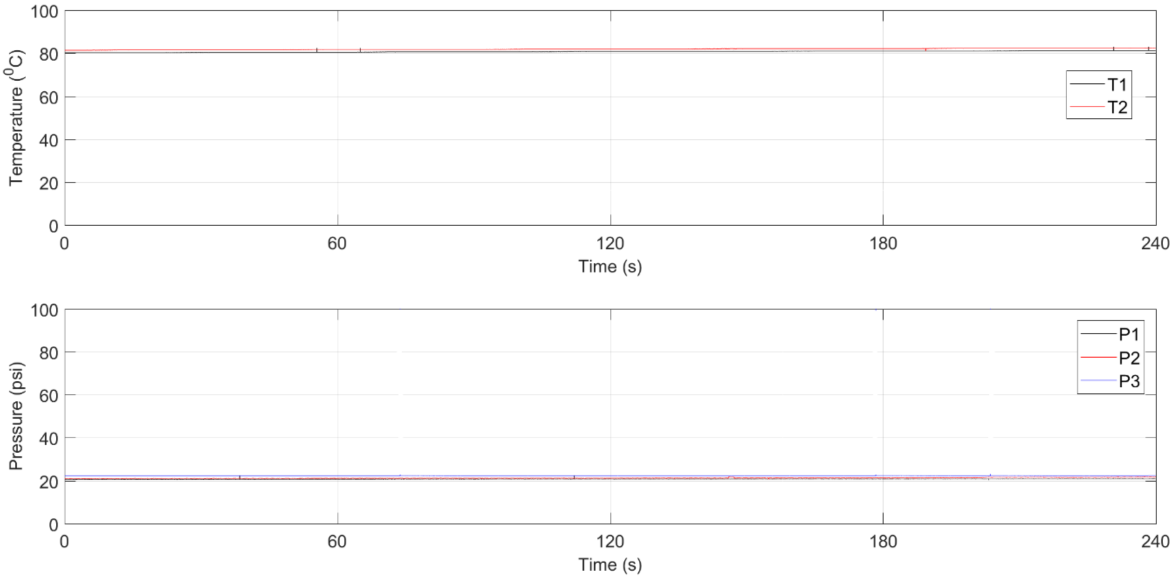

Figure 7.3 Temperature (top) and pressure (bottom) variation during idle engine running condition.

### ***Running at 850 rpm***

After the idle engine running condition, engine was set to run at 850 rpm to evaluate the changes in the temperature and the pressure. There was a small increase in the temperature in both locations (T1 and T2) as seen in the Figure 7.4. However, the constant pressure was observed in all locations (P1, P2 and P3) (Figure 7.4). The pressure at the location P3 was relatively higher than those of locations P1 and P2 as expected.

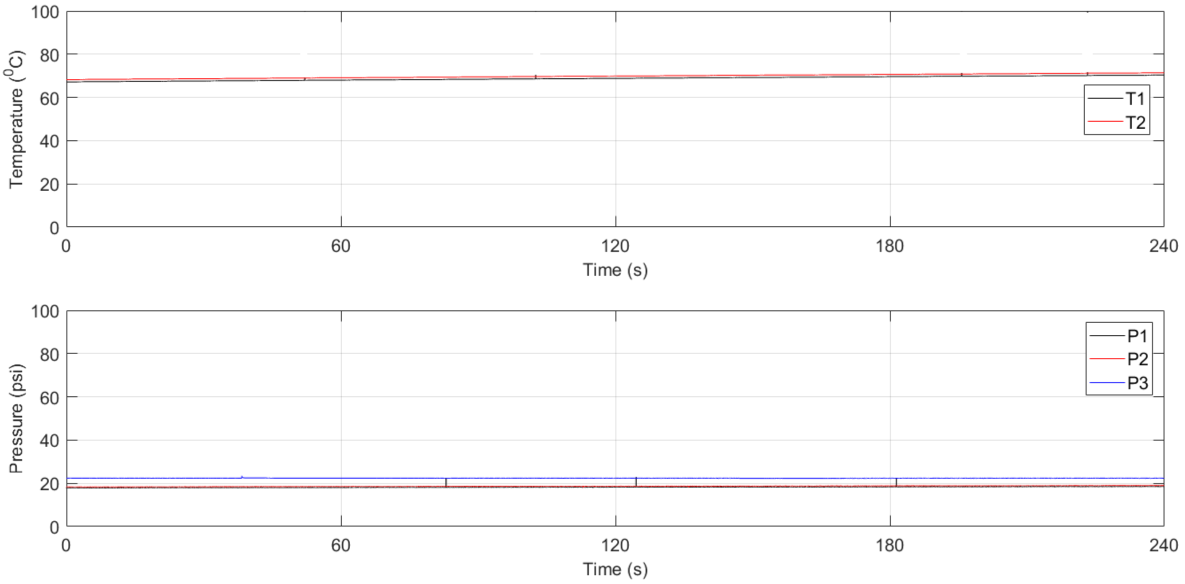

Figure 7.4 Temperature (top) and pressure (bottom) variation during engine running at 850 rpm.

### 7.3.1.2 Temperature and pressure response of the healthy cooling system with vehicle driving in the field.

Temperature and the pressure of the healthy cooling system were measured and monitored during the period of vehicle running in the field (Figure 7.5). The temperatures increased from 45 °C to 60 °C during the measurement time of 4 minutes. The temperature change was seen to decrease towards the end of the measurement phase indicating a gradual arrival of the engine thermal equilibrium, and hence a healthy operating of the engine. The pressures remained constant during the measurement time. However, pressure at location point P3 was higher than the pressure at locations P1 and P2 as expected since higher pressure is required to ensure the adequate flow rate of the coolant to the engine block at elevated power setting (vehicle driven around).

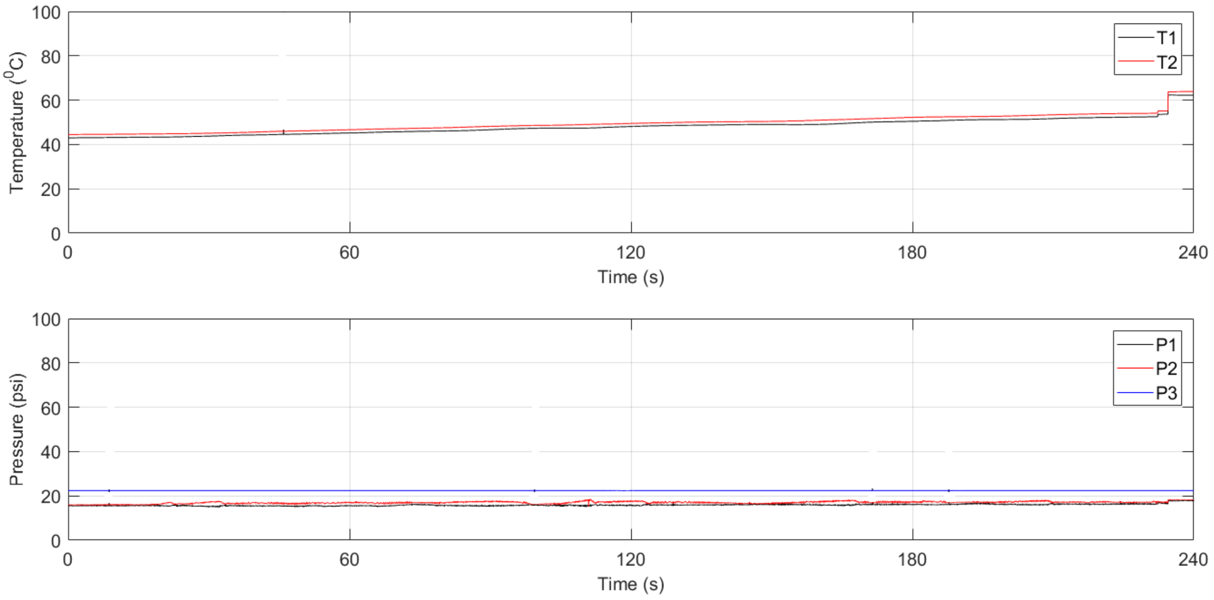

Figure 7.5 Temperature (top) and pressure (bottom) variation during vehicle driving in the field.

### 7.3.2 Temperature and pressure response of the faulty cooling system

#### 7.3.2.1 Temperature and pressure response of the faulty cooling system with different engine running conditions simulated at the lab

Three different faulty mechanisms, half-closed valve, fully-closed valve and belt off, were introduced to the cooling systems to evaluate the temperature and the pressure variation during different engine running conditions. Two engine running conditions, idle and at speed of 850 rpm, were used in the test. These simulated faulty conditions represent the typical examples of the real failures observed in the military vehicle operations. Several repeats were carried out during the pilot test as well as the actual test to ensure the repeatability test.

***Half-closed valve***

Firstly, the control valve was set to half-closed condition, assumed to be a faulty cooling system running condition (leakage/ semi blockage), and the temperature and the pressure were measured with idle (Figure 7.6) and 850 rpm (Figure 7.7) engine running conditions. There was no significant variation in the temperature and the pressure. However, there was a small temperature drop (8 $^{o}$C) when the engine running at the speed 850 rpm.

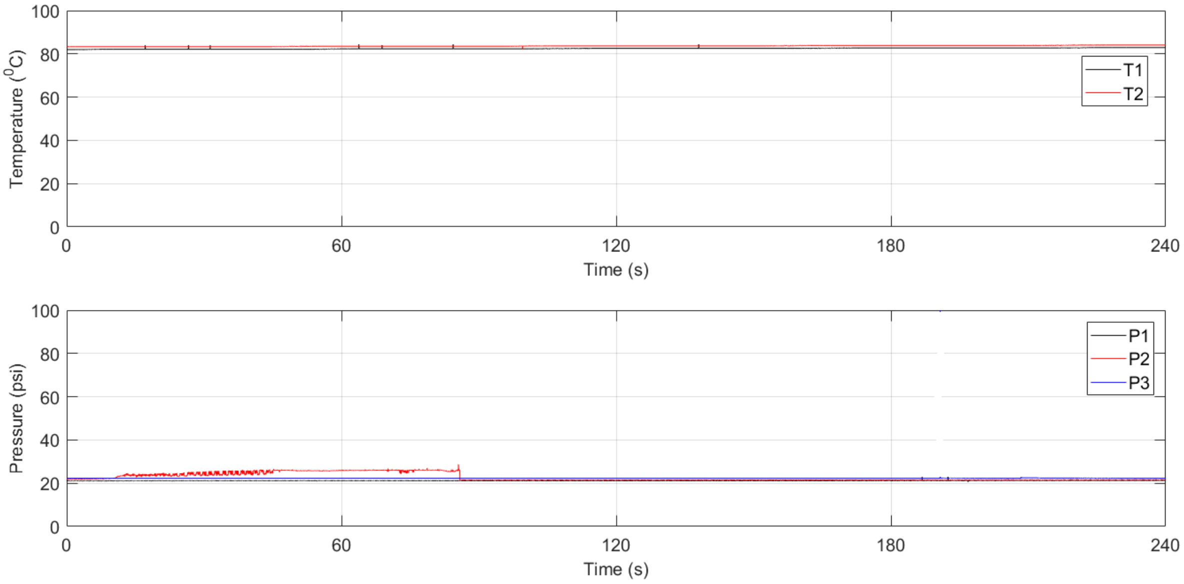

Figure 7.6 Temperature (top) and pressure (bottom) variation in the faulty cooling system with half-closed valve condition – idle engine running condition.

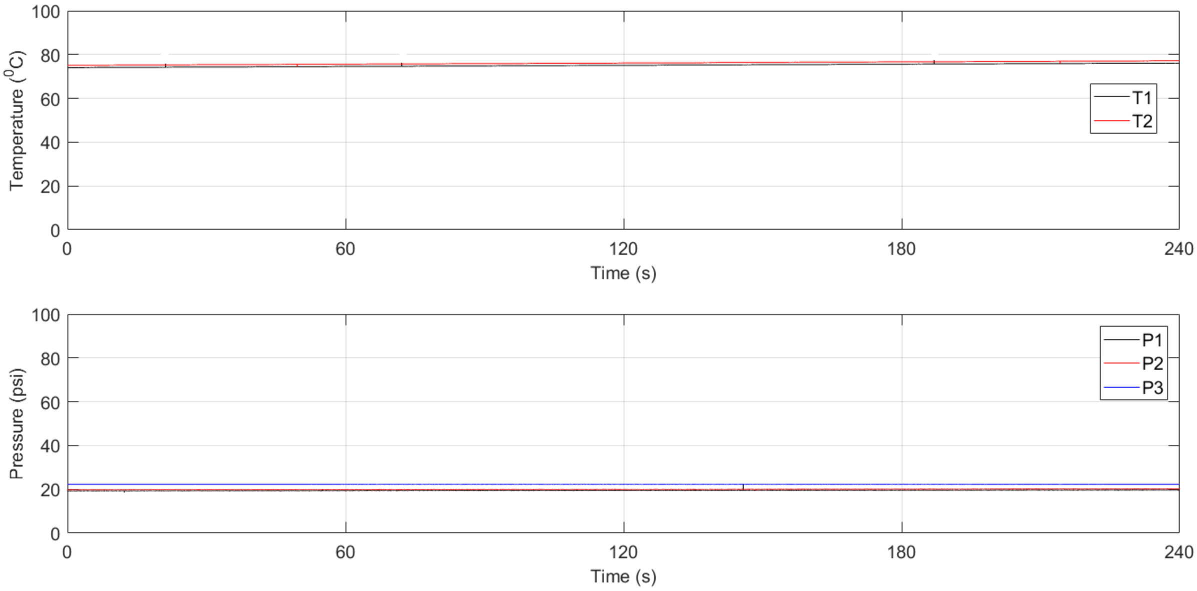

Figure 7.7 Temperature (top) and pressure (bottom) variation in the faulty cooling system with half-closed valve condition – engine running at 850 rpm.

### ***Fully closed***

Secondly, the control valve was set to fully-closed condition (fully blockage/ leakage or a hose cut-off), assumed to be a faulty cooling system running condition, and the temperature and the pressure were measured with idle (Figure 7.8) and 850 rpm

(Figure 7.9) engine running conditions. There was significant variation in the temperature. However, the pressure remained constant during both engine running conditions. The temperature measured at the location T1 increased from 82 ºC to 88 ºC for idle engine running condition (Figure 7.8) and increased from 76 ºC to 82 ºC for engine running at 850 rpm speed (Figure 7.9). However, the temperature measured at the location T2 decreased from 82 ºC to 78 ºC for idle engine running conditions (Figure 7.8) and decreased from 78 ºC to 72 ºC for the engine running at 850 rpm speed (Figure 7.9). The closing of the valve will result in the gradual heating of the engine block. However, the result recorded an increase in T1 and decrease in T2. At first, this trend of temperature variation may seem unreasonable. But, this can be explained as follows: the closing of the valve while the pump is running, empties the coolant in the pipe and hence the temperature sensor at station 2 is not in contact with the coolant. Hence, T2 is seen to decrease despite the expected rise in the engine block temperature. Similarly, the due to the stagnant coolant (without any fluid movement) brought about by the closed valve, the rising temperature in the metal pipe is conducted to the fluid in station 1 (note that the sensor at T1 is in contact with the coolant fluid), and therefore, T1 increases.

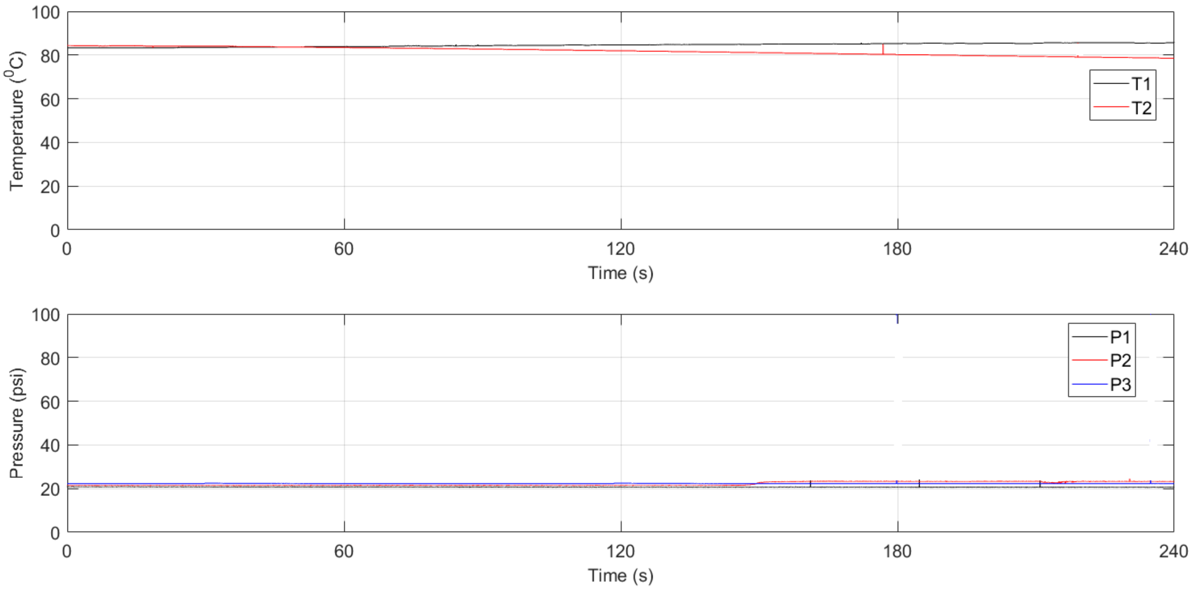

Figure 7.8 Temperature (top) and pressure (bottom) variation in the faulty cooling system with full-closed valve – idle engine running condition.

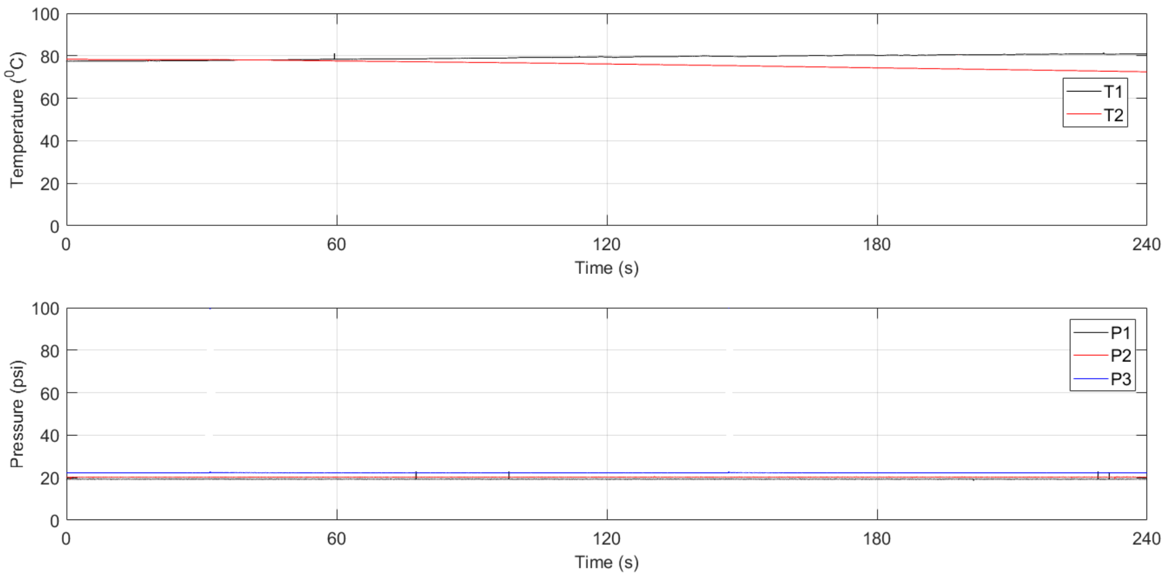

Figure 7.9 Temperature (top) and pressure (bottom) variation in the faulty cooling system with fully-closed valve condition – engine running at 850 rpm.

## ***Belt off***

Lastly, the belt of the pump was removed, assumed to be another faulty cooling system running condition (belt cut-off/ pump failure), and the temperature and the pressure were measured with idle (Figure 7.10) and 850 rpm (Figure 7.11) engine running conditions. There was significant variation in the temperature. However, the pressure remained constant during both engine running conditions. The temperature measured at the location T1 increased from 51 $^{o}$C to 58 $^{o}$C for idle engine running condition (Figure 7.10) and increased from 61 $^{o}$C to 66 $^{o}$C for engine running at 850 rpm speed (Figure 7.11). However, the temperature measured at the location T2 increased from 56 $^{o}$C to 62 $^{o}$C for idle engine running conditions (Figure 7.10) and increased from 62 $^{o}$C to 68 $^{o}$C for the engine running at 850 rpm speed (Figure 7.11). The temperature change trends observed here are consistent with the fact that the engine block gradually starts to get hotter and hotter as a result of disengaged belt.

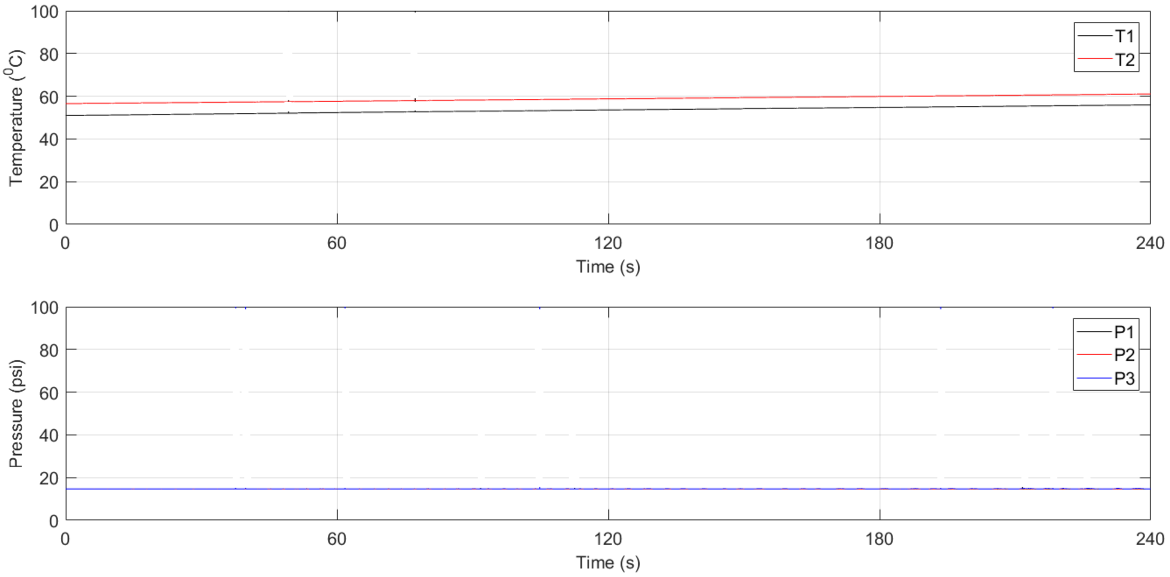

Figure 7.10 Temperature (top) and pressure (bottom) variation in the faulty cooling system with belt off condition – idle engine running condition.

