Enabling Condition Based Maintenance with Health and Usage Monitoring Systems

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Abstract

The U.S. Army Materiel Systems Analysis Activity (AMSAA) is supporting the U.S. Army's Condition-Based Maintenance policy by researching and developing CBM concepts using Health and Usage Monitoring Systems (HUMS). AMSAA has implemented a global field instrumentation program on wheeled vehicles in multiple terrains, climates, and usage scenarios using an engineering development HUMS. AMSAA is using this HUMS as a tool for developing usage, diagnostic and prognostic algorithms that will be implemented on future embedded HUMS. AMSAA also uses the collected data to provide direct feedback to the user, maintainer, Program Manager, and decision makers by reporting usage summaries and usage characterizations. As data analysis continues, AMSAA will refine the algorithms that will eventually lead to diagnostic and prognostic capabilities on board the Army's wheeled vehicles.

AMSAA is also developing and has begun initial fielding of an embeddable HUMS. AMSAA has chosen a small, cost efficient COTS system as a way to produce concise usage and health reports on a larger fleet of vehicles. The system's cost, size, and robustness make it a candidate for installation at vehicle manufacturers, Army depot, or vehicle refurbishment facility. In addition to hardware system development, AMSAA has been developing algorithms, data processing techniques, and reporting formats. Algorithms currently being developed, researched or implemented include terrain surface roughness identification, battery health, coolant system health, and engine condition. This case study will cover system development of the engineering development HUMS and future embeddable HUMS, including algorithms, data processing, and summary reporting. Included are challenges, benefits, lessons learned and a path forward for AMSAA's CBM initiatives.

Keywords: Health and Usage Monitoring, Tactical Wheeled Vehicles, engineering development tool, Seeded Fault Testing, Terrain Regime Identification and Classification, United States Army, systems engineering

Introduction

Condition Based Maintenance (CBM) is a policy of maintenance for a system based upon the actual condition of the system as enabled by the application of usage, diagnostic and prognostic processes executed on a Health and Usage Monitoring System (HUMS). Usage refers to the manner in which the system is employed and gives indications of how and why things are broken or breaking. Usage characteristics include hours running, miles driven, time at idle and fuel consumed among many others collected from on board vehicle sensors. Diagnostics is based on the symptoms or indicators of problems and uses methods to find what is broken and/or breaking in a system. The ultimate goal of HUMS is to leverage the knowledge base gained with usage and diagnostics in developing prognostic algorithms that will enable the prediction of system failures and, therefore, required system maintenance actions before failures occur. This will ultimately improve efficiency, reduce logistics costs, and improve driver and crew safety.

The first purpose of this paper was to explain AMSAA's system employment strategy. AMSAA follows a four phase strategy for implementation of CBM. These phases are similar to the engineering design process. In phase one, AMSAA identified appropriate hardware and software for an Engineering Development HUMS (EDHUMS) and completed initial in-theater installations of data acquisition systems at an Army test center. In order to be used in theater on tactical wheeled vehicles (TWV's) the data acquisition system needs to meet certain specifications. Phase two in AMSAA's strategy consisted of developing a robust military-grade EDHUMS, designing a data analysis process, testing EDHUMS in the Continental United States (CONUS) training environment, and beginning to field EDHUMS in operational units outside of the CONUS including deployed environments. Phase three of AMSAA's strategy was identifying a small, inexpensive Focused HUMS (FHUMS). This would be a HUMS device identified as a commercial system that met most of the requirements identified for the EDHUMS including the requirement of being capable to support all the sensors and data recording devices of the EDHUMS. It also had to meet the additional requirements of being smaller and more cost efficient. The system needed to be small enough in order to fit in more discrete locations than could previously be occupied by the EDHUMS. This was a must as to not interfere with any standard operating procedures of the vehicle and to make it totally autonomous to the operator. It also allows for easier installation and shorter installation times. AMSAA was successful in identifying a company that manufactured vehicle monitoring units (VMU) for this purpose and was willing to work with AMSAA to develop flexible customization of their hardware and software to meet AMSAA's requirements. AMSAA's fourth and final phase is integrating these smaller FHUMS into all military vehicles at the point of manufacturing or, in the case of older vehicles, RESET. These boxes will collect data on fleets as well as have on board algorithms implemented in order to warn the operators of impending failures as well as assist the maintainers and command.

