Cost-Benefit Analysis Trade-Space Tool as a Design-Aid for the U.S. Army Vehicle Health Management System (VHMS) Program

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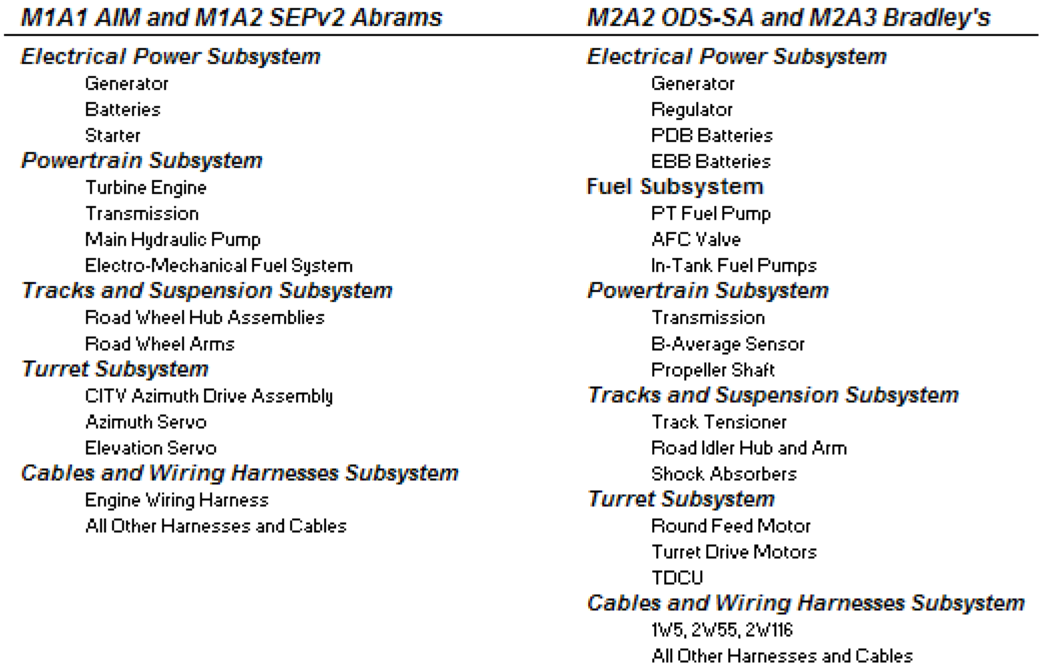
ABSTRACT

The U.S. Army Program Management Office, Heavy Brigade Combat Team (PM-HBCT) is working towards embedding enhanced diagnostic and prognostic capabilities onto the current fleet of HBCT ground vehicles – including the M1A2 SEPv2, M1A1 AIM, M2A2 ODS/SA, M2A3, M109A6 Paladin PIM, and the M88A2 – through the Vehicle Health Management System (VHMS). In order to focus the VHMS design and development effort, and to apply solution technologies to vehicle subsystems and components that offer the greatest benefit, the Applied Research Lab at Penn State University (ARL/PSU) was tasked with developing a cost-benefits based design tool that provides decision-makers with the ability to explore the trade-space of potential VHMS design alternatives. The cost-benefit analysis (CBA) trade-space tool does not automatically identify the "best" design, but instead supports a flexible methodology for examining the relative costs and benefits of alternative designs through the user's selective consideration and weighting of calculated metrics. This approach allows stake-holders with differing perspectives on decision criteria to work collectively towards an optimal design configuration, or set of designs. The developed tool is intended to be used as an engineering design aid, and not as a replacement for a formal CBA or analysis of alternatives (AoA). This paper will describe the trade-space models and the resultant design tool that was developed for the Abrams and Bradley VHMS designs, with specific focus upon the underlying methodology and approach.

1 VHMS PROGRAM BACKGROUND

The VHMS program is directed by U.S. Army PM-HBCT within PEO Ground Combat Systems, and is supported by TARDEC (Tank Automotive Research, Development & Engineering Center), and ARDEC (Armaments Research, Development & Engineering Center). The VHMS program will apply embedded diagnostic and prognostic vehicle health monitoring capabilities to designated variants of the Abrams, Bradley, Paladin, and Hercules systems. The program's key performance parameter is to eliminate the need for off-platform DSESTS (Direct Support Electrical System Test Set) testing at the brigade level and below by embedding those specific diagnostic capabilities onto the platforms. These capabilities are primarily focused on the vehicle's electronic systems. The scope of VHMS extends across all vehicle systems, and much of the design considerations involve systems not currently addressed with existing on-board or DSESTS testing. The future embedded diagnostics must achieve equal or better fault coverage in order to justify the elimination of DSESTS, and gain the subsequent financial and operational benefits. Whether additional systems warrant diagnostic coverage, and the extent of that coverage, constitute the primary decisions addressed by this analysis.