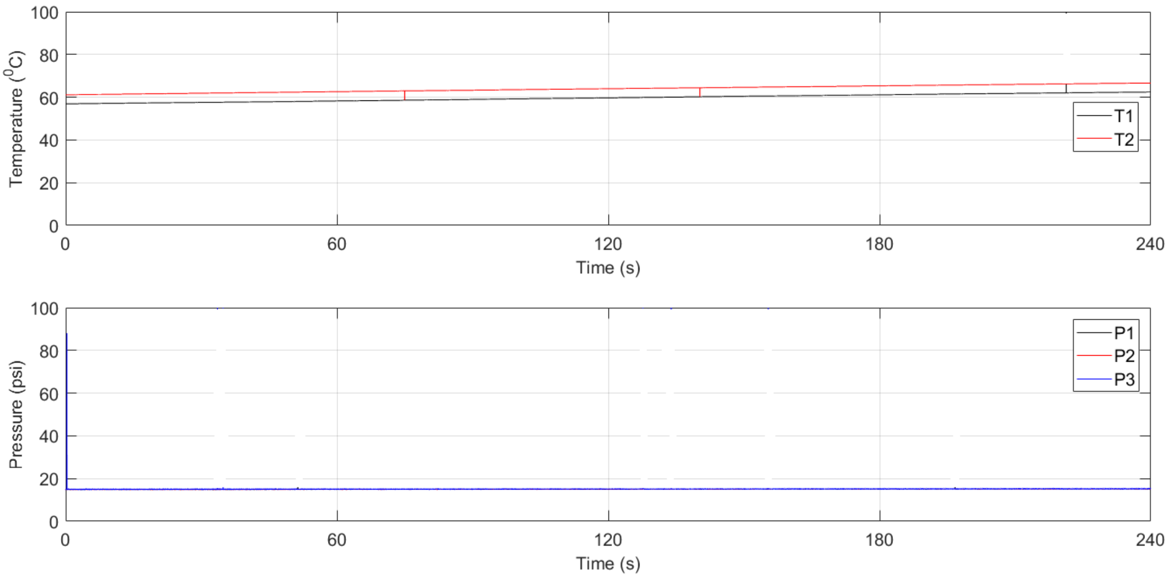

Figure 7.11 Temperature (top) and pressure (bottom) variation in the faulty cooling system with belt off condition – engine running at 850 rpm.

#### 7.3.2.2 Temperature and pressure response of the faulty cooling system with vehicle driving in the field

Temperature and the pressure of the faulty cooling system were measured and monitored during the period of vehicle running in the field. Three different faulty conditions, half-closed valve (represents leakage/ semi blockage), fully-closed valve (represents full leakage due to hose cut off or radiator damage / fully blockage) and belt off (represents pump failure or fan belt cut-off), were introduced to the cooling system.

### ***Half-closed valve***

Firstly, the control valve was set to half-closed condition, assumed to be a faulty cooling system running condition, and the temperature and the pressure were measured with the vehicle running in the field. There was a significant variation in the temperature, however the pressure remained constant during the test. Temperature increased from 76 °C to 82 °C in both measured locations during the test (Figure 7.12). Since the vehicle was being driven around during the measurement, the engine was transmitting power to the transmission system. This in turn leads to the engine block getting hotter, which is reflected in the measured trend of temperature.

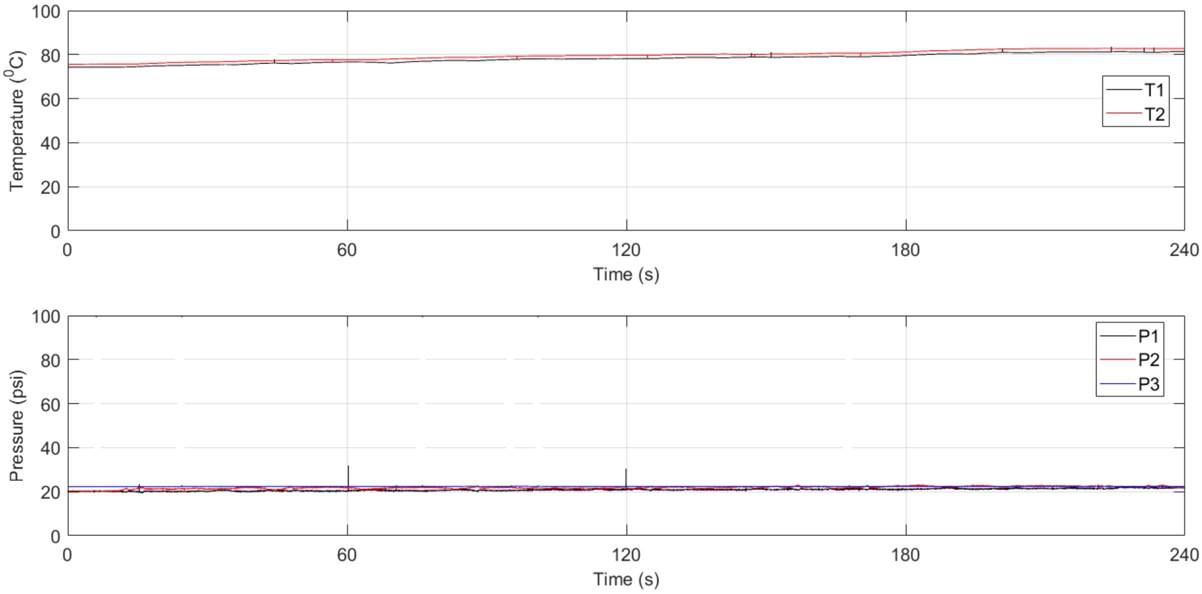

Figure 7.12 Temperature (top) and pressure (bottom) variation of the faulty cooling system during half-close valve condition with vehicle driving in the field.

### ***Fully closed***

Secondly, the control valve was set to fully-closed condition, assumed to be another faulty cooling system running condition, and the temperature and the pressure were measured with the vehicle running in the field. There was a significant variation in the temperature, however the pressure remained constant during the test (though, P1 showed small fluctuations). Temperature increased from 82 ºC to 92 ºC at the measurement location T1 and decreased from 82 ºC to 58 ºC at the measurement location T2 during the test (Figure 7.13). The rate of change of T2 is very high when compared to the case of partially closed-valve. As in the previous section, this is due to the fact that the temperature sensor at station 2 is not in contact with the coolant. Hence, T2 is seen to decrease rapidly despite the expected rise in the engine block temperature. At half-closed case, however, the sensor still has some contact with the coolant and hence, T2 is seen to rise as expected.

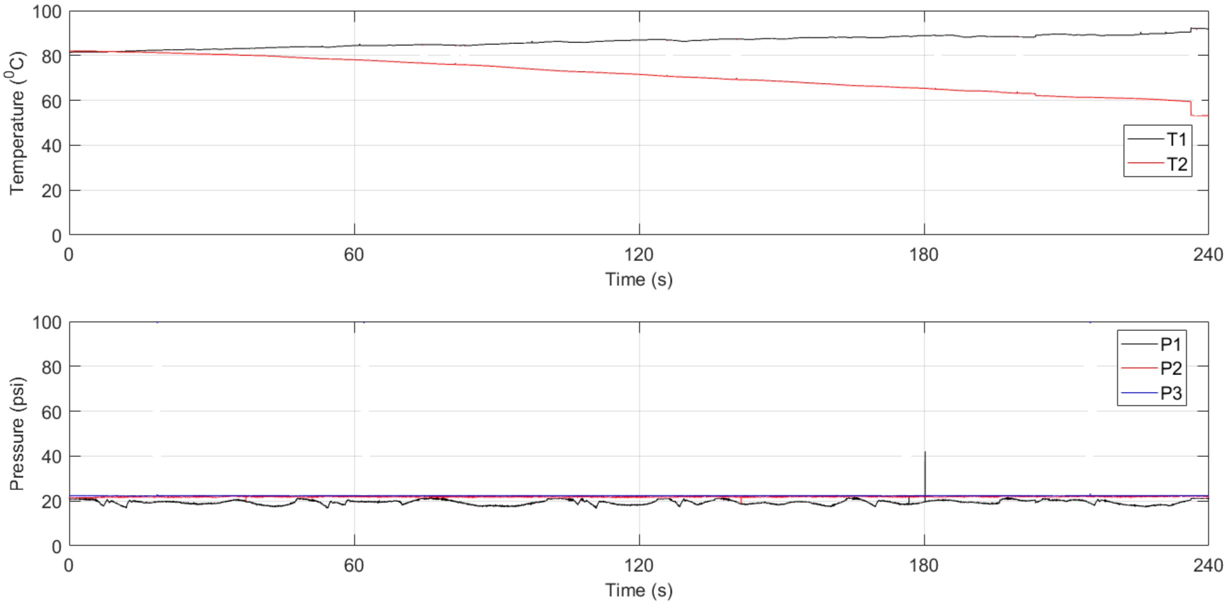

Figure 7.13 Temperature (top) and pressure (bottom) variation of the faulty cooling system during fully-close valve condition with vehicle driving in the field.

## ***Belt off***

Lastly, the belt was removed from the pump, assumed to be another faulty cooling system running condition, and the temperature and the pressure were measured with the vehicle running in the field. There was a significant variation in the temperature, however the pressure remained constant during the test. Temperature increased from 80 ºC to 88 ºC at the measurement location T2 and decreased from 80 ºC to 72 ºC at the measurement location T1 during the test (Figure 7.14). As before, the temperature change trends observed here are consistent with the fact that the engine block gradually starts to get hotter and hotter as a result of disengaged belt. An effective coolant circulation will be disrupted due to the disengagement. It is worth noting here, however, that some small coolant circulation will continue due to a small pressure differential in the coolant flow paths brought about by the vehicle’s movement. This pressure differential essentially maintains a very weak coolant circulation, which is not adequate for the thermal balance, and hence the temperatures T1 and T2 are seen to gradually rise.

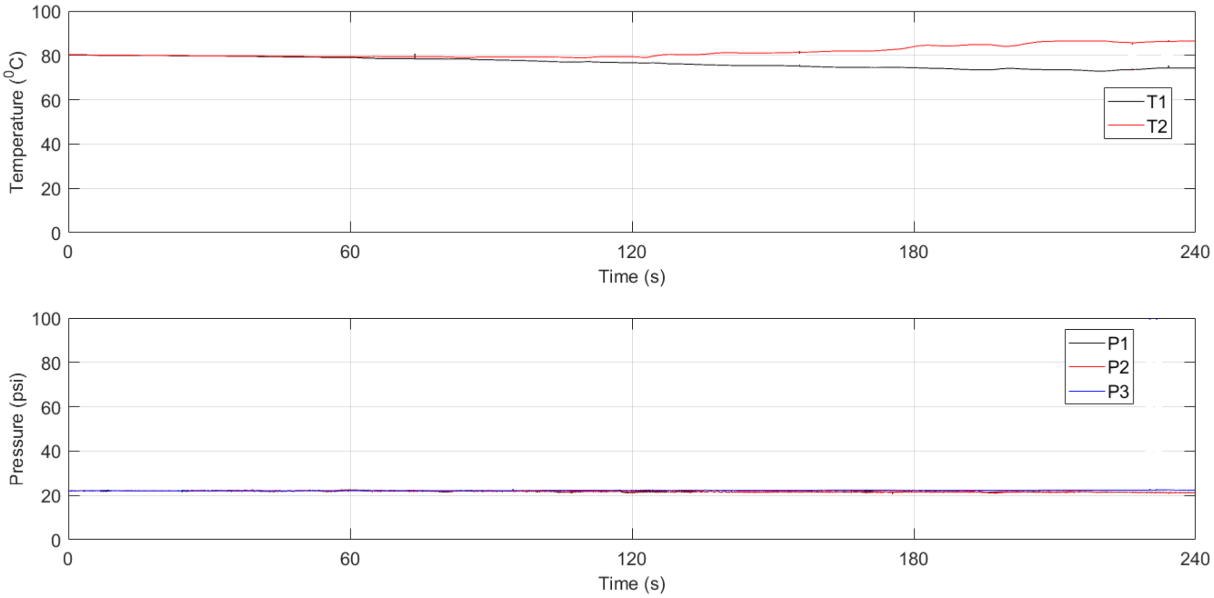

Figure 7.14 Temperature (top) and pressure (bottom) variation of the faulty cooling system during belt off condition with vehicle driving in the field.

## 7.4 Discussion

The health monitoring of cooling system has been investigated in this study. There is no systematic approach available so far to monitoring the failure mechanism of the cooling system. The cooling system plays a vital role in the military vehicle engine performance, thus it is desired to have an integrated monitoring system to monitor the health of the cooling system and thus ensuring the high performance of engine during the operation of the military vehicles.

This study has particularly focus on the failure of the Cooling system in the Land Rover 110 military vehicle. At first, the healthy cooling system was instrumented with temperature and pressure sensors in the different parts of the cooling system to examine the variation in the temperature and the pressure at those designated locations in the cooling system. Then, the cooling system was introduced to some failure mechanism and tested again with same experimental conditions to evaluate the changes in the temperature and pressure between the healthy and the faulty cooling system. Firstly, operating conditions of the engine were simulated at the lab and condition of healthy and faulty cooling system was examined to evaluate the temperature and pressure variations. Secondly, vehicle was driven in the field and the condition of healthy and faulty cooling system was examined to evaluate the temperature and pressure variations.

The temperature and the pressure of the healthy cooling system remained constant during the test in the laboratory for both idle and 850 rpm engine running conditions. When the vehicle was driven in the field, the temperature of the healthy cooling system at two different locations (T1 and T2) increased with the time of operation. The temperature change was seen to flatten towards the end of the measurement phase indicating a gradual arrival of the engine thermal equilibrium, and hence a healthy operating of the engine.

The temperature of the faulty cooling systems (half-closed) simulated in the lab increased at both locations (T1 and T2) for both engine running conditions (idle and 850 rpm). However, pressure remained constant at all locations (P1, P2 and P3). The temperature at the location (T1) of the faulty Cooling system (fully-closed) simulated in the lab increased with the time of engine operation for both engine running conditions and the temperature at the location (T2) decreased with the time of operation of the engine for both engine running conditions. The pressure remained constant at all the locations (P1, P2 and P3). The temperature at locations (T1 and T2) of the faulty cooling system (belt off) increased with the time of engine running for both engine running conditions. The pressure remained constant at all locations (P1, P2 and P3) for both engine running conditions.

Similarly, the temperatures at both the locations (T1 and T2) of the faulty cooling system (half-closed) while running the vehicle in the field increased with the time of engine operation and the pressure at all locations remained constant. The temperature at location (T1) of the faulty cooling system (fully closed) increased with time whilst the temperature at location (T2) decreased with time. All these trends in temperature variation are as expected, and the engineering reason behind these have been explained in Section 7.3. The pressures at all the locations (P1, P2 and P3) show some variation albeit small, not clearly noticeable in the plotted figures. This behaviour repeated for the faulty cooling system of belt-off condition.

The variations in the temperature for the cooling system recorded in this experiment show a very high sensitivity of the HUMS system which can easily be adapted to any military land platform with minimal engineering effort. Such a system can provide a real time temperature data which can be monitored to assess the health of the cooling system, and can provide early warning to the engine health status. The trend in the temperature variations observed for both laboratory and the infield driven testing conditions has clearly indicated that the temperature data can be used as the failure detection parameter for the cooling system health monitoring.

### 7.5 Conclusions

An experimental protocol was developed to examine the failure detection technique for the cooling system of the military vehicle. The temperature and the pressure measurement at different locations of the cooling system was measured and monitored with different engine running conditions at the lab and with the vehicle driving in the field. Temperature and pressure measurements for the healthy cooling system were consistent for both engine running at the lab and the vehicle driven in the field.

When the failure was introduced to the cooling system, the significant variations in the temperature were observed for all the engine running conditions at the lab as well as the test with the vehicle running in the field. The variations observed in the temperature measured in different locations in the cooling system (T1 and T2) could be used to diagnose an early stage of failure in the cooling system, and it can be used to take an action before the actual failure occurs. This study concludes that temperature and pressure measurements at different locations in the cooling system can be used as a viable mechanism to identify the failure in the cooling system.

# Chapter 8

## Development of lab testing mechanism using engine instrumentation to identify the failure of lubricant and cooling system

### 8.1 Introduction

As part of my PhD research and the future work, I have written a proposal to upgrade the lab equipment and the data acquisition system. The current facility at the lab does not have sophisticated instrumentation for the engine to test and acquire the data. The various potential engine test equipment & suppliers were explored to upgrade the testing facility at the laboratory. In this process, I have attended a number of meetings with suppliers (LG Create and Block Automotive Ltd), which are both local and have significant experience of supplying similar equipment in the UK as well as abroad. Recently, I also visited Block Automotive’s site in Lowestoft, UK to see their capability and the range of products they offer. On the visit, I identified one engine test platform which would serve three important purposes:

I. Firstly, it is a turbocharged heavy duty 4-cylinder Diesel truck engine, which is representative of a typical heavy duty application in military vehicles (at least on light military vehicles). Therefore, this would be more appropriate for our future research activities which have focus on military application.

II. Secondly, the supplier has confirmed that they will provide customisation so that it is suitable for HUMS research. In particular, I have asked specific modifications so that health status of engine cooling system & lubrication system can be monitored to evaluate overall engine health status. The modifications include:

    - Pressure and temperature sensors in coolant system input to the radiator
    - Pressure and temperature sensors in coolant system output from the radiator
    - Pressure and temperature sensors after water pump.
    - Gate valve facility into coolant system to vary flow rates (simulating fault on water pump)

- Pressure and temperature sensors into lubrication systems (at two locations: before the oil pump/filter and after pump/filter)

III. Thirdly, the supplier also provided an exhaust viewing section on the exhaust pipe (for flow visualisation) using heat resistant glass. Additionally, temperature and pressure sensors will be mounted pre and past turbocharger in the exhaust system. This will aid to the research activities on fluid flow in turbocharger and exhaust systems.

IV. The engine is a HGV 4 Cylinder Cummins based Tector with Bosch common rail direct injection Diesel. All sensors and actuators will have pin out & data display facility and 10 fault insertion points (these include, common rail pressure sensor, throttle position sensor, coolant temperature sensor, camshaft speed sensor, crank position sensor, intake pressure & temperature sensors etc.). The pin out & data display facility will need to have a pressure and temperature sensors to measure pressure & temperature in the combustion chamber. Examples of faults given but additional faults can be added if required.

This provides the main features of this test bench, and further customisation is possible if required. In addition, this will serve the future research activities as the platform was bought with a Dynamometer.

## 8.2 Apparatus

The engine is a HGV 4-Cylinder Cummins based Tector with Bosch common rail direct injection Diesel. All sensors and actuators will have pin out & data display facility and 10 fault insertion points (these include, common rail pressure sensor, throttle position sensor, coolant temperature sensor, camshaft speed sensor, crank position sensor, intake pressure & temperature sensors etc.).

This instrumented engine provides real time data capturing and monitoring facility while engine running conditions. Additionally, any faulty engine running condition can be introduced in the laboratory using this instrumented engine and can monitor and evaluate the fault detection techniques for lubricant and cooling systems. The Figure 8.1 shows the front and side view of the instrumented engine at the laboratory.

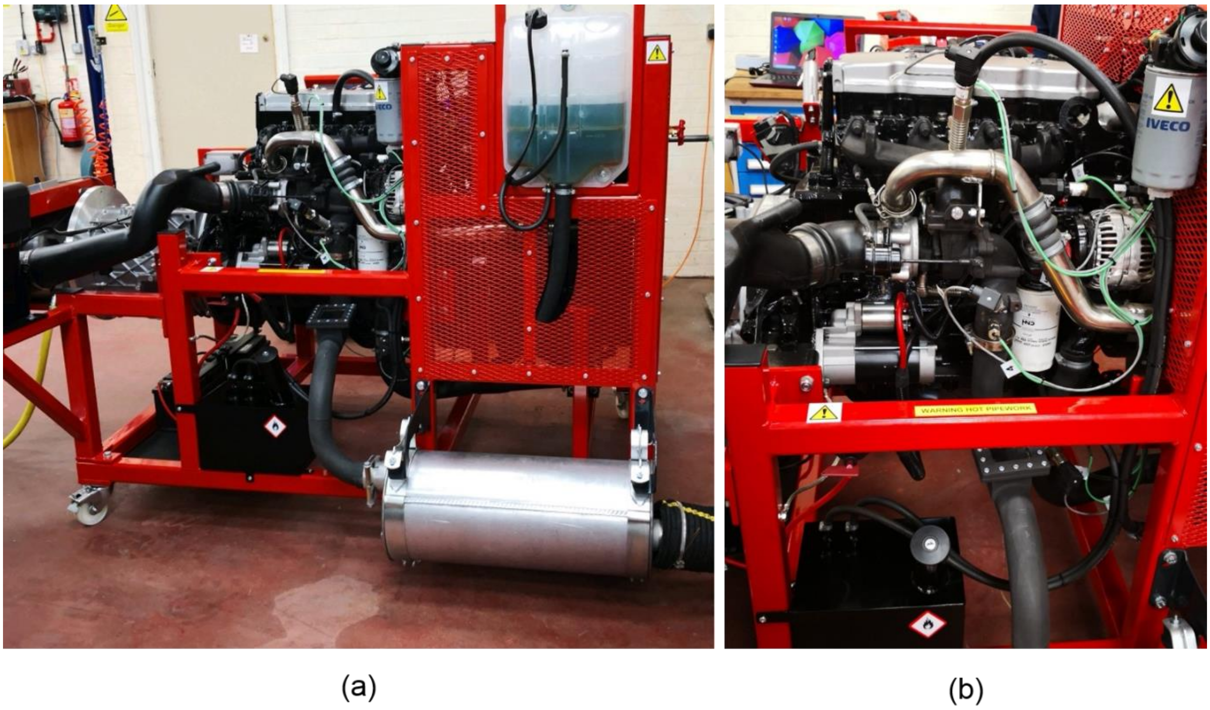
(a) (b)

Figure 8.1 Photograph of instrumented engine, front view (a) and side view (b), commissioned to enhance the testing facility.