The second purpose of this paper is to present to the Army documentation of the vehicle selection criteria for CBM data collection and also chronicle AMSAA's field instrumentation lessons learned and provide an overall measurement of success. This paper details sample size, unit, and location selections during the implementation process. The objective is to document this knowledge so that other organizations as well as AMSAA move forward from this point in the future and not from where AMSAA began four years ago. Neither statistical or optimization techniques were used to conduct sample size and location selection for this program. AMSAA had to use a variety of methods that include convenience sampling, subject matter expert opinion, program management techniques, spiral technology processes, resource allocation and scheduling, as well as many other appropriate management techniques to achieve the optimal sample with as many constraints that were existing. AMSAA achieved an optimal sample without optimization. The problem statement as defined would read: Maximize the number of continuously instrumented vehicles subject to the constraints of time, funding, manpower, transportation, inventory levels, vehicles available, units willing, and reliability of the instrumentation and process of installing instrumentation.

The third and final purpose of this paper is to highlight two testing techniques that have led to on board HUMs algorithms in the field. The first algorithm development testing started with Seeded Fault Testing (SFT). This test introduced, or seeded, known controlled faults into the vehicle in order to replicate common field failures. Common faults included lowering coolant levels, restricting air flow across radiator, lowering of transmission oil levels and lowering of engine oil levels. Data from the vehicle system was then collected and analyzed to observe how the system reacts. With data processing and analysis, multiple predictive algorithms capable of fielding were made possible. Terrain Regime Identification and Classification (TRIC) began at AMSAA on the proving grounds using a motion pack, unsprung mass accelerometer and global positioning system antenna. TRIC allows AMSAA to compute terrain traversed by the vehicle in twenty seven dimensions on board the HUMS. With this capability, a future maintenance manager may schedule maintenance for suspension and steering components or even drive-train components on condition.

The Self-Fulfilling Strategy

In 2006, AMSAA envisioned a strategy of HUMS system development and fielding for the Army it believed it could not or should not be involved with due to its analytical mission. In 2010, AMSAA has now realized what it once thought to be an error in roles and responsibility has now directly or indirectly become true. AMSAA determined four phases in its strategy would be most appropriate: 1. identify the hardware and software appropriate for an engineering development tool; 2. Ruggedize, test and field the EDHUMS; 3. Learn from the EDHUMs to focus the data collection and choose a more appropriate sampling device; 4. Miniaturize and propagate the cheapest system possible to a fleet level.

In 2006, AMSAA identified a COTs data acquisition system to ruggedize for fielding in operations in deployed environment. The specifications the system had to meet were:

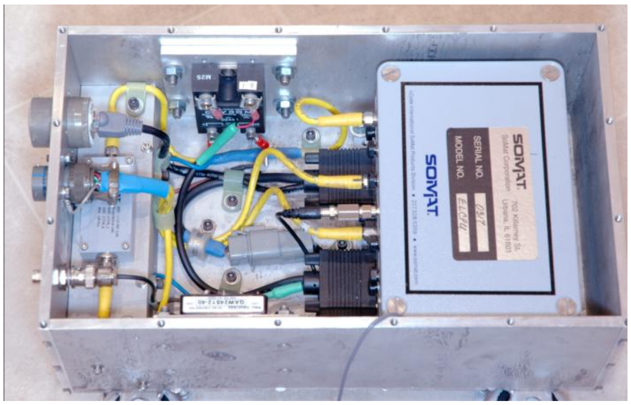
- dust-tight and water-tight
- small overall size
- use robust military-grade cable connections
- accept 12V and 24V power inputs
- provide method for remote switching of the unit (on/off)
- supports vehicle bus, GPS, displacement, strain, acceleration, and temperature gauges

- operates in maximum outside ambient temperature of 120°F (49°C) with a solar radiation load up to 1120 W/m^2
- meets conducted emissions and susceptibility requirements of MIL-STD-461
- survives typical vibration levels of various TWV's

In comparison to other systems at the time, it was one of the more elite systems for engineering development. AMSAA then moved to the next phase rapidly to enclose the system and protect it from heat, water, shock and interference. The package design took one engineer a month to complete, took one machinist 2 weeks to fabricate, and took five engineers and analysts 2 weeks to produce and operationally test ten prototype systems. These first systems were tested at a training center in extreme heat and terrain conditions and survived. The prototype designs were then transferred to a company to mass produce for sampling around the world.