## 8.3 Data Acquisition System

The instrumented Diesel engine was commissioned in the Engineering Dynamic Centre (EDC) laboratory as part of the PhD research (Figure 8.1) to explore advanced faulty detection techniques in the cooling and lubricant systems. The time history of the temperature and pressure data from various locations in the engine can be recorded during the engine operation. Additionally, there is a display unit integrated with the engine to provide the real time monitoring capability for the measured data. The data monitored in real time are shown as an example in Figure 8.2 – temperature and pressure readings are shown.

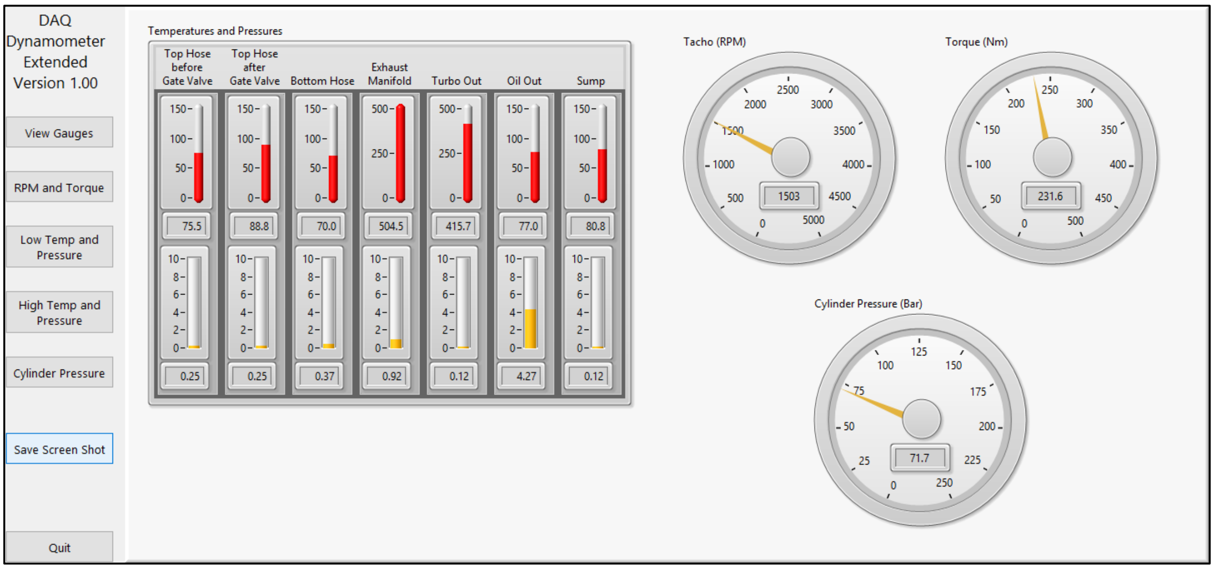

Figure 8.2 Photograph of the display unit in the instrumented engine to monitor the data acquisition system.

## 8.4 Preliminary result

The ten channels of temperature and the pressure, time histories were sampled simultaneously with duration of engine running period. The time histories were then transformed to different computer for the analysis purpose.

The results shown in this chapter are preliminary results as the instrumented engine was commissioned at the end of the PhD study and hence most of the research plans are discussed in the future work based on this engine testing facility.

At first, engine was set to idle engine running condition with normal engine settings and then inlet valve was half- and fully-closed to simulate some faulty condition to observe the potential variations in the temperature and the pressure. Secondly, the engine was set to run with the maximum load and the same experiment was repeated as first one.

The following notations describe the measurement details:

T1 – THbGV Temp - Temperature measured at the top hose before gate valve

T2 – THaGV Temp - Temperature measured at the top hose after gate valve

T3 – Bottom Hose Temp - Temperature measured at the bottom hose

T4 – Oil Out Temp - Temperature measured at the oil outlet

T5 – Sump Temp - Temperature measured at the sump

P1 – THbGV Pressure - Pressure measured at the top hose before gate valve

P2 – THaGV Pressure - Pressure measured at the top hose after gate valve

P3 – Bottom Hose Pressure - Pressure measured at the bottom hose

P4 – Oil Out Pressure - Pressure measured at the oil outlet

P5 – P5-Sump Pressure - Pressure measured at the sump

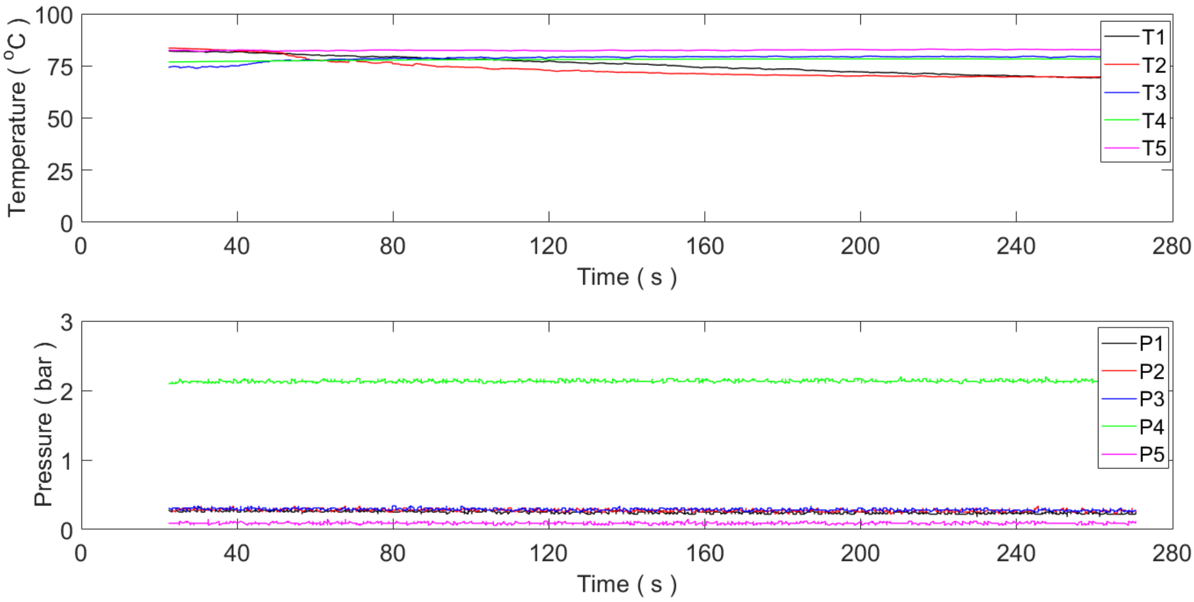

Figure 8.3 Temperature (top) and the pressure (bottom) time histories measured at different location of the engine cooling and lubricant system with idle engine running condition. T1-THbGV Temp, T2-THaGV Temp, T3- Bottom Hose Temp, T4-Oil Out Temp, T5-Sump Temp, P1-THbGV Pressure, P2- THaGV Pressure, P3-Bottom Hose Pressure, P4-Oil Out Pressure, P5-Sump Pressure.

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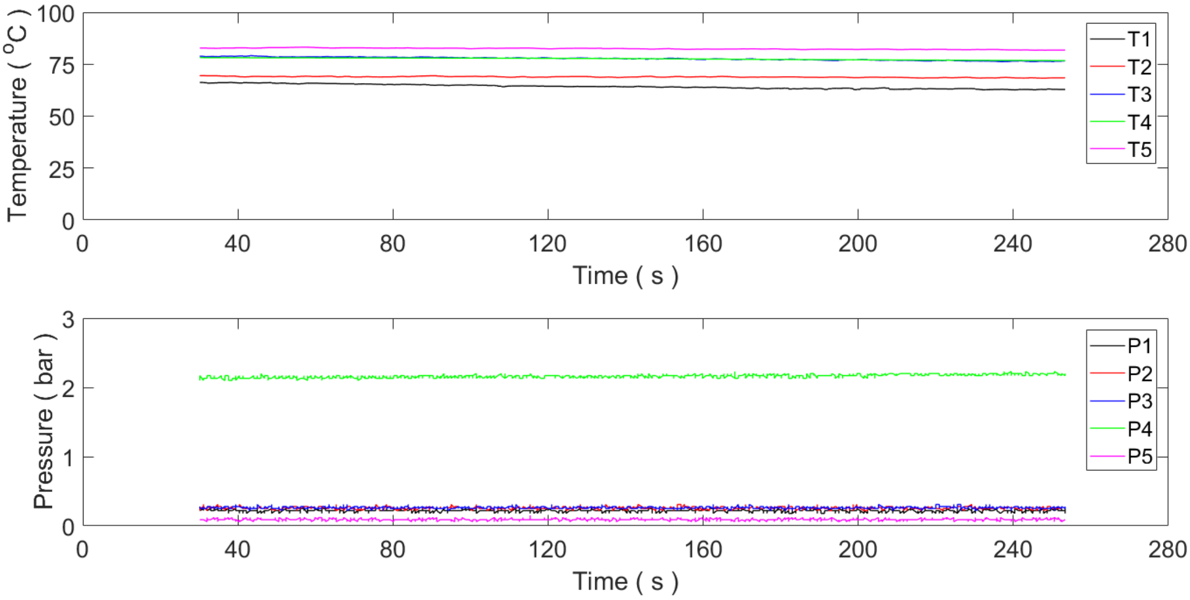

Figure 8.4 Temperature (top) and the pressure (bottom) time histories measured at different location of the engine cooling and lubricant system idle engine running condition – inlet valve was half-closed. T1-THbGV Temp, T2-THaGV Temp, T3- Bottom Hose Temp, T4-Oil Out Temp, T5-Sump Temp, P1-THbGV Pressure, P2- THaGV Pressure, P3-Bottom Hose Pressure, P4-Oil Out Pressure, P5-Sump Pressure.

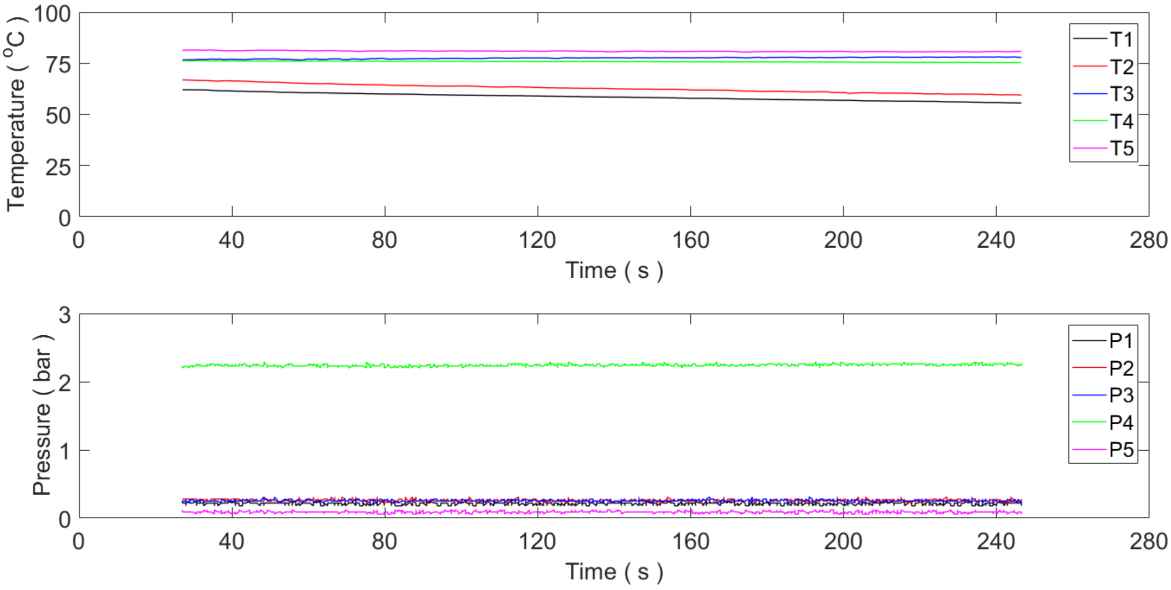

Figure 8.5 Temperature (top) and the pressure (bottom) time histories measured at different location of the engine cooling and lubricant system idle engine running condition – inlet valve was fully-closed T1-THbGV Temp, T2-THaGV Temp, T3- Bottom Hose Temp, T4-Oil Out Temp, T5-Sump Temp, P1-THbGV Pressure, P2- THaGV Pressure, P3-Bottom Hose Pressure, P4-Oil Out Pressure, P5-Sump Pressure.

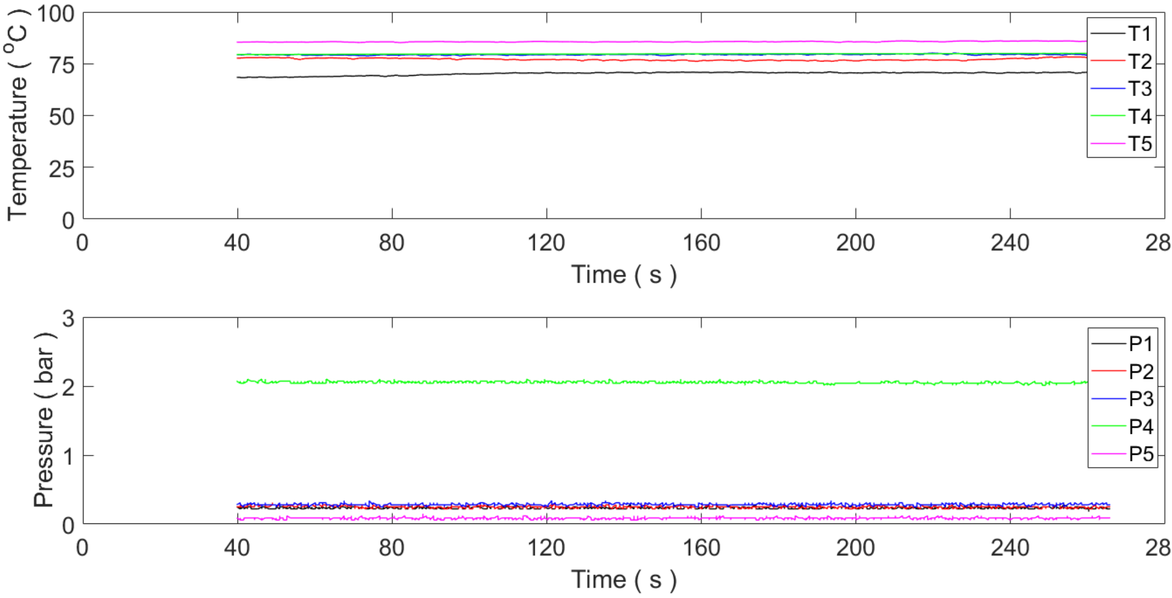

Figure 8.6 Temperature (top) and the pressure (bottom) time histories measured at different location of the engine cooling and lubricant system with engine running with maximum load. T1-THbGV Temp, T2-THaGV Temp, T3- Bottom Hose Temp, T4-Oil Out Temp, T5-Sump Temp, P1-THbGV Pressure, P2- THaGV Pressure, P3-Bottom Hose Pressure, P4-Oil Out Pressure, P5-Sump Pressure.

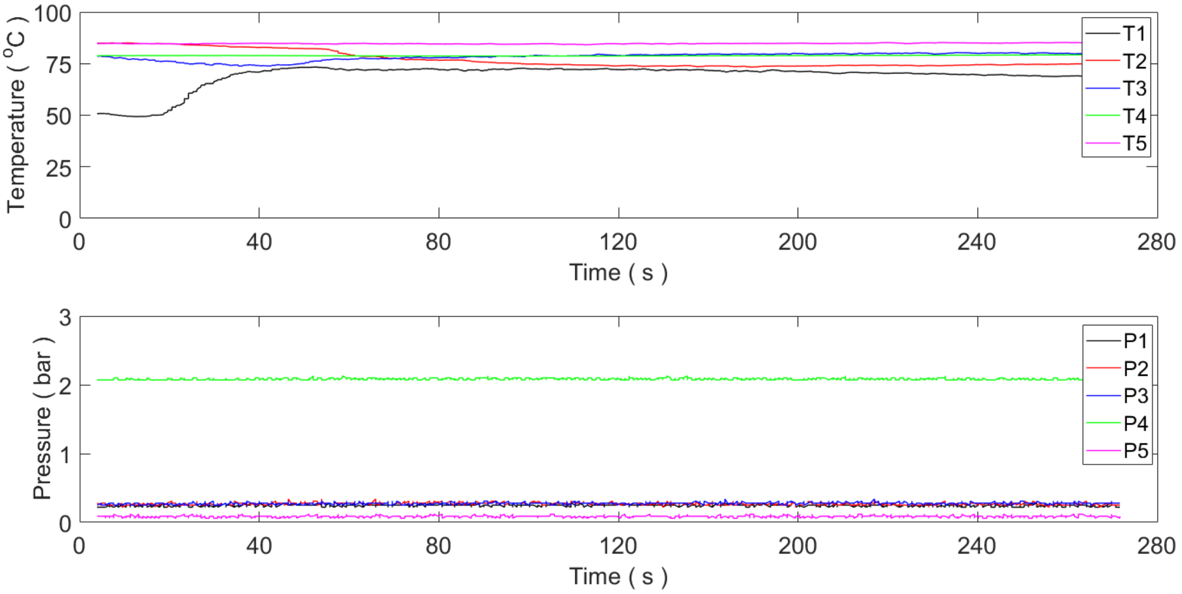

Figure 8.7 Temperature (top) and the pressure (bottom) time histories measured at different location of the engine cooling and lubricant system with engine running with maximum load – half-closed valve. T1-THbGV Temp, T2-THaGV Temp, T3- Bottom Hose Temp, T4-Oil Out Temp, T5-Sump Temp, P1-THbGV Pressure, P2- THaGV Pressure, P3-Bottom Hose Pressure, P4-Oil Out Pressure, P5-Sump Pressure.

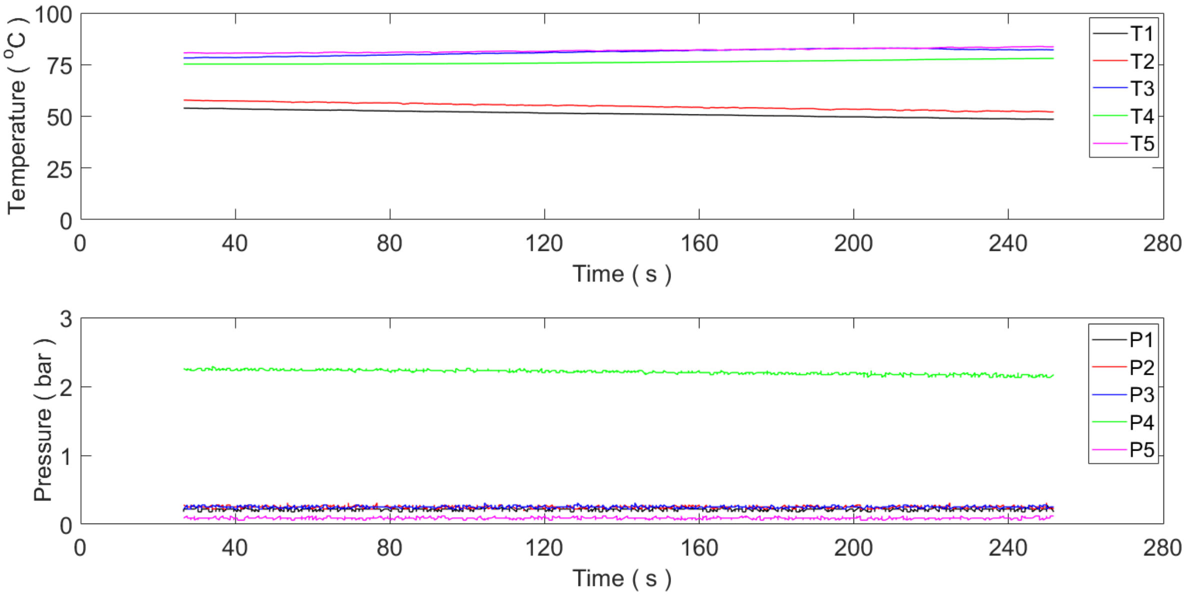

Figure 8.8 Temperature (top) and the pressure (bottom) time histories measured at different location of the engine cooling and lubricant system with engine running with maximum load – fully-closed valve. T1-THbGV Temp, T2-THaGV Temp, T3-Bottom Hose Temp, T4-Oil Out Temp, T5-Sump Temp, P1-THbGV Pressure, P2- THaGV Pressure, P3-Bottom Hose Pressure, P4-Oil Out Pressure, P5-Sump Pressure.

## 8.5 Discussion and Conclusion

The sophisticated engine testing facility was developed using the instrumented Diesel engine at the laboratory. The systematic health monitoring of cooling and lubricant system has been explored in this study. There is no systematic approach available so far to monitoring the failure mechanism of the cooling and lubricant system comprehensively. The cooling and lubricant systems play a vital role in the military vehicle engine performance, thus it is desired to have an integrated monitoring system to monitor the health of the cooling and the lubricant system and thus ensuring the high performance of engine during the operation of the military vehicles.

This study has particularly focused on developing the systematic lab testing facility to explore the different health monitoring techniques for the cooling and lubricant systems. The instrumented Diesel engine is capable of providing temperature and the pressure measurements at different locations of the cooling and lubricant systems with different engine running condition. The integrated data acquisition system in the engine provides real time measurements of different temperature and pressure sensors at different locations in the cooling and lubricant systems. In addition, there is a display unit to monitor all the measurements in real time. Instrumented Diesel engine is capable of simulation different engine running conditions at the lab, healthy- and faulty- running conditions.

The preliminary results were shown as examples in the Figure 8.3 to 8.7. The preliminary results seem to suggest that the temperature and the pressure behaviour with different engine running conditions with some fault simulation is close to the one observed in the Land Rover 110 military vehicle engine test described in Chapter 7. The detailed information and the plans for the future tests methods are discussed in the future work chapter. Although, this chapter was intended to explore only future testing methods for failure detection techniques in the cooling and lubricant systems, this study has contributed significantly to develop and build new effective lab testing facility and the protocol to improve the testing method of different failure detection techniques in the cooling and lubricant systems.

## Chapter 9

## General discussion

The previous chapters have focussed on the cost modelling and the case study on the military vehicles. Chapter 4 was covered on developing a simple and effective method to analyse the financial implication of integrating HUMS system. The case study on evaluation of frequency of failure of different systems in two different military vehicles was presented in Chapter 5. The failure detecting technique for the suspension system and the effective lab testing mechanism was studied (Chapter 6). The failure detection technique for cooling system and the effective lab testing mechanism was studied (Chapter 7) and then using similar approach to the cooling system, the lubrication system and their failure was studied in Chapter 8. The main outcomes of these chapters are summarised and discussed in this section.

### 9.1 Cost Modelling

The aim of this chapter was to develop a simple and effective method to analyse the financial implication of integrating HUMS system for military vehicles. The mathematical model developed in this study provides logical steps to estimate the yearly repair cost, operational availability and the overall costs. This helps understanding of the financial implication of HUMS integration over the whole service life. The available vehicle data from previously published literatures was used to validate the developed method, and it was found that the model predict similar break-even time as it has been observed by many researchers. And then, the model was also used to assess the financial viability of integrating HUMS in other military platforms e.g. light armoured vehicle, Piranha and Main Battle Tank, Challenger 2. In all the cases considered in this study, the analysis showed significant financial savings in the long term.

### 9.2 Case study on history of military vehicle (Piranha and Challenger 2) usage in the Royal Army of Oman

This study conducted a case study survey to identify the frequency of failure of different systems in two different military vehicles. The survey was conducted using the data obtained from the Royal Army of the Sultanate of Oman. The 20 challenger 2 and 40 Piranha military armoured vehicles were considered over the period of 10 years of their service in the Oman army. The main systems such as suspension, lubrication, cooling, electrical, driveline systems and other parts were studied using the data. The study showed that most affected parts in Challenger 2 and Piranha are cooling system, lubrication system and the suspension system. The study also found that the failure to monitor these systems leads to a catastrophic failure of engine and hence cause massive cost and the time delay for the military operation. Based on these findings, the cooling system, lubrication system and the suspension system are selected as the model systems to design and develop a HUMS system to diagnose the failures in the military vehicles, e.g. Land Rover 110 in Chapters 6, 7 and 8.

## 9.3 Investigation of effective lab testing mechanism to identify the failure of military vehicle suspension system

This study focussed on the failure detection technique for the suspension system. An experimental protocol was developed to examine the failure detection technique for the suspension system of the military vehicle. Land Rover 110 was used as the test platform vehicle. The frequency response function, transmissibility was used to evaluate the effectiveness of identifying the failure in the suspension system. Data obtained from the healthy and the faulty dampers was compared to identify the failures. The key resonance frequencies corresponding to the axle- and the body-mode were identified for the suspension system with the healthy damper (i.e. body mode 2.5 Hz and axle mode 11 Hz). Although the resonance frequency of the body- and the axle-mode were similar for the healthy and faulty damper, the small changes were observed when the excitation magnitude were increased. The strong conclusion on this finding couldn't be made as the narrow band (0.813 – 1.586g r.m.s) of excitation magnitudes were used. Two different vibration waveform were tested and the effect of vibration waveform was found to be negligible. However, the small changes in the resonance frequencies using different magnitudes of base excitation seems to suggest that excitation magnitude has the potential to identify the failure based on the frequency response function. Additionally, the effect of vibration exposure for the crew inside the vehicle was evaluated using the healthy and the faulty dampers. The higher vibration exposure at the seat when faulty damper was fixed to the vehicle seems to suggest that failure in the suspension system causes health risk to the crew inside the vehicle. The modifications and the future testing plans are discussed in the next chapter.

## 9.4 Investigation of effective lab testing mechanism to identify the failure of military vehicle cooling system

The failure detection technique for the cooling system was studied in Chapter 7. An experimental method was developed to examine the failure detection technique for the cooling system of the military vehicle. The temperature and the pressure measurement at different locations of the cooling system was measured and monitored with different engine running conditions at the lab and with the vehicle driving in the field. It was found that temperature and pressure readings for the healthy cooling system were consistent for both engine running at the lab and the vehicle driven in the field.

The failure was simulated to the cooling system by closing the inlet valve (to simulate the leakage of the coolant or the blockage of the System) and then removing the belt of the pump (to simulate the failure of the pump or cut-off of the pump driving belt). When the failure was introduced to the cooling system, the significant variation in the temperature was observed for all the engine running conditions at the lab as well as the test with the vehicle running in the field. When the inlet valve closed to the half position, the temperature increased at both locations (T1 and T2) over time. For the fully-closed valve position, temperature increased at the location T1 and decreased at the location T2. When the belt of the pump removed, the temperature measured at the location T1 decreased and temperature at location T2 increased over time. The similar behaviour was observed in both testing conditions, at the lab and the vehicle driven in the field. The variation observed in the temperature measured in different locations in the cooling system (T1 and T2) seemed to suggest that there is a failure in the cooling system causing the temperature fluctuations.

## 9.5 Development of lab testing mechanism using engine instrumentation to identify the failure of lubricant and cooling system

Chapter 8 was designed to develop a lab testing facility to examine failure detecting technique for the cooling and the lubrication system. The instrumented Diesel engine was commissioned for this test facility at the laboratory. The systematic health monitoring of cooling and lubricant system has been explored using this new instrumented engine system. The literature shows that there is no systematic approach available so far to monitoring the failure mechanism of the cooling and lubricant system comprehensively. The health monitoring of the cooling and the lubricant system ensures the high performance of engine during the operation of the military vehicles.

The instrumented Diesel engine is capable of providing temperature and the pressure measurements at different locations of the cooling and lubricant systems with different engine running condition. The integrated data acquisition system in the engine provides real time measurements of different temperature and pressure sensors at different locations in the cooling and lubricant systems. In addition, the display unit on the engine provides real time monitoring function for all the measurements during the test. Instrumented Diesel engine is capable of simulating different engine running conditions at the lab, healthy- and faulty.

The preliminary results were shown as examples in Chapter 8. The temperature and the pressure behaviour seem to match with the one observed in Chapter 7. The detailed information and the plans for the future tests methods are discussed in the chapter 10. Although, this chapter was intended to explore only future testing methods for failure detection techniques in the cooling and lubricant systems, this study has contributed significantly to develop and build new effective lab testing facility and the protocol to improve the testing method of different failure detection techniques in the cooling and lubricant systems at the lab.

# Chapter 10

# General conclusions, limitations and recommendations

## 10.1 General conclusions

The study described in this thesis attempts to develop a viable laboratory testing method to identify the fault conditions in the suspension, cooling and lubricant systems in military vehicle that can be used for the purpose of HUMS. An in depth experimental investigation has been conducted using different lab testing methods on the military Land Rover 110 vehicle to evaluate the effectiveness of different fault detection techniques. A cost modelling was conducted to analyse the financial implication of integrating HUMS system was proposed for the military land vehicles. And a case study was conducted using the data obtained on two military vehicles to identify the probability of failures in different components. Finally, a new laboratory testing facility was developed for future work in this area.

### Cost study findings

This study presented a simple and effective method to analyse the financial implication of integrating HUMS system was proposed for the military land vehicles. The model provides estimates of the yearly repair costs, operational availability and the overall costs to understand the financial implication of HUMS integration over the whole service life. The method was validated by using the available vehicle data from previously published literatures, and it was found to predict similar break-even time. The model was also used to assess the financial viability of integrating HUMS in other military platforms e.g. light armoured vehicle, Piranha and Main Battle Tank, Challenger 2. In both the cases, the analysis showed significant financial savings in the long term.

### Case study finding

This case study aimed to study failure of different systems in two different military vehicles widely used by the Royal army of the Sultanate of Oman. The failure history of Challenger 2 and the Piranha were studied using 20 Challenger 2 and 40 Piranha over the period of 10 years. The study showed that most affected parts in Challenger 2 and Piranha are cooling system, lubrication system and the suspension system.

The failure to monitor these systems can lead to a catastrophic failure of engine and hence cause massive cost and the time delay.

### Failure detection of suspension system

This study aimed to develop an experimental protocol to identify the failures in the suspension system of the Land Rover 110 military vehicle. The frequency response function was used to evaluate the effectiveness of identifying the failure in the suspension system. The changes in the resonances frequency of healthy and the faulty damper was used to identify the failure. Although the resonance frequency of the body- and the axle-mode were similar for the healthy and faulty damper, the small changes were observed when the excitation magnitude were increased. The strong conclusion on this finding could not be made as the range of excitation magnitudes was narrow (0.813 – 1.586g r.m.s). It was also found that effect of vibration waveform is negligible. However, the small changes in the resonance frequencies using different magnitudes of base excitation seems to suggest the excitation magnitude has the potential to identify the failure based on the frequency response function. Additionally, the effect of vibration exposure for the crew inside the vehicle was evaluated using the healthy and the faulty dampers. The higher vibration exposure at the seat when faulty damper was fixed to the vehicle seems to suggest that failure in the suspension system causes health risk to the crew inside the vehicle.

### Failure detection of cooling system

This study aimed to develop an experimental method to examine the failure detection technique for the cooling system. The changes in the temperature and the pressure were used to identify the failures in the cooling system. The temperature and the pressure measurement at different locations of the cooling system were measured and monitored with different engine running conditions at the lab and with the vehicle driving in the field. Temperature and pressure measurements for the healthy cooling system were consistent for both engine running at the lab and the vehicle driven in the field.

When the failure was introduced to the cooling system, the significant variation in the temperature was observed for all the engine running conditions at the lab as well as the test with the vehicle running in the field. The variation observed in the temperature measured in different locations in the cooling system indicates that temperature fluctuations were caused by the failure in the cooling system. This study concluded that temperature measurements at different locations in the cooling system can be used as a viable mechanism to identify the failure in the cooling system.

### Development of new testing facility

As part of this PhD study, new lab testing facility was developed to enhance the testing methods described in the Chapter 7 and Chapter 8. The new diesel engine with all the required all the inbuilt sensor instrumentation was commissioned at the lab. The preliminary test was conducted using this new facility to compare the response with the one obtained using Land Rover 110 vehicle engine. The preliminary results seem to suggest that the temperature and the pressure showed similar behaviour to the one observed in the Land Rover 110 military vehicle engine test.

## 10.2 Limitations

This section provides the limitations which have been encountered for this research study. The main limitations came from the experimental studies. The followings are the main limitations found to be for this particular research:

1. The small population of data for the case study was used as the restrictions on obtaining the data from the military vehicle.
2. The limitation of narrow band excitation magnitude

The experiment of suspension system failure was conducted using the narrow band excitation magnitudes – this limitation comes from the health and safety issue of the testing facility. Wider ranges of excitation magnitudes would be more realistic cases as these military vehicles mostly operates in remote off-road desert areas and mountain such as in the Sultanate of Oman. These operating areas expose the vehicle to the highest excitation magnitudes.

3. The limitation of testing time for the lubrication system

The simulation of failures in the lubrication system or running the engine till the failure point was not the ideal scenario. The engine was not set to run until the failure point.

4. Health and safety issues regarding testing methods

Majorities of testing limitations came from the health and safety concerns such as vibration exposures, testing time and introducing some failure to the engine.

## 10.3 Recommendations

This section provides the recommendations for the future study on this area.

1. In this research I was not able to find vehicles with HUMS fitted. Therefore, analytical analysis was made based on assumption such as scheduled maintenance data. Hence, as part of future work, it is recommended that maintenance data concerning with and without HUMS is compared to refine some of the cost modelling analysis.
2. Case study – use more population of data from different types of military vehicles (current study only considered two types of vehicles).
3. Suspension system failure detection – the testing method can be improved using wide range of frequency and the amplitudes with longer period of testing time.
4. Suspension system failure detection – design a new rod damper to introduce different types of failures for fault detection testing (this will allow us to introduce realistic failure in real time such as leaking an oil from the damper while the vehicle is running on test).
5. Suspension system failure detection – carry out the data capturing while driving the vehicle in the street for longer period with faulty damper.
6. Cooling system failure detection – use the newly instrumented engine testing facility to test the different fault conditions introduced to the engine with different engine running conditions and then compare the results with the same faulty conditions introduced to the vehicle engine with infield running conditions.
7. Lubrication system failure detection – use the newly instrumented engine testing facility to test the different faulty conditions introduced to the lubrication system with different engine running condition and then compare the result with the data obtained with the vehicle running in the field.

8. Although literature review was undertaken to access a potential communication network system that coupled with HUMS would lead to autonomic logistics system. However, to majority of research time was spent in developing an approach to demonstrate HUMS diagnostic system and as a result ALS has not been considered. Therefore, it is recommended that the future research should be to develop an effective Autonomic Logistics System. Which could link with HUMS diagnostics to yield efficient fleet maintenance and operational availability.

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# Appendix

## Appendix A

## Health and usage monitoring of the suspension system of the Land Rover military vehicle

### Suspension Systems

#### Introduction

The vehicle suspension systems have been designed to maintain contact between a vehicle’s tyres and the road, and to isolate the frame of the vehicle from the harmful vibration comes from the road to keep the vehicle and the crew safe. The suspension systems work incorporating with other sub-systems of the vehicle such as tyres, wheels, braking system, steering systems to provide the safe and the ride comfort. The main functions of the suspension systems include, support the weight of the vehicle, wheel alignment, keep the tyres in firm contact with the road, provide comfortable ride and etc.

The shock absorbers parallel with spring are widely used to damp out the oscillation comes from the road by absorbing the energy. A shock absorber is one of the most important elements in a vehicle suspension system. The shock absorbers provide better handling, comfort, and safety while driving a vehicle by controlling the damping of the relative movement between the wheel and the vehicle body. The shock absorbers are designed to ensure the durability of other parts of the vehicle body. The shock absorbers are the crucial elements in the vehicle to provide the ride comfort of the crew to ensure the health and the safety of the crew.

In the context of the military vehicle, the performance of the military crew inside the vehicle is important as it has the specified tasks, hence the isolation of vibration coming from the road to the vehicle body is crucial which can only be achieved by applying efficient suspension system to the vehicle. The failure of suspension system causes catastrophic damage to the crew (see Fig 6.18) and the weapon systems installed in the vehicle. The speed of the vehicle proportionally increases the error in the accuracy of the target point of the weapon systems used in the vehicle, because if the suspension system fails to damp out the excessive vibration coming from the high speed operating military vehicle which then cause the weapons to vibrate. Thus the accurate operation of the weapons mounted on the military vehicle is obtained only via healthy suspension systems.

### Types of suspensions in the military vehicle

The suspension system can be mainly categorised into two groups, dependent suspension and independent suspension system. These two different types were widely used in many military vehicles depends on the purpose of the suspension in the military environment. The pros and cons of these two types varies between different variants of them.

### Dependent suspension system

The dependent suspension system refers when the suspension system allows the movement on the one-wheel transmit to other wheel. This types of suspension includes, beam-axle, leaf-spring, de-Dion tube etc. The main advantage of this type suspension is that they can take high load capacity. This suspension system is widely used in the military vehicles.

### Independent suspension system

The independent suspension system refers when the suspension system allows the movement on one wheel purely restricted to that particular wheel without transmitting to other wheels. This types includes, swing axle, MacPherson strut, multi-link suspension and etc. These are not widely used in the military vehicle as they have low load carrying capacity, but high ride comfort.

### Shock absorbers

There are two categories of passive dampers widely used in the automotive industry as shown in Figure A.1, mono-tube and twin-tube. Contrast to the twin-tube damper, a mono-tube damper (Figure (A.1 - a)) composed of one cylinder filled with oil through which a piston with an orifice is moving. When the fluid passing through the orifice, a resultant damping force was developed due to the pressure drop between the compression and extension chambers. The presence of the gas chamber allows the volume of the piston rod to enter the damper. The gas in the chamber brings a spring effect to the force generated by the damper which maintains the damper at its extended length when no force is applied [63].

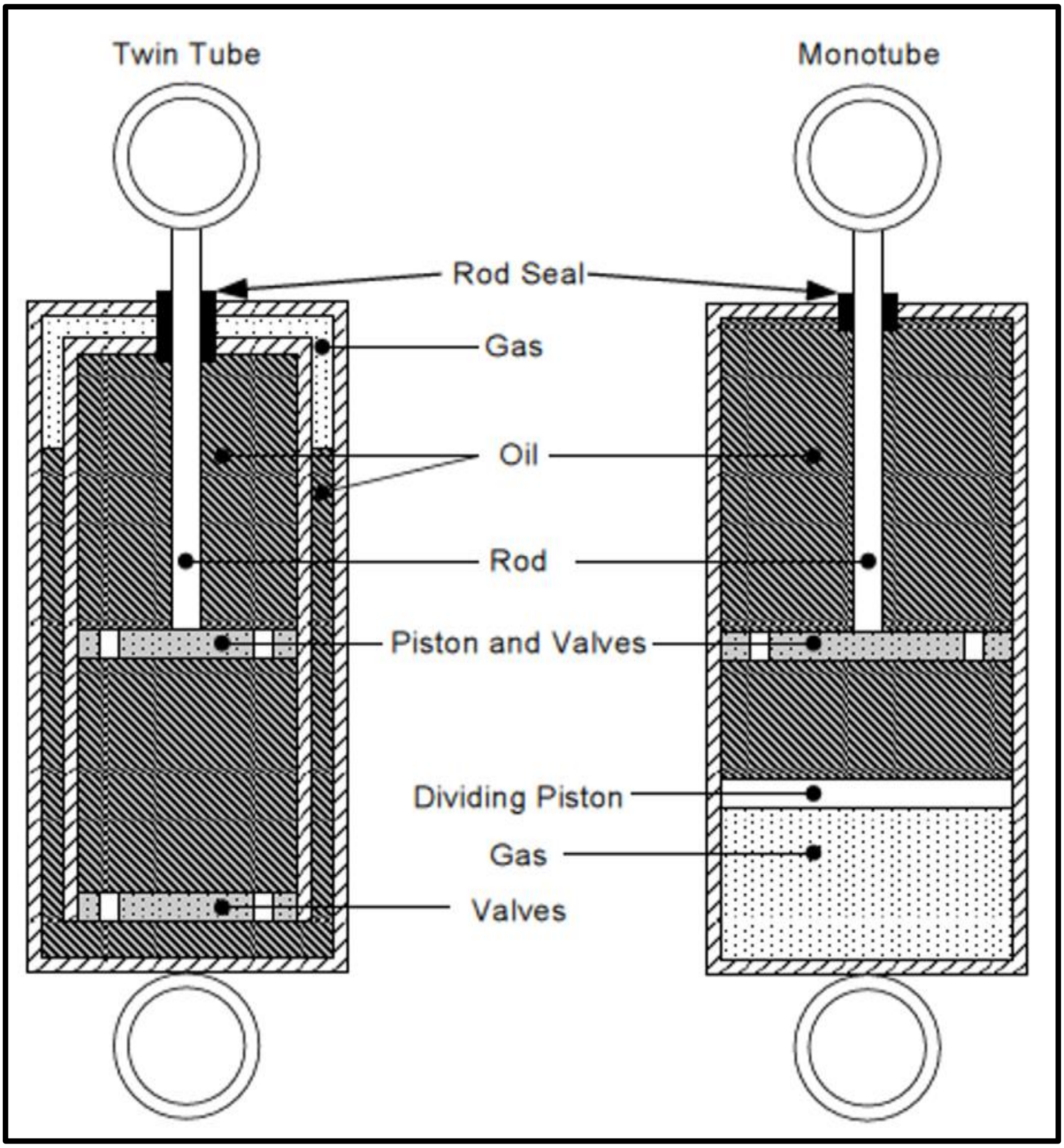


Figure A.1 Schematic of the (a) – twin-tube damper and (b) –mono-tube damper [63].

*<u>Mono-tube shock absorbers</u>*

The mono-tube dampers are simpler in term of structure, lighter due to the fewer parts. Due to its structural design, the mono-tube shock absorbers are filled with the gas under high pressure, which consist only of a tube and have main valve giving the user flexibility to be installed without concerning the direction of the tube. In the tube there are two pistons namely separating piston and working piston. Working piston design has a very similar design to that of twin tube shock absorbers. The tube of the mono-tube shock absorber is wider than that of a twin tube – causing difficulties of using this type of shock absorbers in the vehicle whose original equipment shocks are twin tube type. Separation valve is moving freely and divide gas from oil at the bottom of the shock absorber. The area below the valve is filled with gas at a pressure of about 360 psi [64]. This gas sustains some the vehicle's weight as it brings the spring effect during the suspension travel.

Pros:

- The mono-tube can be mounted in any direction
- And this type cools easier because the main pipe is exposed to air

Cons:

- Thus type is difficult to be used with the vehicle whose original equipment manufacturer shocks are twin tube
- And failure of the tube causes the destruction of the shock absorber.

### *Twin-tube shock absorbers*

In the twin-tube shock absorber, the lower part of the reservoir tube contains oil and at the top of the pressure pipe, piston rod passes through sealed guide. The piston rod is lowered when the suspension take movement which then pumps the excess oil through the valve at the base of the tube. The fluid movement through the valve causes the dissipation of the energy during the suspension travel. The twin tube gas shock absorbers provide more stability by adding nitrogen gas with low pressure at the bottom of the pipe. The ppressure of the gas inside the tube is in the range between 100 and 150 psi depending on the amount of liquid in the bottom of the reservoir tube [64].

Pros:

- Twin-tube shock absorber Improves stability of the vehicle by reducing the rotation, swing and momentum when braking applied
- And this reduces aeration, which improves control over different types of road surfaces compared with non-gas filled shock absorbers

Cons:

The twin-tube shock absorbers can be mounted in a specific one direction as it has a specific structural functionality.

**Springs**

The spring is mainly used as one of the main component in the suspension system. There are different types of springs used in the military vehicle which includes coil, leaf and torsion bar. The main function of the spring is to support the body weight and stimulate the resonance frequency of the body.

Spring shock absorber is designed to absorb the jerks or bumps usually using coil spring. The spring shock absorber is usually designed with the stiffening characteristics by tightening the spring element. The centre part of the spring shock absorber usually attached with rebound dampening unit. Up and down wards motion of the shock absorber changes the length of the shock absorber allowing the fluid inside the shock absorber to start to move. Springs length is usually controlled by turning the disc at the bottom of the spring on the threads. The shorter spring length increases the preload - making the rear wheel more resistant to upward motion. The dampening is both controlled and adjusted in the spring shock absorber by controlling the fluid reservoir with the valve by controlling the fluid flow.

**Dampers**

The damper is a mechanical or hydraulic device designed to absorb and damp shock impulses. There are different types dampers used in the military vehicle which includes, mono and twin tube dampers, electro-magnetic dampers and etc.