Fig. 1: Installed ARMY eDAQ TWV Package

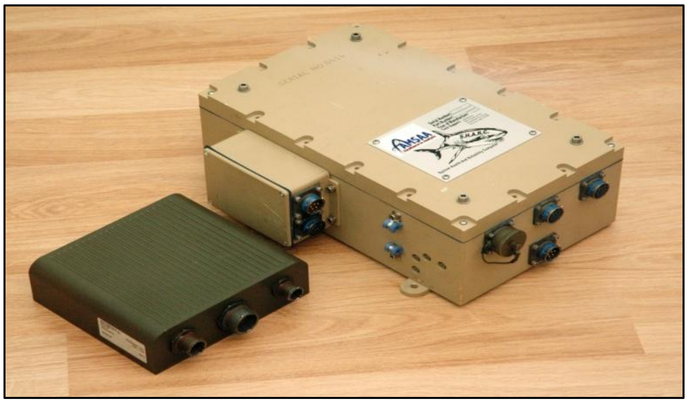
Fig. 2: ARMY eDAQ TWV Package with lid removed



By 2008, two years later, AMSAA had instrumented over 75 vehicles world-wide and was now moving concurrently into phase three, miniaturization. By learning from time-series data at high sample rates, AMSAA determined best approaches for compressing data volume with more efficient formats such as histograms and summary statistics. An inexpensive focused HUMS

(FHUMS) would make it possible to achieve a return on investment in an acceptable amount of time form a Program Manager's perspective.

Fig. 3: Miniaturization of HUMS



AMSAA's FHUMs would slowly evolve into a system capable of recording the same elements of data as the EDHUMS but more efficiently and cost effective in orders of magnitude. For instance, AMSAA's FHUMs costs around $2,000 US dollars whereas the EDHUMs costs around $25,000 US dollars. Also, to achieve the same or similar analysis results, the FHUMS would only need to store 1/200th the volume of data as the EDHUMS. Phase three was a significant phase in AMSAA's strategy and took about two years to fully mature. During Phase three, AMSAA deployed nearly 100 of the FHUMS for large sample studies. A typical deployment for an FHUMs consisted of one year in a deployed environment without any critical system failures. Meanwhile, around 20-30 EDHUMs stayed concurrently deployed for special studies where rich data sets were needed. By fall of 2010, Phase four was just around the corner.

AMSAA began phase four in September 2010 in collaboration with the program managers for tactical vehicles and the life cycle managers. AMSAA supported the life cycle command by using all of its field experience with data acquisition to write the requirements and specifications for fleet level data acquisition in support of CBM+ on Tactical Wheeled Vehicles. Currently AMSAA anticipates system deployment to commence in the summer of 2011.

Determining the Sample Composition

It was understood up front AMSAA's effort would have boundaries given limited resources to include time. The CBM installs were a sample data collection on numerous TWV's in different world climate regions and terrain. Using a two year period for install would allow for a significant sampling to take place. The data and lessons learned would in turn determine what areas needed more focus for army wide importance and learning. The time period would also allow time to begin data analysis and seek immediate returns. Three follow on slides demonstrate the approach and methodology used to develop the CBM timeline. Critical was also working a methodology that sampled most climates and regions, but also took into account unit rotation schedules for wartime service in theater. Data results initially were more focused on vehicle usage than actual CBM.

AMSAA targeted an equal distribution of climates and terrains. The intent was not a climate and terrain study but to capture as much data as possible in regions best to study CBM.

Fig. 4: Location and Condition Matrix

	Sand &/or Dust	High Altitudes	Snow & Ice	Significant Mud	Rain with Dampness/moisture	Rugged/Rocky Terrain
Location 1	■					
Location 2	■			■		
Location 3	■	■	■	■		■
Location 4						
Location 5			■			

AMSAA targeted an equal distribution of climates. Unit mission profiles correlate to locations and climatology.

The schedule that was developed was very ambitious however approximately 85% of the installations were completed. AMSAA determined the decision variables that would enable the sampling optimally and then developed a schedule for implementation of the instrumentation. AMSAA decided to travel to each site to conduct a recon of the vehicles about three months prior to the scheduled mission. During this recon, AMSAA would have determined suitability of the instrumentation suite with feedback from the operators and maintainers. AMSAA would also brief the target unit command on the initiative to get their buy-in prior to instrumentation. After the recon, AMSAA would rapidly design, document and fabricate the harness and sensor suite to meet the unique mission. Approximately a month prior to the mission, AMSAA would begin check outs and bench tests of the complete instrumentation systems prior to packing and shipping. Once on site, AMSAA would typically install on 6 vehicles in the unit's motor pool area: sometimes in a motor pool bay and sometimes in the dust sand and elements. After the mission was complete, After Action Reviews were conducted to ensure documentation of lessons learned. Lessons learned were used to evolve the process into an increasingly efficient one. Toward the end of the 3 year expansion effort, a system could be fielded in a month and a half after the recon was complete. Total costs are difficult to ascertain given the tempo of operations particularly in theater of operations. However using approximate quantities and average costs and hours AMSAA was able to determine an approximate total cost of $2,672,000 for around 120 systems installed with end to end program support