The damper can be either mechanical or fully relies on fluid. The damper absorbs the energy by controlling the fluid flow inside to the outside of the chamber by controlling the fluid flow using the orifice of the valve during the piston actuation.

The main dampers in the military vehicle can be initially classified as [64]:

(a) dry friction with solid elements;
    scissor
    snubber

(b) hydraulic with fluid elements;
    lever-arm
    telescopic

The modern military vehicles mainly use hydraulic type dampers.

## Functionalities of the suspension systems

The main functions of the suspension system include, support the weight of the vehicle, wheel alignment, keep the tyres in firm contact with the road, provide comfortable ride and etc. The suspension system can be selected for a particular application depends on the main functionality of the vehicle.

The spring and shock absorbers compress and expand while the vehicle is hitting through the bumps on the roads when the vehicle is moving. The spring will act as absorber of the impact loads and allow the wheel to follow the uneven terrain of the roads while maintaining the vehicle body stationary. After passing through the bumps, spring starts to release the absorbed energy and become to its original position by rebounding.

The sprung and un-sprung masses of the vehicle vibrate in different frequency ranges while the vehicle is moving in the rough terrain. The spring and shock absorbers in the vehicle control the motion transmitted though the sprung mass to un-sprung mass to prevent large oscillation of the un-sprung mass of the vehicle and ensure the continuous road grip which provides good tracking and braking. Damping therefore plays a vital role in driving safety and comfort. The body motion of the vehicle is largely control by the suspension system – acting as the filter to remove unnecessary vibration passing to the body and crew. The humans are sensitive to certain frequency ranges of the motion (i.e. 4 – 10 Hz) and good suspension system should eliminate the motion within these frequencies range to transmitted to the crew inside the vehicle.

## Main causes for the failure in the suspension systems

The different parameters govern the failure mechanism of the suspension systems which includes, terrain characteristics, sprung mass load on the vehicle, terrain vibration frequency and amplitude, temperature of the dampers and etc. The potential dangers of worn shock absorbers, or that the safety of their vehicle, its occupants and other road users is seriously compromised even if all other safety features are working correctly. The main issues associated with the worn shock absorbers are: It reduced braking efficiency resulting in longer stopping distances, reduced efficiency of Anti-Lock Braking Systems (ABS) and Electronic Stability

Control (ESP), Increased risk of skidding in the wet environmental conditions (i.e. Dhofar, areas in south of the Sultanate of Oman and Jabal Al Akhdar areas in middle part of the Sultanate of Oman), aquaplaning occurs at lower speeds, less control when cornering or caught in a cross wind, Increased driver tiredness and reduced speed or response, Increased wear of tyres and other suspension components and Increased passenger discomfort.

The main causes for the worn shock absorber come from different sources such as poor handling of the vehicle – low skill crew, subject the vehicle with heavy loading conditions, operating the vehicle in the harsh environmental conditions and poor maintenance of the vehicle. However, spring collapse does happen and there are even indications that it may be becoming more common. Several factors can contribute to spring collapse:

Bumps: Most spring collapses occur when the car or truck hits a bump, but it takes a very large or high-speed bump to break a normal, healthy spring. Oman has lots of rock-land, uneven terrain, deep valleys and the mountain areas where the military vehicle suffers lot from the suspension failures.

Overloading the vehicle: A spring that is heavily overloaded can break, but as with bumps, it takes greatly excessive load, usually far in excess of the vehicle's load rating, to break a typical automotive spring that's in good condition.

Rust or the corrosion effect: Almost military vehicle's springs are made of steel, and all steel rusts to some extent. Rust and other corrosion is the combination of a metal (such as the iron that forms the basis of steel) with oxygen from the atmosphere. Corrosion greatly weakens steel, rendering the springs much more subject to collapse. Salt, particularly the salts used on roads in snowy areas, greatly increases the rate at which steel rusts (i.e. Oman is surrounded by the sea and almost all the areas where the military operates have the corrosion issues to the vehicle).

### Failure detection techniques health monitoring issues

The failure detection or the health monitoring of the military vehicles is not well developed topic though some advance vehicle systems have some embedded mechanisms to detect some particular health issues. The vibration characteristics and the operating conditions of the suspension system are normally used to evaluate the health issues in the suspension components. However, there is no novel health monitoring systems available in the literature up to date.

The most parts of the suspension system wear out slowly, and with proper maintenance and periodic inspection they can be expected to experience only small, incremental problems. However, occasionally a suspension will fail suddenly and dramatically and the vehicle will in effect fall down — sometimes a couple of inches, until metal touches metal, and sometimes all the way only one or more wheels. This sort of sudden failure results when a spring or other weight-bearing part breaks, and is referred to as a collapse. The sudden failures of the suspension system cause the dramatic damage to the vehicle and its crew and potentially leads to entire collapse of the vehicle and ultimately loss of life of the crew. The proper structured Health and Usage Monitoring System (HUMS) usually helps to identify or send the signal of failure before it starts to collapse entirely. However, such universal systems are very sparse in the military vehicles – thus it begs or highly demanded the need for such universal HUMS system for the military vehicle.

### Military vehicle suspension systems

This section describes the suspension systems used in the different military vehicles and its functionalities and the advantages and disadvantages of those particular suspension system. These suspension systems are heavily used in different environment and hence the understanding of likely failure mechanism of these suspension systems while deployed in different harsh environment is essential to design the HUM systems for the military vehicles.


(a) (b) (c)

Figure A.2 Photograph of the Nissan patrol vehicle and its suspension system.

This vehicle is used as the patrol vehicle. As this vehicle is used in the harsh environment most of the time with the heavy load, the suspension systems are very vulnerable to failure. Although the suspension system of this kind can be replaced with the heavy duty one, the failure is still a high stake.

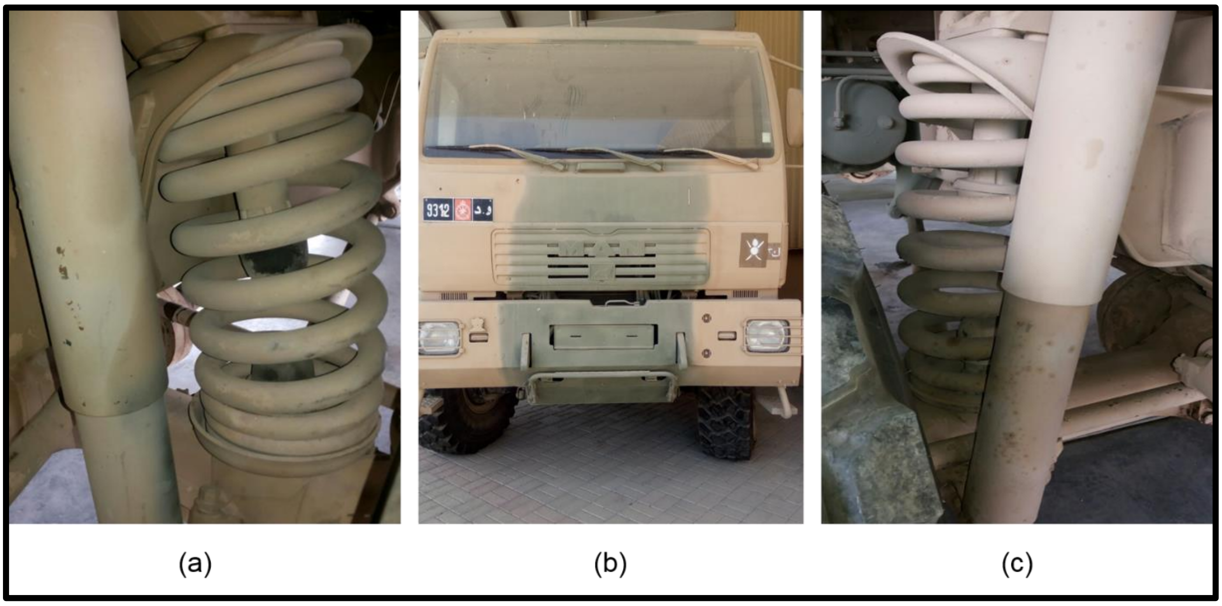

(a) (b) (c)

Figure A.3 Photograph of the MAN vehicle and its suspension system.

The MAN vehicle is used as a troop and logistics transporter. This vehicle has the very reliable suspension systems. This vehicle also operating in the harsh environment most of the time. Due to the operation in the unprepared roads, the suspension system of this vehicle also fails occasionally.

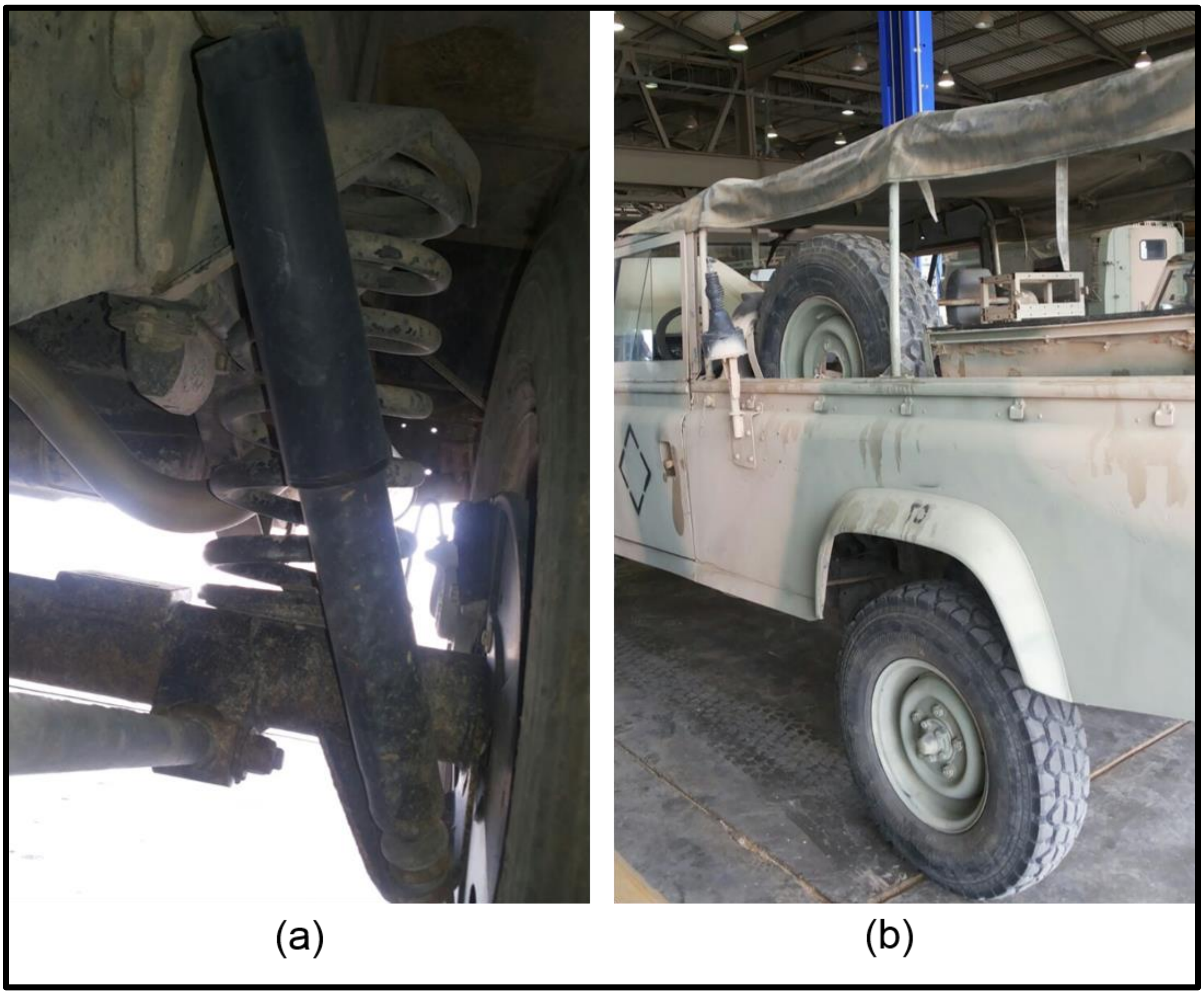
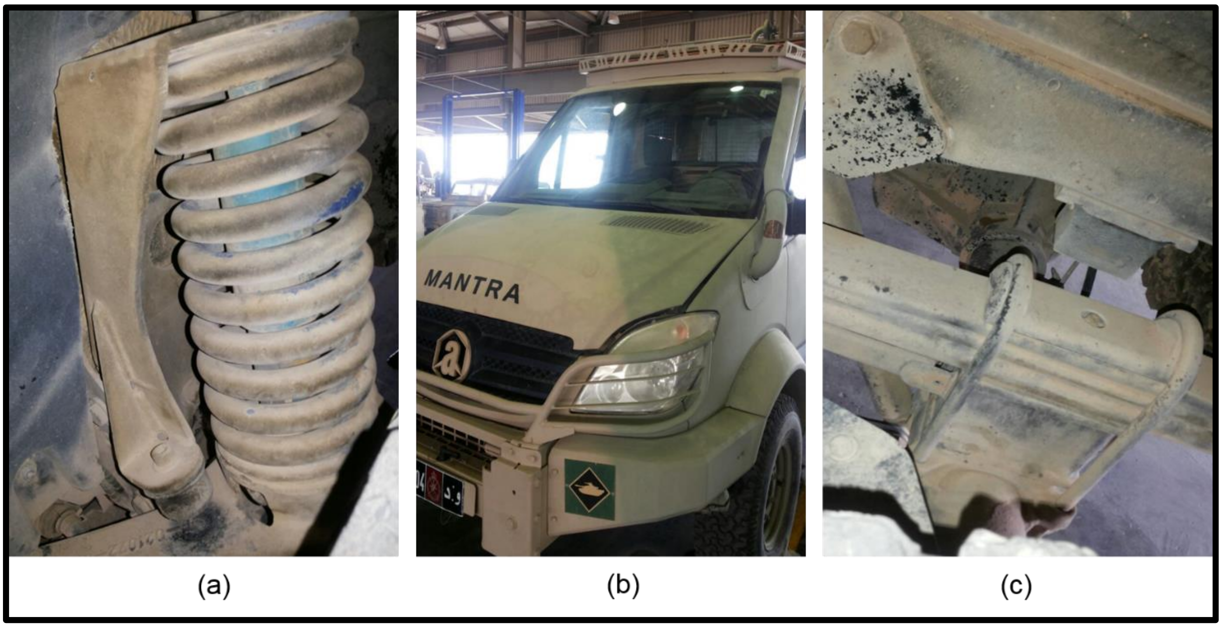


Figure A.4 Photograph of the Land Rover vehicle and its suspension system.

This Land Rover vehicle is used as the troop carrier. This vehicle also has a reliable suspension system; this vehicle has been in the service from early 50s. This vehicle also operates in the harsh environment. Due to the operation in the unprepared roads and overload operating conditions, the suspension system might fail occasionally.



(a) (b) (c)

Figure A.5 Photograph of the MANTRA vehicle and its suspension system.

This MANTRA vehicle is used as multi role troop carrier. This vehicle has not very reliable suspension system. This vehicle also operates in the harsh environment. Due to the operation in the unprepared roads and overload operating conditions, the suspension system often get failed.

(a) (b) (c)

Figure A.6 Photograph of the OSHKOSH vehicle and its suspension system.

This OSHKOSH military vehicle is used as heavy duty tactical transporter. This also transports troops, weapons, fuels and different logistics supply. This vehicle is used in harsh environment too. This vehicle suspension system is very robust and the vehicle is very reliable on unprepared road, rough terrain, high steep mountain slopes and the rocky roads (common deployment areas of the Royal Army of Oman) (see the Figures A.1, A.2 and A.3 for harsh terrain profile in Oman).

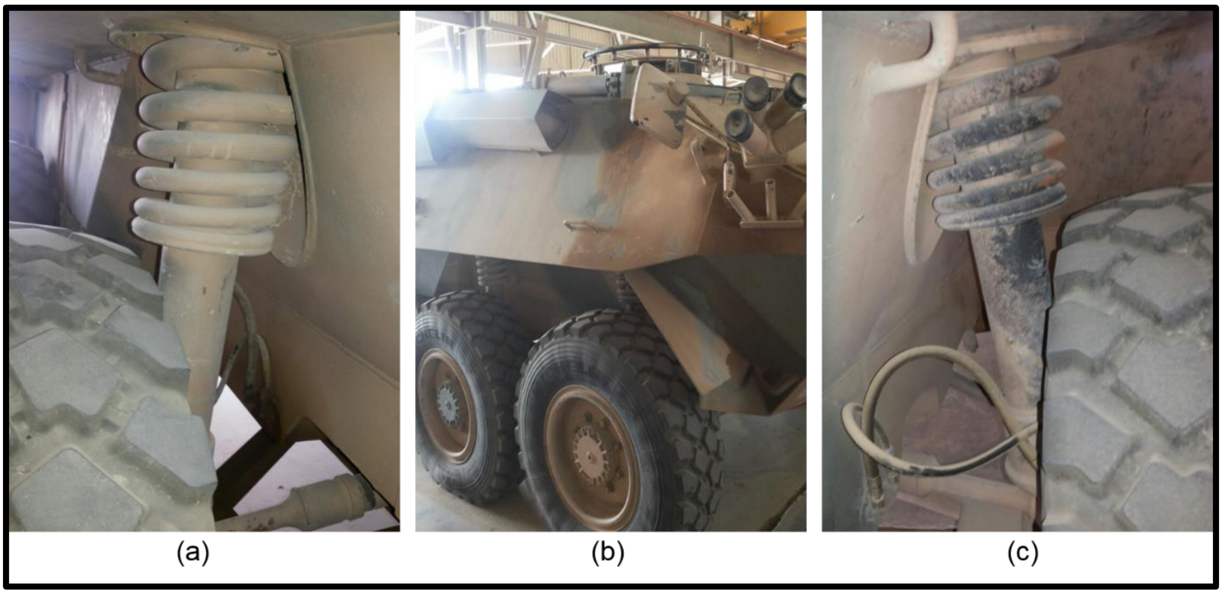


Figure 6.7 Photograph of the PIRANHA vehicle and its suspension system.

The piranha is used as Armoured Personal Carrier (APC). It is designed to operate in the on and off road terrain. This vehicle has a solid suspension system with heavy coil spring provide some armoured features to the vehicle. This vehicle has good mobility features for operating in the harsh environment with different terrains.

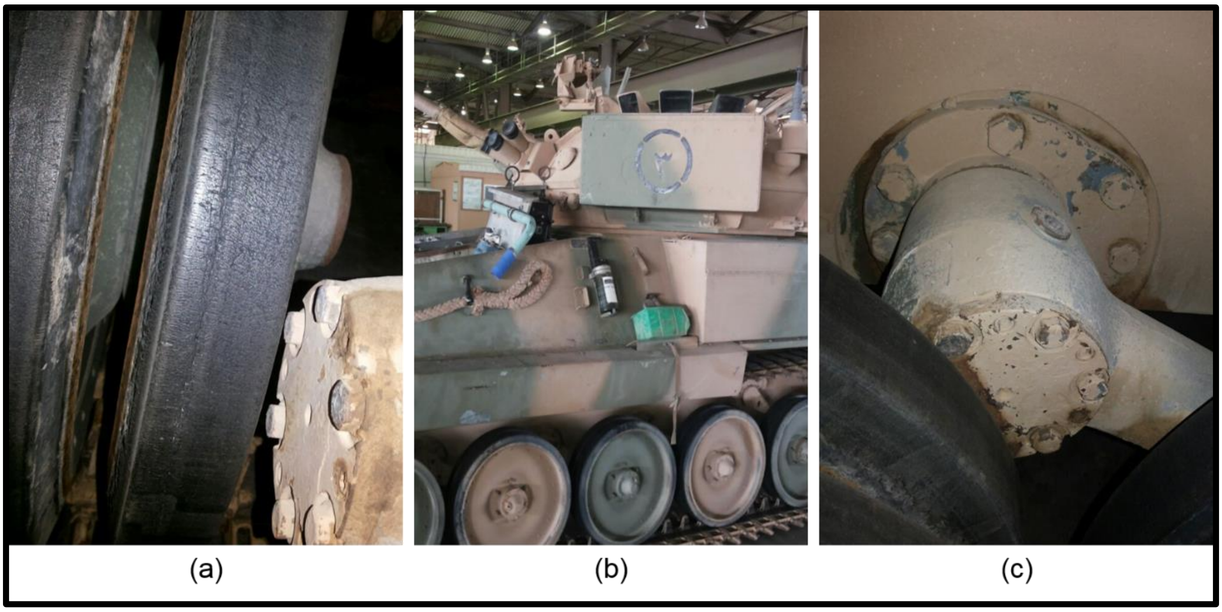

(a) (b) (c)

Figure A.8 Photograph of the SCORPION vehicle and its suspension system.

This SCORPION military vehicle is used as armoured reconnaissance vehicle. It is designed to be light, fast and agile to provide speedy operation. It is designed to operate in different terrain environment for collecting information about the enemy's strength and weapons. The suspension system of this vehicle is very reliable and durable.

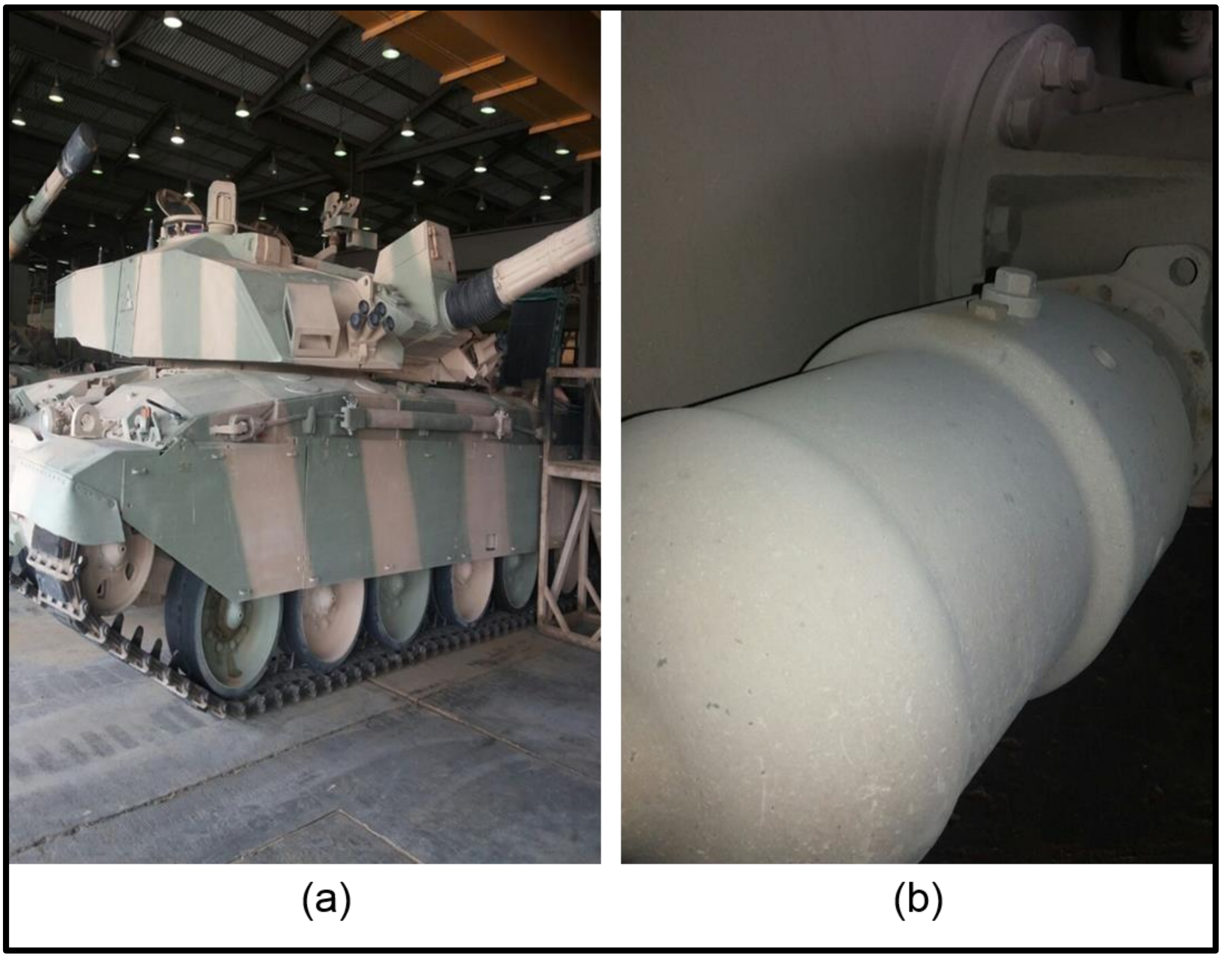
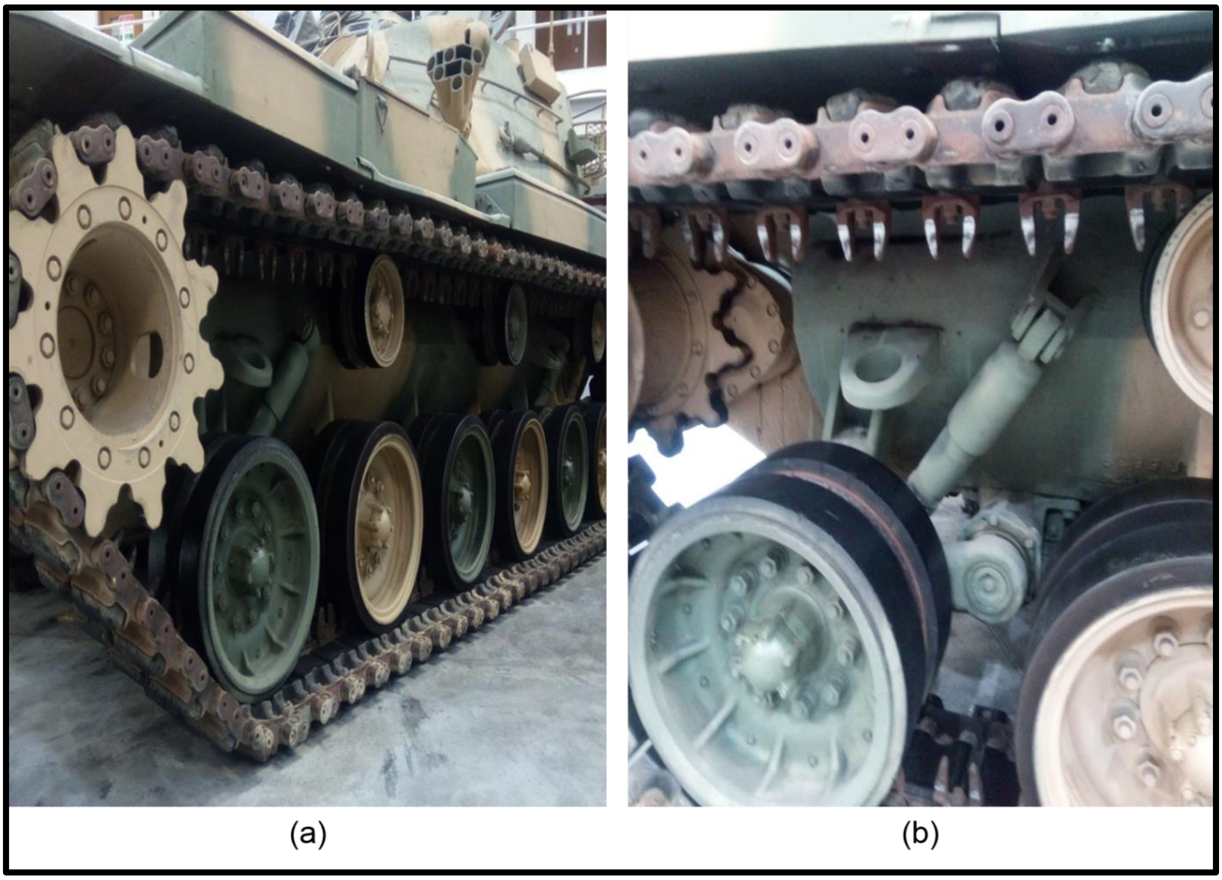


Figure A.9 Photograph of the M60 MBT and its suspension system.

This vehicle is used as Main Battle Tank (MBT). This vehicle has heavy duty torsion bar suspension system providing heavy duty features. The suspension system is very reliable. This vehicle is highly agile in operating harsh environment. The failure of the suspension system is very occasional.



(a) (b)

Figure A.10 Photograph of the CHALENGER 2 MBT and its suspension system.

This vehicle is used as main battle tank (MBT). This vehicle has heavy duty hydro-gas suspension system providing heavy duty features. The suspension system is very reliable. This vehicle is highly agile in operating harsh environment. The failure of the suspension system is very occasional. This vehicle is designed with superior fire power and armoured protection, viewing the mobility as least important.

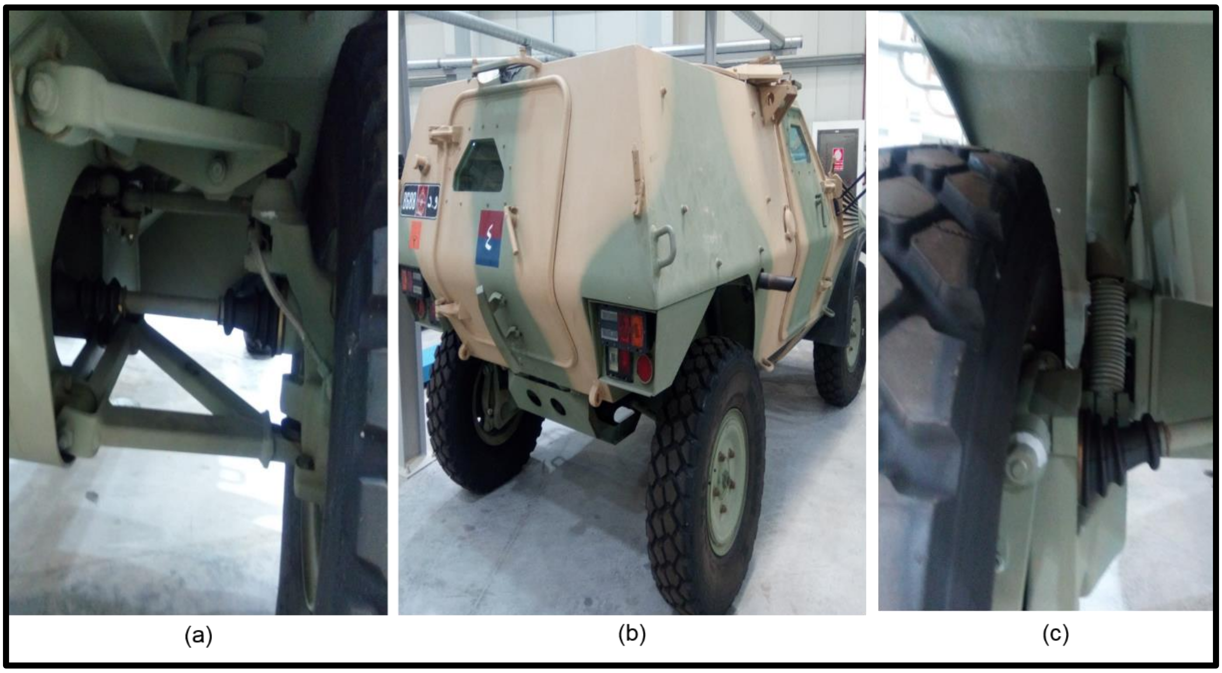


Figure A.11 Photograph of the PANHARD military vehicle and its suspension system.

This vehicle is used as light tactical vehicle. This vehicle has heavy duty double wish-borne type suspension system providing heavy duty features with high mobility. The suspension system is very reliable. This vehicle is highly mobile in operating harsh environment. This vehicle is used to launch the missiles often and hence requires good suspension system to response with the high impact loading of missiles while operates.

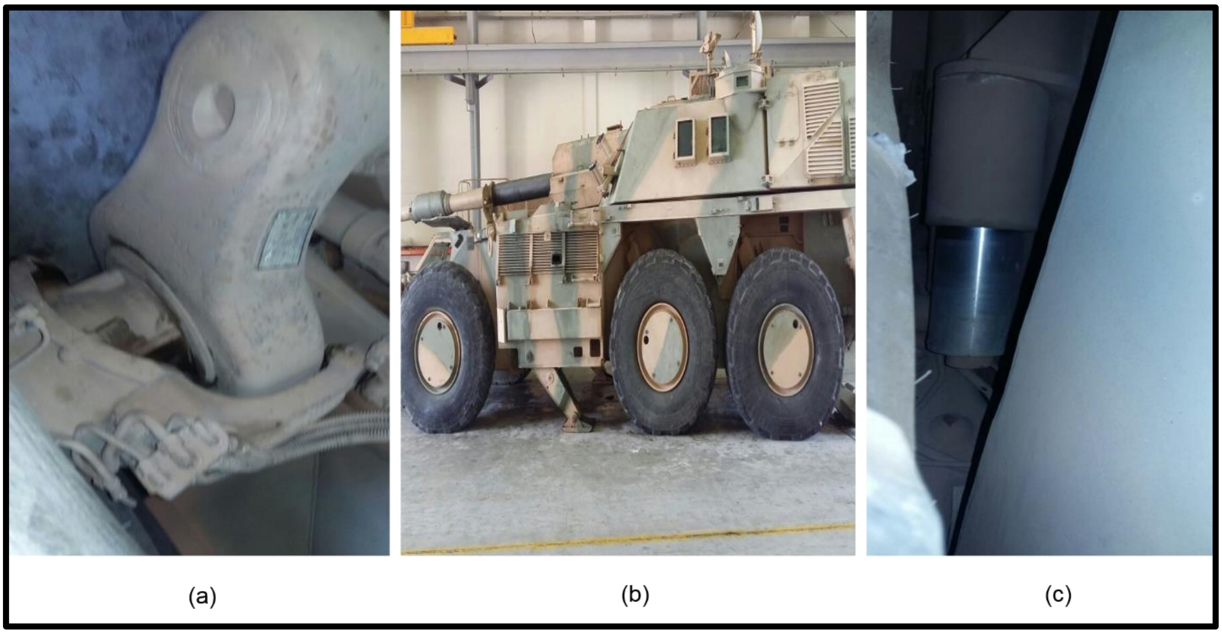

(a) (b) (c)

Figure A.12 Photograph of the 155mm self-propelled gun (G6) military vehicle and its suspension system.

This vehicle is used as main fighting vehicle with 155mm gun system. This vehicle has heavy duty type suspension system providing heavy duty features with high mobility. The suspension system is very reliable. This vehicle is highly mobile in operating harsh environment. This vehicle is used to fire enemy using long range gun system while on the operation and hence requires good suspension system to response with the high impact loading of gun system.

## ***Examples of some military vehicle suspension failures in Oman***

The following sections provide some examples of military vehicle failures. All these examples were recorded during the Oman military operations.

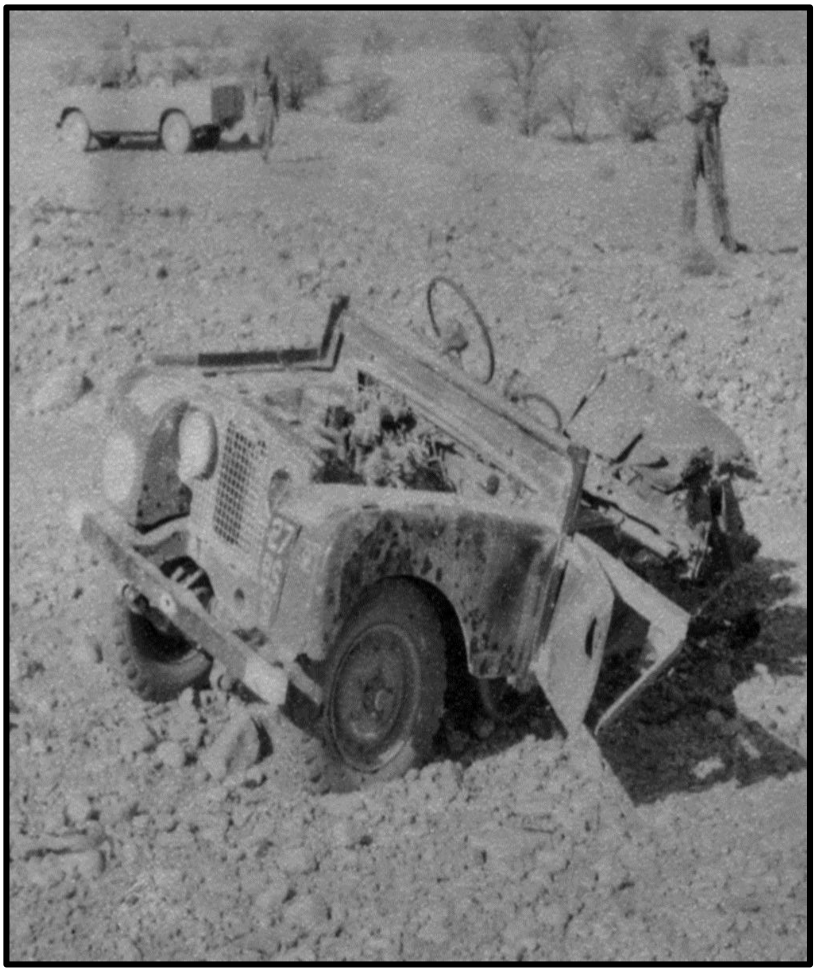


Figure A.13 Photograph of the failed Land Rover military vehicle its suspension system.

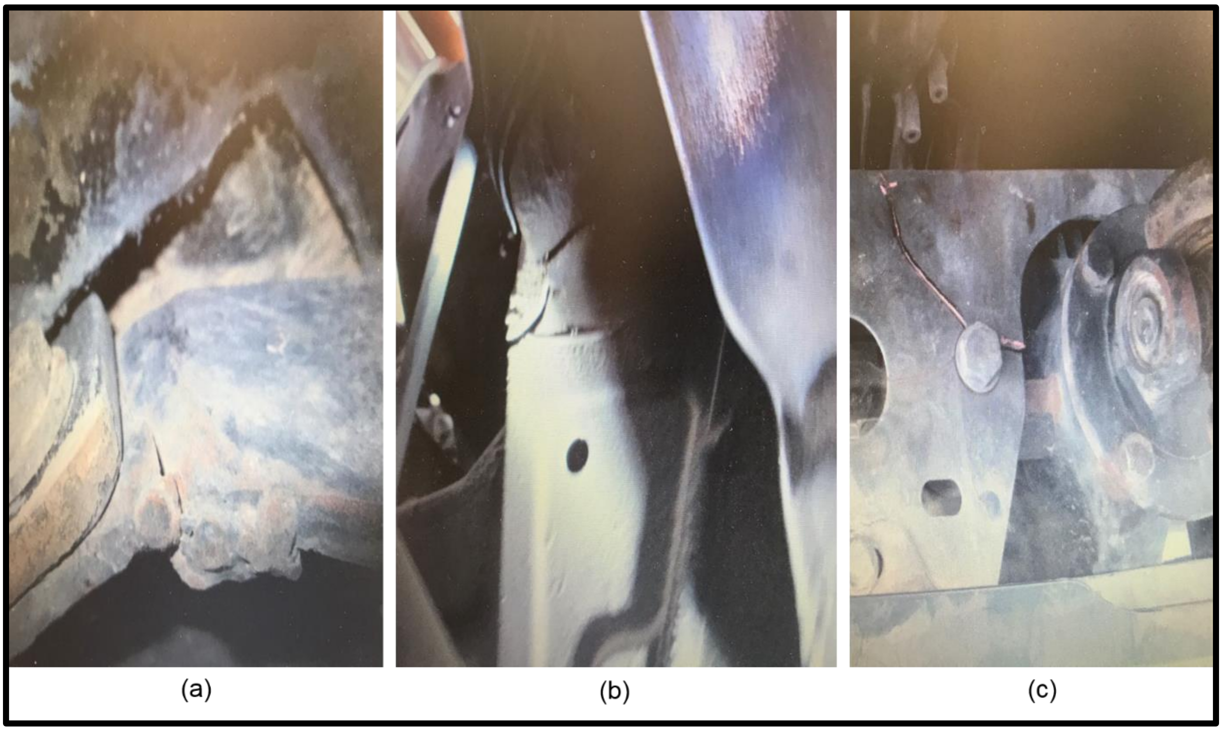


Figure A.14 Photograph of the failed MANTRA military vehicle its suspension system.

This failure occurred in the MANTRA military vehicle where fatigue crack was initiated at the different parts of the body and the crack was developed with the time while the vehicle is in use. This crack is believed to be initiated due to the weakness in the suspension system of the vehicle.

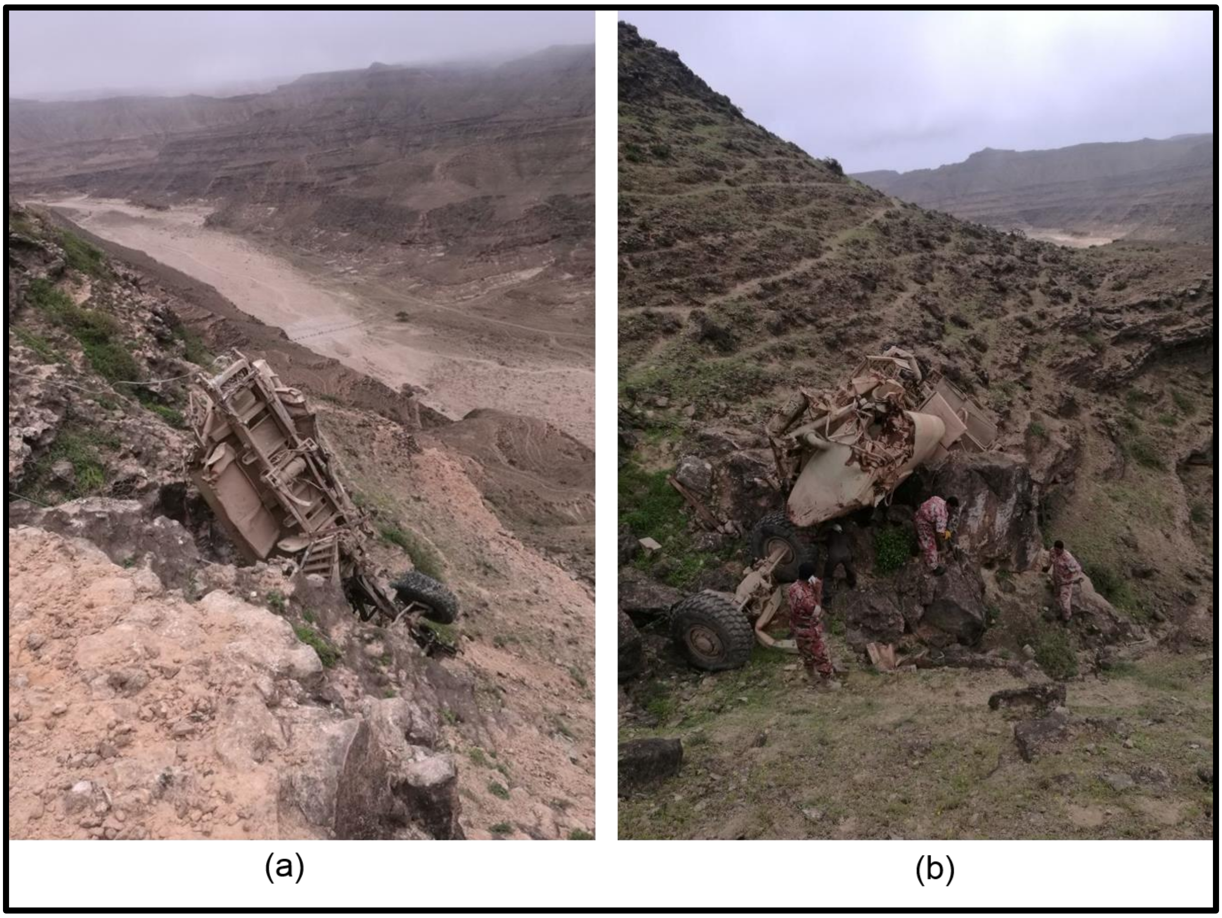


Figure A.15 Photograph of the failed MAN water tanker military vehicle its suspension system.

This accident occurred in the MAN water tanker military vehicle. The accident is believed to be caused by the shock absorber failure. The MAN has the robust suspension system, however the particular failure of the suspension was identified before the accident happened and the vehicle user was informed and negligence of the information lead to the accident (this accident was happened at the south part of the Oman mountain).

## ***Terrain details of the military vehicles used in the SULTANATE of OMAN***

This section describes some adverse environment of military deployment in different areas of the Sultanate of Oman where the Royal Army operates. These are some of the rough terrain areas where Royal Army of Oman operates. The harsh nature of these terrain often cause failure to the suspension systems of the vehicle which operates in this areas. The terrain in these areas often has steep slopes and sudden curves cause difficulties in mobility of the vehicle with failed suspension system.