Review of CBM data collected over the last two years will allow for more insight on the value of the data collected. While initially only usage data has provided up front returns there remains large amounts of data to be analyzed in order to attempt the development of any algorithms for predictive maintenance purposes. Analysis will also allow for AMSAA to determine what the path forward will be for data collection to ensure the most effective return on investment. AMSAA has also learned that use of a core team of contractors is best for install purposes. Use of contractors allows for greater continuity as they are single task orientated while DA civilians have multiple task and priorities to consider. The use of operational vehicles in Oversea Contingency Operations (OCO) is the best data sample. Pre-deployment Training Equipment (PDTE) in CONUS is also useful. Other CONUS equipment is less desirable due to low usage especially when a unit deploys, and the equipment moves to Left Behind Equipment (LBE) status. However, overall trade-offs may sometimes be beneficial in trying to balance terrain, climate, usage, and vehicle types. Be careful to verify and quantity equipment usage with the unit as usage rates can change. The sample methodology in the end provided a successful data sample collection for the AMSAA CBM initiative.

SEEDED FAULT TESTING & ALGORITHM DEVELOPMENT

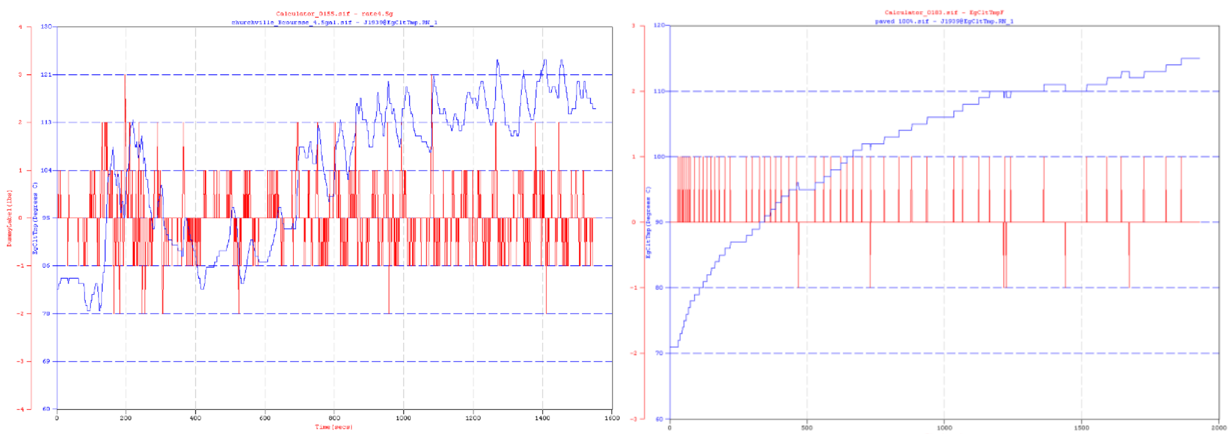
AMSAA's seeded fault testing was created in order to develop prognostic algorithms for CBM's EDHUMS box as well as the Syen VMU. During this test AMSAA introduced known controlled faults into the vehicle in order to replicate common field failures. Common faults included lowering coolant levels, restricting air flow across radiator, lowering of transmission oil levels and lowering of engine oil levels. It is predicted that this will cause the vehicle cooling system to fail or overheat which is a major cause of in theater failures. Testing was conducted at many Army test centers to encompass a full range of terrain types and conditions. The extremely high temperatures during the June/July desert testing at an Army test center mimic closely that of a deployed environment. It is also predicted that the outside air temperature has a large effect on the cooling system and performance of vehicles which is why a specific Army test center was selected in the test plan. This test will provide many useful findings. First, the results will be used in order to advance the development of CBM and predictive vehicle algorithms coordinated with diagnostics and prognostics methods. Second, there has not been, to AMSAA's knowledge, any experiment detailing the vehicle's performance under extreme and unconventional conditions. These conditions include running the vehicle over rough terrain in excessive heat while the vehicle overheats or is pushed close to failure. Third, it shows indisputable evidence of whether or not our EDHUMS is capable of showing faults in the data as well as having the potential to deliver the required algorithms.