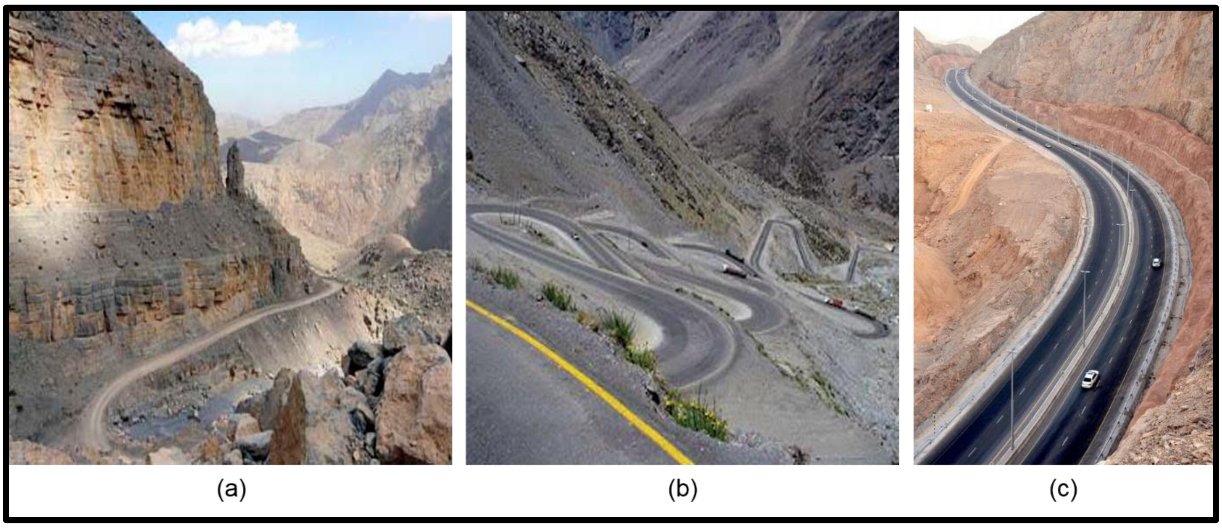


Figure A.16 Photograph of the harsh road profiles where Royal Army of Oman operates.

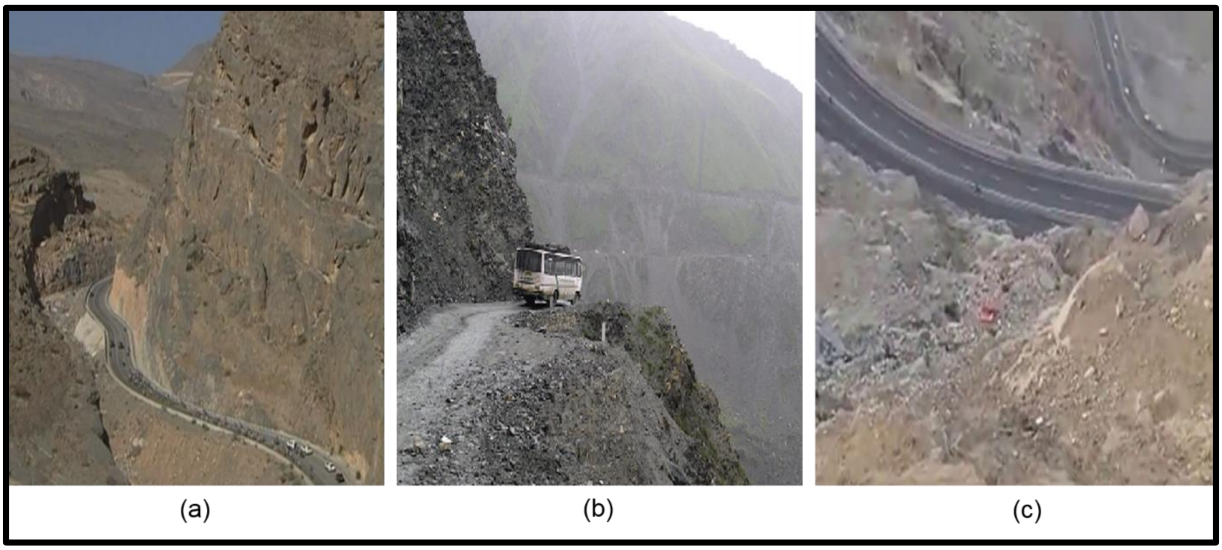


Figure A.17 Photograph of the harsh road profiles where Royal Army of Oman operates.

***Summary***

The scope of the of this chapter is to develop a novel health and usage monitoring system for the suspension systems in the military vehicles based on vibration characteristics and the operating conditions of individual components. The detailed description of the methodology is described in the particular chapter.

# Appendix B

## ***Health monitoring of the cooling and lubricant systems of the engine***

This Section describes the health monitoring procedures adopted in the cooling and lubricant system used in the military vehicles. Section describes the literature on the cooling system and the functionalities of the cooling system in the military vehicle. The following section describes the literature on the lubricant systems and the functionalities of the lubricant systems in the military vehicles.

### **Cooling Systems**

#### ***Introduction***

A cooling system is used in the vehicle to prevent the components of the engine from the overheat. There are some other advantages of an effective cooling system such as reducing the fuel consumption, retaining the strength of the components, prevents wear caused by friction between piston and cylinder, prevents high-temperature corrosions and reduces exhaust emission.

The cooling system is also responsible for the heating of the passenger space in a vehicle during the operation in the cold environment. Almost all the vehicles produced today equipped with liquid cooling systems. In the past, the vehicles were commonly used with air cooled engines. The air cooled engines are not common in the recent years due to the high power output engines, and therefore increased heat energy. The heat produced in a liquid cooled engine is transferred to the air, whereas in an air cooled engine the heat is transferred to the air directly.

#### ***Types of cooling systems in the military vehicle***

The cooling system can be mainly categorised into two groups, air cooled system and liquid cooled system. The liquid cooled system is widely used in the modern military vehicles due to the high output power of the engines. The air cooled systems are no longer used in the modern military land vehicles.

#### ***Cooling system function and components***

The cooling systems in the vehicles consist of radiator, thermostat, coolant, coolant recovery systems, heater core, water jacket and water pump. These individual components have their own functions and the purposes to keep the engine healthy.

The main function of the coolant system is to keep the engine operating temperature within the designed range to obtain the optimal performance [65]. The individual functionalities of each of the components as follows:

- Radiator – it removes heat from the cooling system in liquid-cooled engines of the vehicle from the outer wall of the radiator (fins).
- Thermostat – It is used to block the flow of coolant to the radiator until the engine has warmed up and once the engine reaches its operating temperature, it opens the flow to the radiator.
- Coolant – It is a fluid that carries excessive heat from the engine.
- Coolant recovery system – It is a supply tank which is attached to the radiator, that contains overflowed coolant and supply coolant as required to the radiator.
- Heater core – it is heat exchanging device that transfers heat from the engine coolant to the surrounding air.
- Water jacket - A hollow passage around the engine cylinders where coolant circulates to cool the engine.
- Water pump – It is a pump that pump coolant throughout the engine.

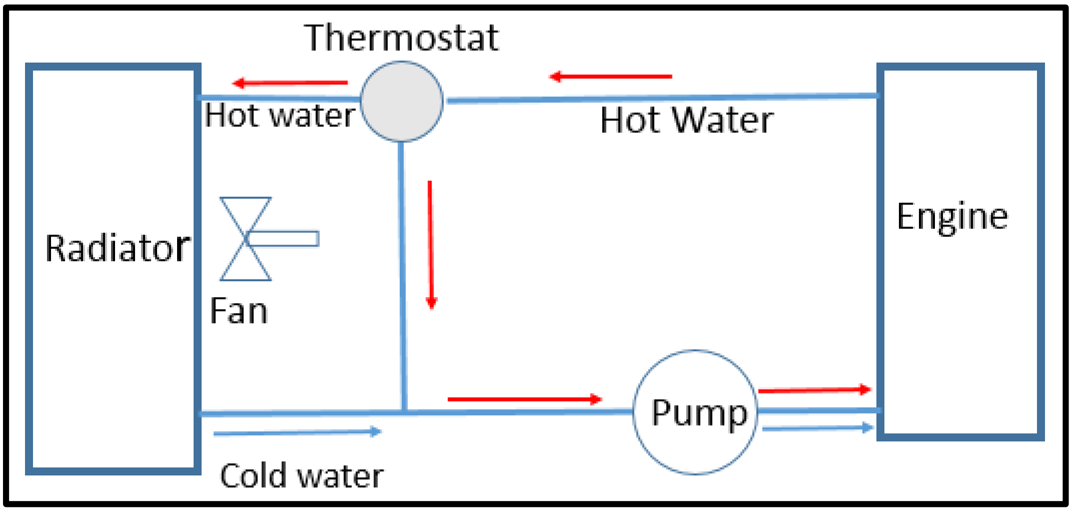


Figure B.1 Components of the cooling system in the vehicle.

The cooling system is a system, which controls the engine temperature to regulate the engine temperature within recommended operating range. The cooling system is provided in the vehicle internal combustion engine for the following reasons:

- In the engine, the temperature of the burning gases in the cylinder reaches up to 1500 to 2000°C [65] This temperature range is above the melting point of the material of the cylinder body and head of the engine. For example, Platinum -has one of the highest melting points, melts at 1750 °C, iron at 1530°C and aluminium at 657°C [65]). Hence, it is required that the heat must be dissipated to prevent failure of the engine components such as piston, cylinder, piston valve and rocker arm etc.
- The layer of the lubricating oil commonly gets oxidized due to the higher temperature, thus deposit carbon layers on the surface. This will result in piston seizure.
- During the overheating, the large temperature differences cause a deformation of the engine parts due to the thermal stresses. Thus, it is necessary for the temperature variation to be kept to a minimum.
- The efficiency of the engine reduces due to the higher operating temperature.

The main difficulties in accessing desired cooling system optimal temperature is that engine speed and load in the actual driving condition can change faster than the coolant temperature can respond, especially on heavy acceleration and sudden deceleration during the harsh environment. The low response of the coolant temperature is due to the thermal inertia present in the engine wall structure and also in the coolant [66]. Hence, the response time of the coolant temperature is longer during warm-up and cool-down compared to the engine speed and load change [66].

### ***Main causes for the failure in the cooling system systems***

When the cooling system fails (e.g. heating doesn’t heat, engine doesn’t reach operating temperature or overheats), the problem can be observed with easy means. Firstly, the cooling system should be checked for sufficient coolant, contamination, antifreeze and leaks. The V-belt or V-ribbed belt should also have sufficient tension. If the faults are not found in the above mentioned procedure, then it requires the systematic health monitoring systems which indicates the potential failure and the location of the failure in the cooling system. In the modern vehicles, there are some individual sensors which indicates the error in the corresponding sensor reading, however they are not sufficient for the complete failure detection mechanism.

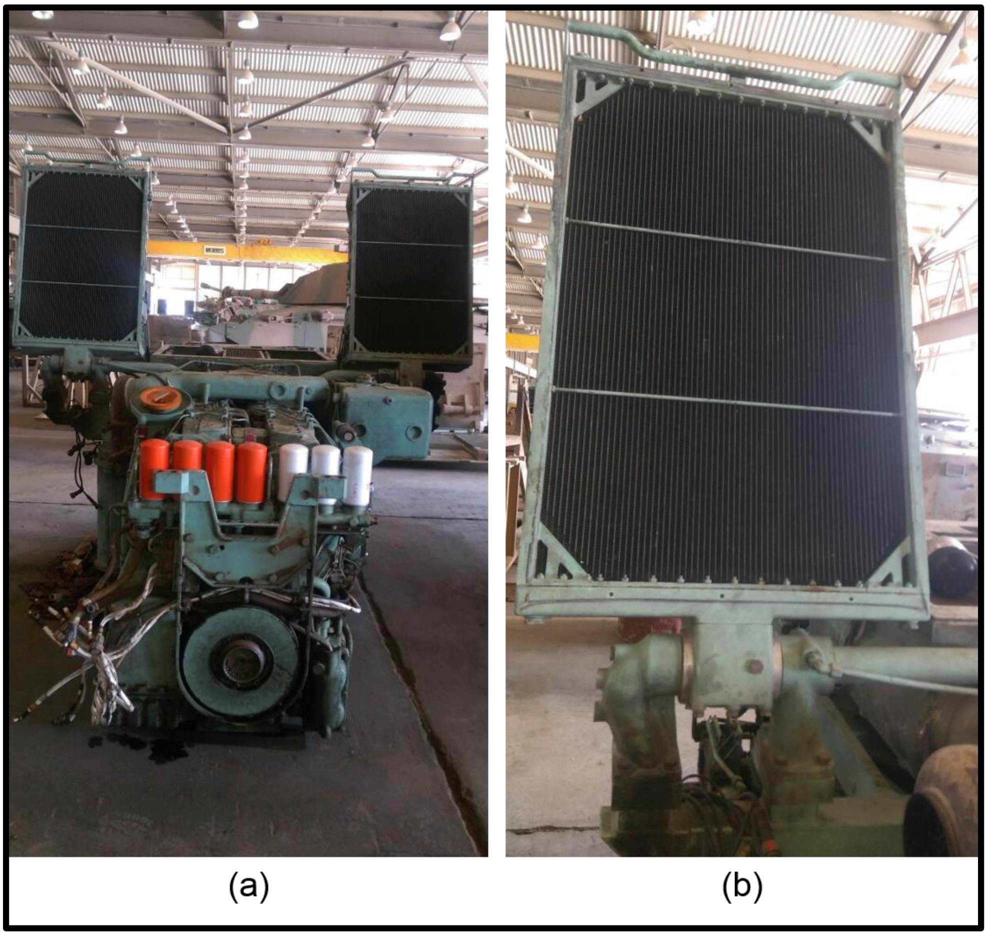
### ***Failure detection techniques used in the cooling system***

The failure detection or the health monitoring of the military vehicles is not well developed topic though some advance vehicle systems have some embedded mechanisms to detect some particular health issues in the cooling systems. The operating conditions of the cooling system are normally used to evaluate the health issues in the cooling systems components. However, there is no novel health monitoring systems available in the literature up to date.

The most parts of the cooling system wear out slowly, and with proper maintenance and periodic inspection they can be expected to experience only small, incremental problems. However, occasionally a cooling system will fail suddenly and dramatically and the vehicle engine will in effect fall. This sort of sudden failure results when a cooling system dramatically fails, the engine will cease automatically and results in entire vehicle failure. The sudden failures of the cooling system cause the dramatic damage to the engine and its sub-system and potentially leads to entire collapse of the vehicle and ultimately loss of life of the crew. The proper structured Health and Usage Monitoring System (HUMS) usually helps to identify or send the signal of failure before it starts to collapse entirely. However, such universal systems are very sparse in the military vehicles – thus it begs or highly demanded the need for such universal HUMS system for the cooling system in the military vehicle.

### ***Military vehicle cooling systems***

This section describes the cooling systems used in the different military vehicles and its functionalities and the advantages and disadvantages of those particular cooling system. These cooling systems are essential components in the military vehicle and hence the understanding of likely failure mechanism of these cooling systems while is prerequisite to design the HUM systems for the cooling systems in the military vehicles.



(a)

(b)

Figure B.2 Photograph of the Challenger 2 engine and its cooling system.

The cooling system of the Challenger is robust and reliable, however, the water pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman sandy desert.

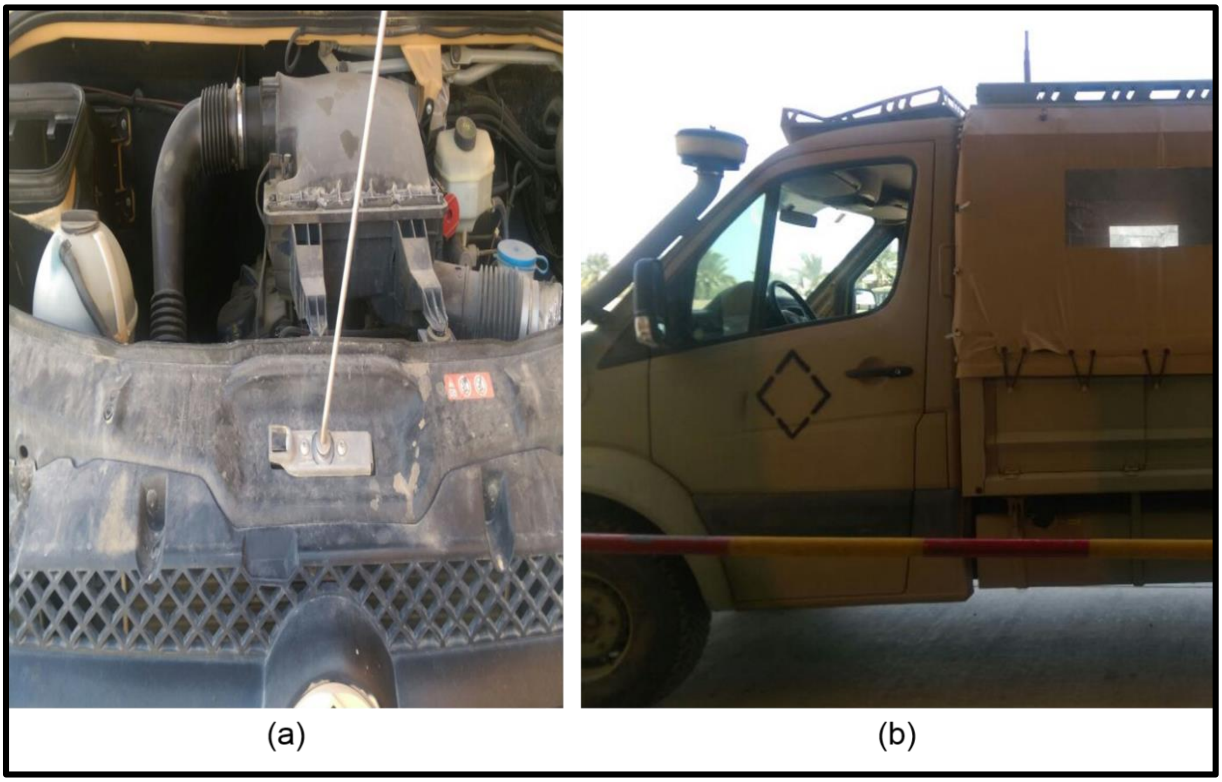
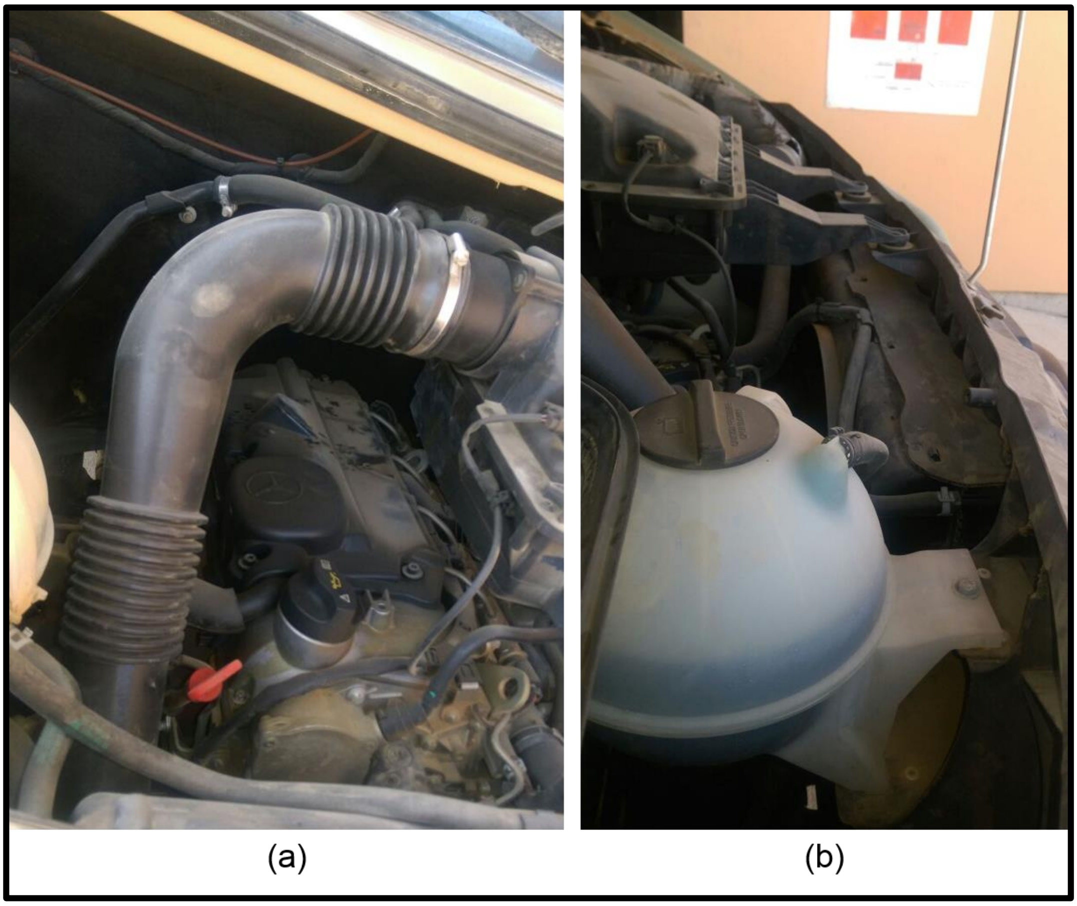

(a)
(b)

Figure B.3 Photograph of the Mantra vehicle and its cooling system.

The cooling system of the Mantra is robust and reliable, however, the water pump and the radiator of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman. The blockage occurs frequently as this vehicle is operating in the harsh environment. Recently, some modifications have been done to overcome these blockage issues.



(a) (b)

Figure B.4 Photograph of the Nissan patrol vehicle engine and its cooling system.

The cooling system of the Nissan patrol vehicle is robust and reliable, however, the water pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman. Recently, some modifications have been done to meet the requirement of the Royal Army of the Sultanate of Oman. The modifications added extra weight on to the vehicle. Overload weight cause some performance issues to the cooling system.

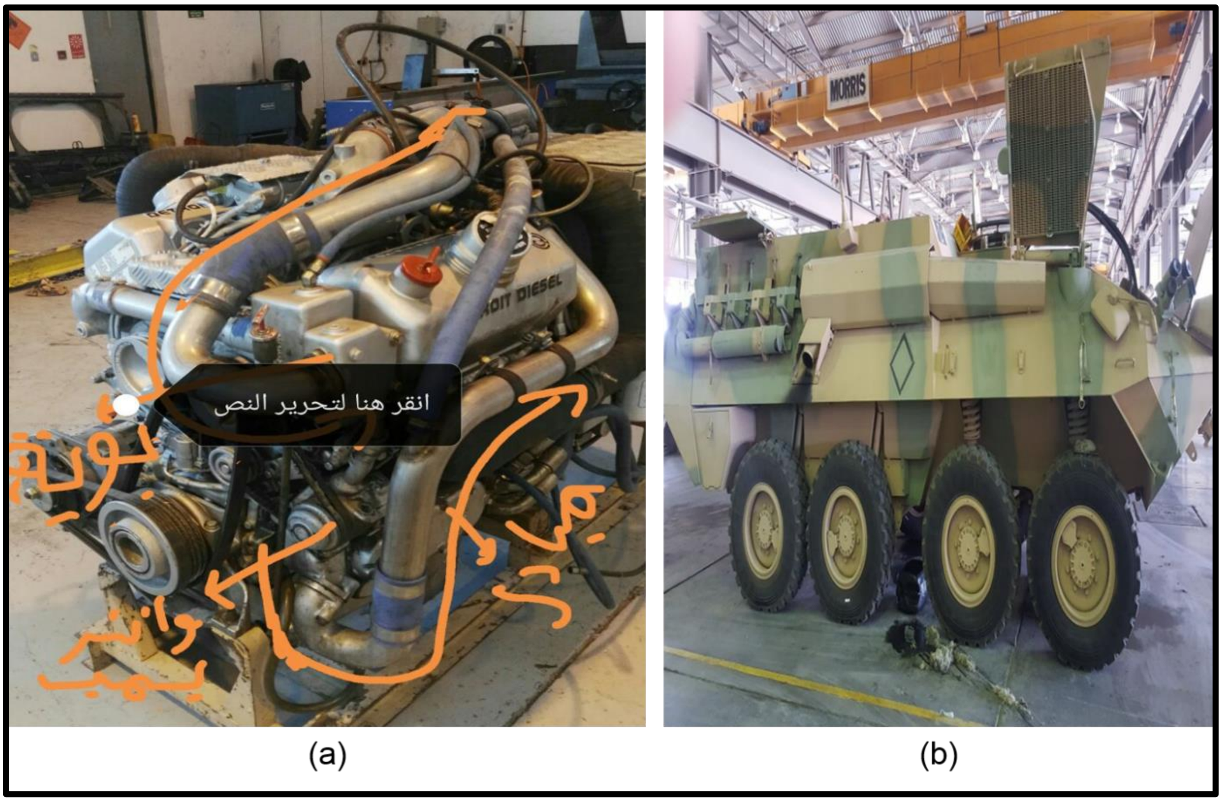


Figure B.5 Photograph of the Piranha vehicle engine and its cooling system.

The cooling system of the Piranha is robust and reliable, however, the water pump, fan and the radiator of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman. Water pump fails in very frequent way as the vehicle is in operation through harsh environment like dusty and sandy conditions.

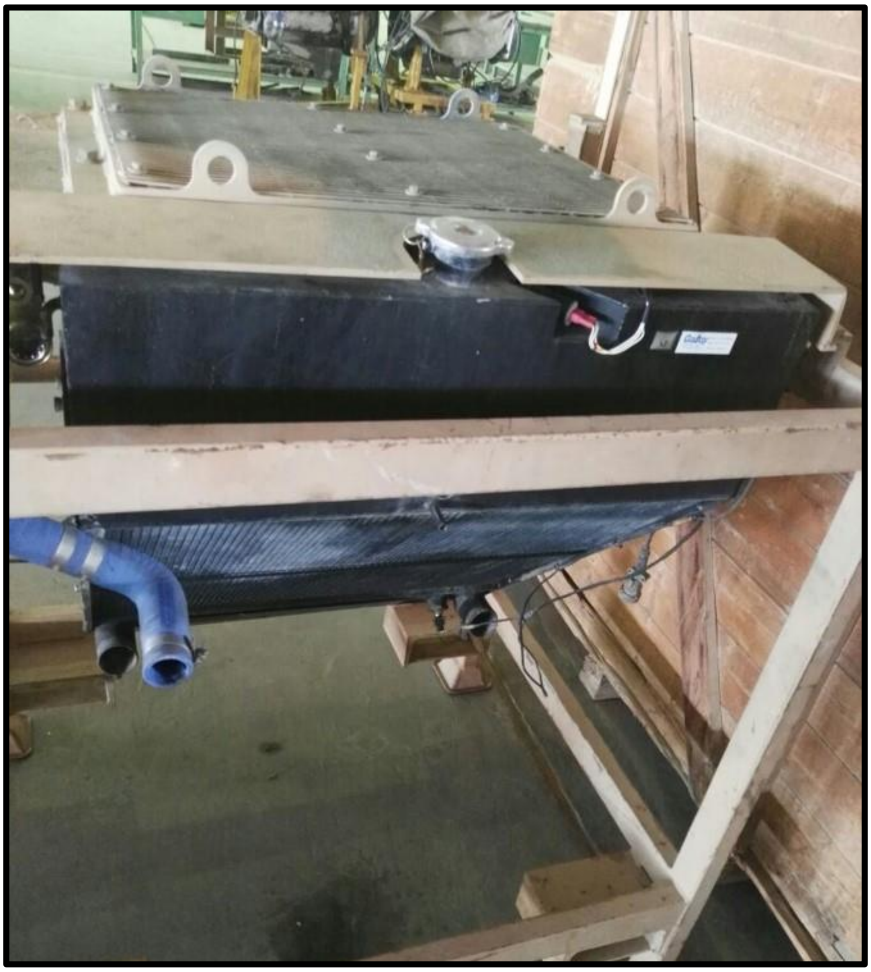


Figure B.6 Photograph of the Land Rover vehicle and its cooling system.

The cooling system of the Land Rover vehicle is robust and reliable, however, the water pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman. The radiator also suffers from the harsh environment with dusty and sandy conditions. The engine gets overheated during the operation in the inclined terrain roads as the cooling systems suffers from low pumping rate of the coolant. However, the cooling system of this vehicle is very robust compared with other military vehicles.

The cooling system of the Scorpion is robust and reliable, however, the water pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman. The overheated engine due the conversion into diesel engine and it transfer the heat to the crew cabin.

The cooling system of the M60 BMT is robust and reliable, however, air-cooling of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman.

The cooling system of the Panhard is robust and reliable, however, the water pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman sandy and dusty desert. Some modifications have been done to overcome the issues in the cooling system.

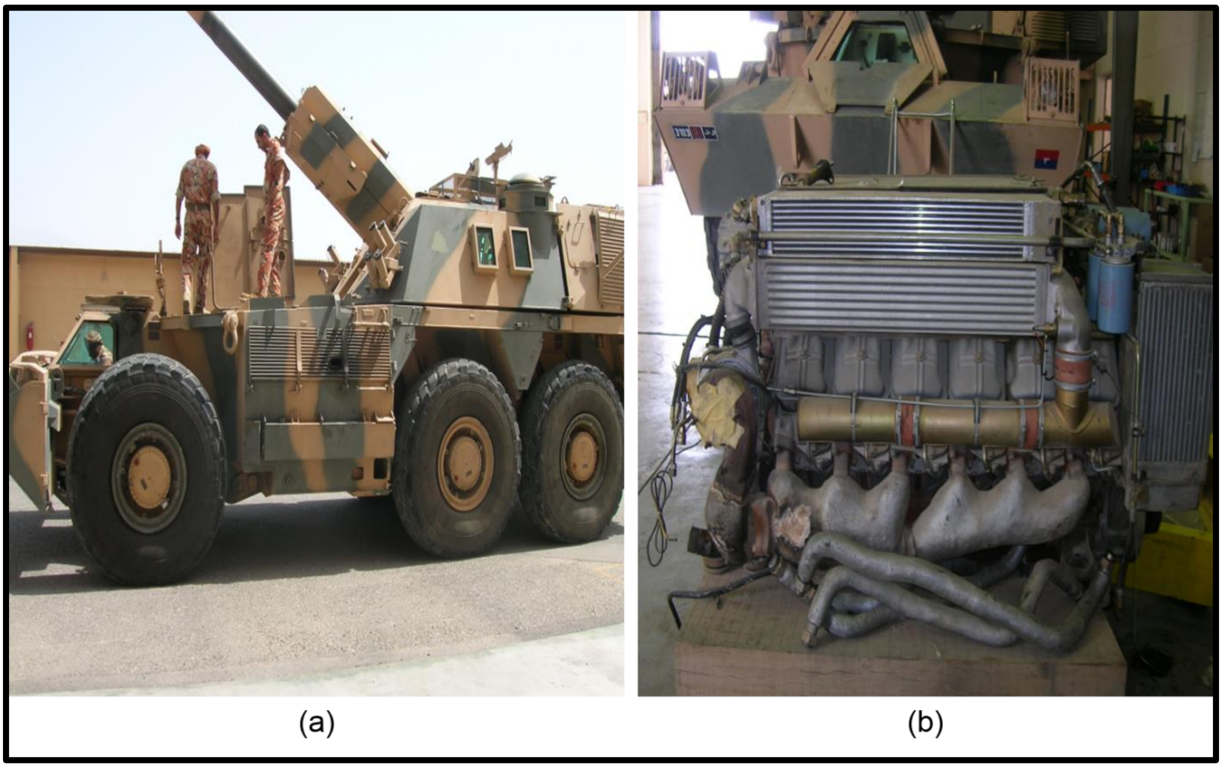

(a) (b)

Figure B.7 Photograph of the 155mm self-propelled gun (G6) military vehicle and its cooling system.

The cooling system of the 155mm self-propelled gun (G6) military vehicle is robust and reliable, however, the water pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman. The leaking in the cooling system is the issues in this vehicle. The heat exchanger and the radiator frequently cause trouble.

## ***Typical damage in the components of the cooling system***

### ***Radiator***

The radiator faults cause reduction in the performance. It is not common for repairing the faults in modern radiators, partly because of the welding issues in the aluminium and the small ducts might get clogged by the welding. Sealant is not commonly used, because it clogs and causes reduction in the performance of the radiator.

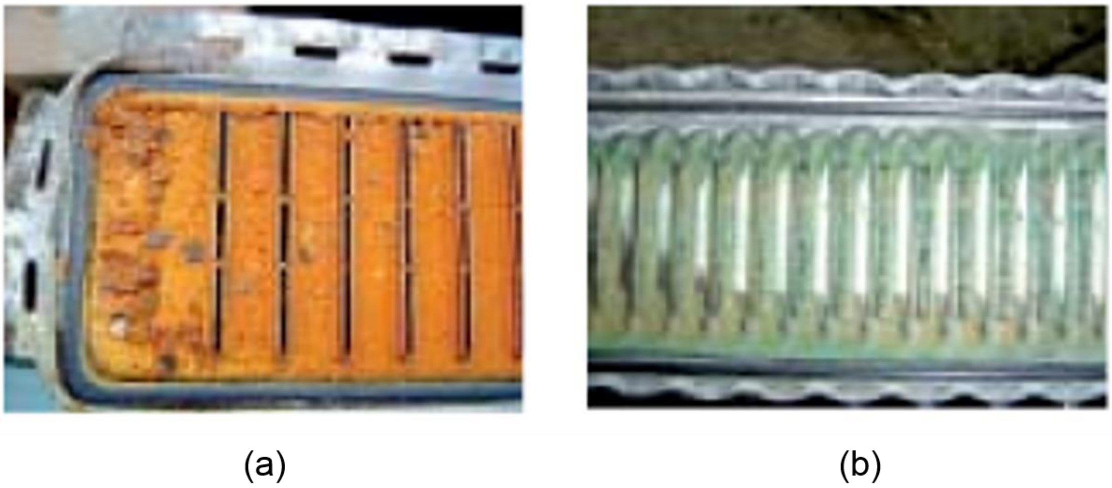


Figure B.8 Picture showing failed radiator: (a) – deposit due to oil existing stem from the engine oil which get into the coolant passages due to the damaged cylinder head and (b) – furring due to the use of pure water (without coolant) [66].

### ***Heat exchanger***

The main issue in the heat exchanger is that furring and the use of sealants may clog the heat exchanger in the same way as the radiator to cause failures. The conventional way of removing this deposits is that they can be removed by flushing with certain cleaning detergents – this cleaning a detergents are normally recommended by the manufacturers. This is the common failure in the Challenger2 Main Battle Tank and other heavy equipment.

Figure B.9 Picture showing failed heat exchanger – furring and the use of sealant clog the heat exchanger [67].

## ***Examples of some military vehicle cooling system failures in the Royal Army of Oman***

The following section provides some example of military vehicle cooling system failures. These failures were reported during the operation of Royal Army of the Sultanate of Oman.

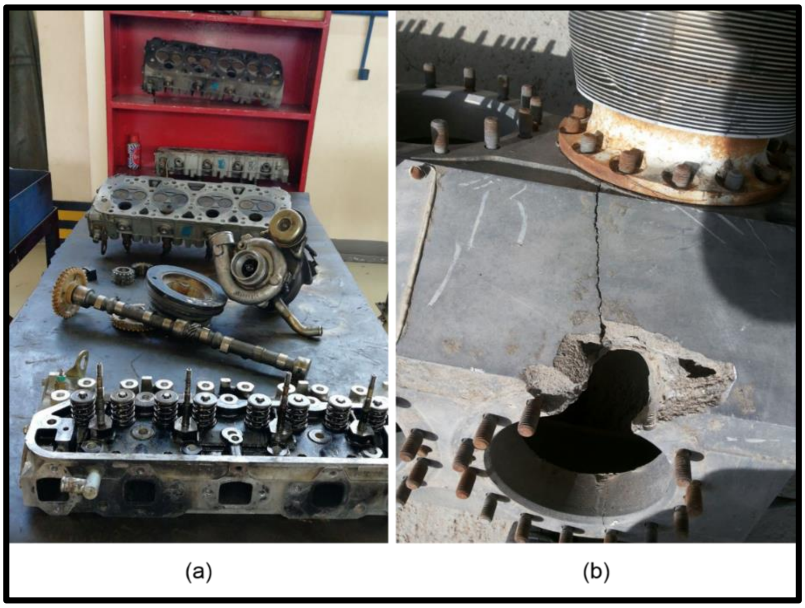

(a) (b)

Figure B.10 Photograph of the failed military vehicle its cooling system: (a) – Piranha and (b) - Challenger.

This failure occurred in the Challenger 2 military vehicle cooling system. Picture (a) and (b) show the water pump failure and the engine over-heated and the fatigue crack was formed and the complete crack was formed. The picture was taken in the workshop of the Oman Army unit. The failure in Figure B.10 (b) cannot be replaced and the failure in Figure B.10 (a) can be replace with the high cost.

There are some examples of the reasons for the failure in the engine due to the faulty lubrication system. There are various studies reported the mechanisms for failure by wear due to lack of a coherent lubricant film [65 - 67]. Vibration is often the cause of failure, as it causes fatigue or wear. There are many examples of this, such as those highlighted for a valve train system [66] and in rotor and spindle bearings [65]. Lubricant oil monitoring during use is one of the most important procedures in engine system monitoring and diagnostics, due to the importance of the oil's functions in this system. Contaminated oil in the lubricating system of an engine can be dangerous to engine operation. Lubricating oil can be contaminated through operational conditions (dusty or sandy places, or high operating temperatures), faulty maintenance practices, and part failures. This is very important for the military vehicle engine health monitoring when the vehicle is continuously running in the harsh environment of the Sultanate of Oman Royal Army deployment fields. Lubricants are generally used to separate moving parts in a vehicle engine system.

There are several benefit of reducing friction and surface fatigue together with reduced heat generation, operating noise and vibrations in the engine to avoid the catastrophic failure of the engine of the vehicle due to the faulty lubrication system.

### ***The lubricant systems in the military vehicle***

The health monitoring of lubrication system in the military vehicle is of interesting subject as many reported failures of the engines in the military vehicles are due to the failures in the lubrication system. The main difficulties come from accessing the lubrication system to inspect the failures as they are fitted inside the engine casing. The nature of armoured military vehicles, it is not feasible to access the engine components if they fail during the operation, thus requires an inbuilt systematic health monitoring system to monitor the parts of the lubrication system.

### ***The purpose of the lubricant systems in the military vehicle***

The main purpose of the lubrication system in engine of the vehicle is to ensure the effective functionalities of some of the engine components such as gear box, turbine area, bearings and seal kit etc. The lubrication system in the engine serves several functions essential to the safe and reliable operation of the components of engine as described above. These functions include:

- Lubrication of the rotor bearings
- Lubrication of the gears and bearings of the gearboxes
- Cooling of the bearings inside the engine area
- Removal of the contaminants and additive from the lubricant
- Support of the sealing of the bearing
- Supplying of a firm layer between the bearing outer races and their housings for oil dampened bearings to prevent metal to metal contact.

The main function of the oil damping dissipates the transmission of dynamic loads of the rotors to the casings. This feature reduces the vibration levels and the fatigue loads for the casings. The lubricant reduces friction by replacing solid friction with fluid friction. The effective lubrication system inside the engine should be able to provide a firm layer between metal contact surfaces moving relative to each other with high relative velocities under high loads and temperatures.

## ***Main causes for the failure in the lubricant system systems***

The main causes for the engine failures come from accidents, obsolesce and surface degradation. The surface degradation occurs from corrosion wear and mechanical wear. These two wears occur due to the poor lubrication supply to the engine components while in operation. The main cause for the mechanical wear is the particle contamination due to poor lubrication system. When the oil lubricant is not filtered to remove the dirt particles before they sent through the lubrication system, then they are adding extra contamination to the contact area of the mechanical components. The dusty and desert environment like in the Sultanate of Oman highly affects the lubrication systems in the engines. The case study showed that use of some of the un-recommended oil pump and out of specified oil lubricant caused frequent failure of some parts of the engine or the engine as a whole.

The common issues in the lubrication system include:

- Excessive oil consumption
- Low oil pressure and
- Excessive oil pressure

The issues associated with the excessive oil consumption are:

  - more oil goes to combustion chamber and gets burnt
  - some leakage occurs in some part of - the line and
  - loss of oil in form of vapour through ventilation system. Oil could leak from the combustion chamber through rings and cylinder walls, worn piston rings and bearings.

The low oil pressure occurs form the weakness of the relief valve spring, damage oil pump, damaged oil line, contaminations in the oil lines, worn out bearing. To ensure the effective functionalities of the lubrication system, proper inspections should be carried out to resolve these defects to increase the oil pressure in the lubricating system. When the pressure indicator shows low pressure due to defect, the system should be checked and repair to eliminate any damage in the engine.

The excessive oil pressure occurs from plunge relief valve, strong valve, contaminated oil line and very thick oil.

These defects should be systematically diagnosed and repair to remove excessive oil pressure to ensure the effective function of the engine. When the pressure indicator indicates the high oil pressure, these defects should be repaired to ensure the effective oil pressure of the lubrication system.

### ***Failure detection techniques used in the lubricant system***

The monitoring of lubricant oil during use is one of the most important procedures in engine health system diagnostics, due to the necessity of the lubrication system function inside the engine. The advantage of this real time health monitoring of lubrication system is that the prediction about the failures of this system can be obtained in real time while the vehicle is in operation. In the military vehicle contest, modern trends in diagnostics have moved towards an increasing interest of oil monitoring, which has resulted in an increased interest in inspection of the properties of oil and its nature. The main reasons towards increasing effective design and use of diagnostic procedure of the lubrication system is to keep the engine components reliability and effectiveness, as well as in economic considerations and protection of the environment from harsh exhaust from the vehicle. So far, there is no generalised health monitoring system available for the lubrication system in the military vehicles, although, there are some inbuilt sensors to provide some information about the characteristics of the oil lubricant. However, they don’t provide any diagnostic information about the failures in the lubrication system. When the military vehicles operate in the dust and hot environment like in the Sultanate of Oman, they require more care about the monitoring system of lubrication, as these environment cause damage to the lubrication system in general.

### ***Military vehicle lubricant systems***

This section describes the lubricant systems used in the different military vehicles and its functionalities and the advantages and disadvantages of that particular lubrication system. These lubricant systems are essential components in the military vehicle as the provide effective functionalities to the individual engine components. Hence the understanding of likely failure mechanism of these lubrication systems while the vehicle in operation is prerequisite to design the HUM systems for the lubrication systems in the military vehicles.

The lubricant system of the Challenger2 is robust and reliable, however, the oil pump of this system fails frequently (Table 5.1; Chapter 5). When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the lubricant system failure specially in the Sultanate of Oman.

The lubricant system of the Mantra is robust and reliable, however, the oil pump and the radiator of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the lubricant system failure specially in the Sultanate of Oman. The blockage occurs frequently as this vehicle is operating in the harsh environment. Recently, some modifications have been done to overcome these blockage issues.

The lubricant system of the MAN is robust and reliable, however, the water pump and the radiator of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the lubricant system failure specially in the Sultanate of Oman. The blockage occurs frequently as this vehicle is operating in the harsh environment. Recently, some modifications have been done to overcome these blockage issues.

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The lubricant system of the Land Rover vehicle is robust and reliable, however, the oil pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the lubricant system failure specially in the Sultanate of Oman. The radiator also suffers from the harsh environment with dusty and sandy conditions. The engine gets overheated during the operation in the inclined terrain roads as the cooling systems suffers from low pumping rate of the coolant. However, the cooling system of this vehicle is very robust compared with other military vehicles.

The lubricant system of the Scorpion is robust and reliable, however, the oil pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the lubricant system failure specially in the Sultanate of Oman. The overheated engine due the conversion into diesel engine and it transfer the heat to the crew cabin.

The lubricant system of the M60 BMT is robust and reliable, however, the oil pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the lubricant system failure specially in the Sultanate of Oman.

The lubricant system of the Panhard is robust and reliable, however, the oil pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman. Some modifications have been done to overcome the issues in the lubricant system.

The lubricant system of the 155mm self-propelled gun (G6) military vehicle is robust and reliable, however, the water pump of this system fails frequently. When this vehicle is operating in the harsh environment, dust and the sand are the main sources for the cooling system failure specially in the Sultanate of Oman. The leaking in the lubricant system is the issues in this vehicle. The heat exchanger and the radiator frequently cause trouble.