The vehicle was instrumented with J1939 data bus recording capability and GPS to replicate the instrumentation AMSAA uses in the field. Twelve thermocouples were also instrumented on the vehicle in specific locations as a validation of the temperatures being recorded from the J1708 data bus. .

For each of the 3 fluid level reduction tests, fluid was removed in increments relative to the total fluid capacity in order to produce a large enough sample size as well as a linear comparison curve in the data. Each level of fluid in the vehicle represented one run around the course and the test was done until the vehicle recorded failure of any kind including overheating. During the radiator blockage test the same ideas were put into place and runs were conducted as a percentage blocked of the total area. The data was then recorded and analyzed.

Preliminary results show that AMSAA's EDHUMS data can in fact show differences between runs of failure and non failure for the faults tested. Engine coolant reduction and radiator blockage showed elevated coolant temperatures as expected as well as elevated oil temperatures and intake air temperatures. The difference in data also shows that there is a distinguishing factor between overheating by coolant loss and by radiator blockage seen in the figure below.

Fig. 5: Coolant temperature and rate of change for vehicle overheating caused by coolant loss (left) and radiator blockage (right)



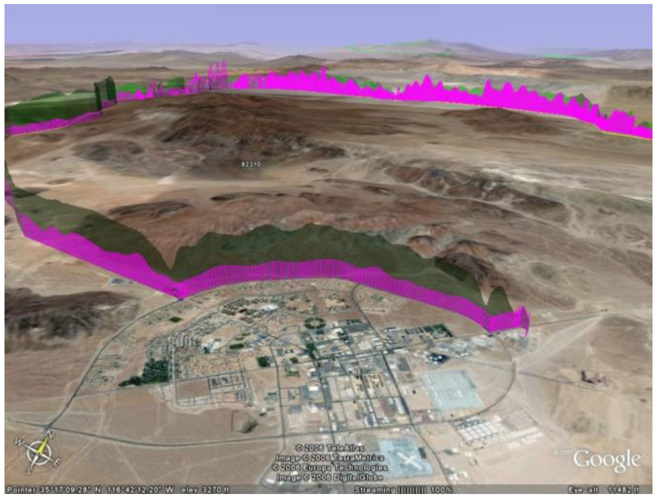
The graph on the right shows a coolant loss failure and the graph on the left shows overheating by radiator blockage. The blue lines represent to temperature of the actual coolant and the red line shows the rate of change of the coolant temperature. This was calculated by differentiating the coolant temperature, it is not a data stream that comes directly off the vehicles J1939 electronic control module. From the data both graphs show a rise in coolant temperature to a critical level however their nature is much different. The coolant loss chart shows a maximum rate of change to be +3 degrees and -2 degrees. However the radiator blockage chart chows only a maximum rate of change as +/- 1 degree. AMSAA currently developed and algorithm that can distinguish between these two faults and will soon be in the process of testing and validating this algorithm. AMSAA also is in the final stages of developing an oil loss algorithm. These algorithms have the potential to predict vehicle failure and warn the operator of impending failures possibly 10 to 15 minutes before they occur, allowing the operator sufficient time to get to safety.

Future work in seeded fault testing is necessary and will be conducted by AMSAA. This involves testing many different faults under in theater conditions as well as verifying any algorithms created. It is AMSAA's overall goal to use seeded fault testing in conjunction with CBM to have the ability to use algorithms developed by seeded fault implanted in theater and save cost, time and increase the efficiency of vehicle maintenance and safety.

Terrain Regime Identification and Classification

One of the most promising analyses AMSAA has performed is the mapping of terrain severity. This has led to a terrain-identification algorithm that has been implemented on all vehicles currently instrumented in a deployed environment. While somewhat rudimentary right now, this algorithm is currently being refined to account for vehicle loading and tire pressure. It can currently only identify short-wavelength aspects of a terrain profile which can be thought of as being vibratory in nature but we are in the process of expanding the algorithm to identify long-wavelength aspects of terrain profiles that are important for mobility and power train issues such as fuel consumption. Figure 5 shows a graphical display of terrain-identification data report.

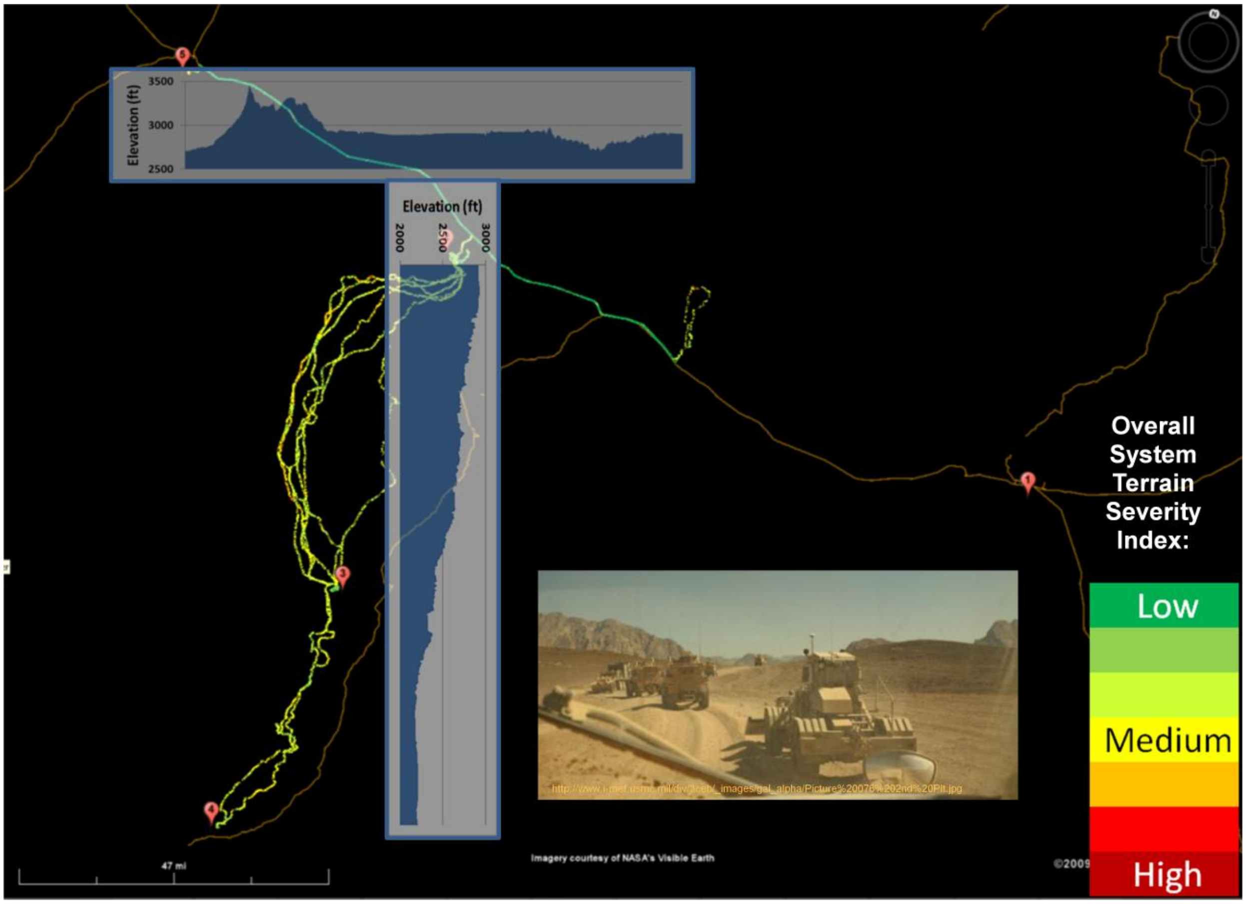
Fig. 6: Latitude and longitude plot of speed (green) and RMS acceleration (pink) values



As AMSAA has further developed TRIC over the last two years, it is now able to map terrain severity in 27 dimensions. See figure 7. TRIC and Figure 8: Terrain Map. These analytical techniques may someday lend themselves to anticipatory logistics and predictive maintenance. What is required is large samples of vehicles to understand the relationships between component failure and terrain severity over time. AMSAA will continue to analyze the data as it accumulates.

Fig. 7: TRIC

Fig. 8: Terrain Map



Conclusions

Building the framework of a CBM environment in the field is difficult and takes time. It should be approached using the "crawl, walk. Run" approach. If it is not then one small error can propagate quickly and keep a continuous collection of data from occurring. CBM data can provide the organizations responsible for a fleet an omniscient view. You may be privy to the last seconds of Soldiers' lives or may be responsible for having avoided Soldiers' deaths through predictive maintenance. If you are developing CBM doctrine and hardware, you should always stay focused on the previous sentence and you cannot go wrong.

Acknowledgements

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References