ARL/PSU has supported the VHMS development effort by conducting field interviews and performing engineering analyses that provided insight into high failure rate components, dominant component failure modes, and general maintainability issues. These analyses involved interviews conducted with chief warrant officers and OEM field service representatives (FSR's) at Ft. Hood, Ft. Carson, Ft. Sill, and Aberdeen Proving Grounds. Information gleaned from these interviews was supplemented with maintenance records from FSR reports provided by BAE and GDLS, in addition to input from subject matter experts from TACOM and the U.S. Marine Corps. Components that were found to degrade operational capabilities and/or contribute towards high Operation and Support (O&S) costs were described in vehicle degrader analyses conducted by ARL that included Failure Mode Effect and Criticality Analyses (FMECA). The components and subsystems identified by these reports are described in Figure 1. These analyses serve as the primary reference point for the VHMS trade-space tool, and are supplemented by O&S and logistics data. Data sources include the Operating and Support Management Information System (OSMIS) database, AMSAA Sample Data Collection (SDC), LOGSA Integrated Logistics Analysis Program (ILAP) database, and Average Monthly Demand (AMD) data from Army item-managers. The analyses also leverage work conducted by the Logistics Innovation Agency (LIA) for PM Stryker Brigade Combat Team and the Common Logistics Operating Environment (CLOE).



M1A1 AIM and M1A2 SEPv2 Abrams

Electrical Power Subsystem
- Generator
- Batteries
- Starter

Powertrain Subsystem
- Turbine Engine
- Transmission
- Main Hydraulic Pump
- Electro-Mechanical Fuel System

Tracks and Suspension Subsystem
- Road Wheel Hub Assemblies
- Road Wheel Arms

Turret Subsystem
- CITV Azimuth Drive Assembly
- Azimuth Servo
- Elevation Servo

Cables and Wiring Harnesses Subsystem
- Engine Wiring Harness
- All Other Harnesses and Cables

M2A2 ODS-SA and M2A3 Bradley's

Electrical Power Subsystem
- Generator
- Regulator
- PDB Batteries
- EBB Batteries

Fuel Subsystem
- PT Fuel Pump
- AFC Valve
- In-Tank Fuel Pumps

Powertrain Subsystem
- Transmission
- B-Average Sensor
- Propeller Shaft

Tracks and Suspension Subsystem
- Track Tensioner
- Road Idler Hub and Arm
- Shock Absorbers

Turret Subsystem
- Round Feed Motor
- Turret Drive Motors
- TDCU

Cables and Wiring Harnesses Subsystem
- 1W5, 2W55, 2W116
- All Other Harnesses and Cables

Figure 1 Top Degraders Identified for the Abrams and Bradley Weapon Systems

2 COST-BENEFIT ANALYSIS

A traditional CBA is used to provide a comparison of alternative solutions that decision-makers can use to identify the most cost-effective approach to accomplishing a clearly defined goal. Typically, only a small number of alternatives are presented, with the purpose of determining and justifying a general course of action. A CBA will also provide an understanding of performance requirements that must be met in order to make a particular alternative worthwhile. These performance requirements will have some effect on determining details of the final design, but are generally insufficient for guiding the design and development phases of the program. Additional methodologies must be employed to ensure cost-benefit considerations are incorporated as detailed design decisions are made. Added challenges are encountered when costs cannot be directly measured, or when there is no obvious metric to use for quantifying particular benefits. This is often the case when the considered benefits are process improvements, for example.

Performing a cost-benefits analysis for CBM-related programs is a challenging task for several reasons. Typically, the case for CBM implementation is made using a large number of loosely stated, generic, benefits that can be made to fit almost any system or maintenance environment (Banks and Merenich, 2007). Actually extending these arguments to a specific implementation is a much more difficult task, and requires a realistic assessment of the performance capability of the implemented technology in light of the operational context and support environment of the system that will be monitored. This not only requires an understanding of how the diagnostic/prognostic capabilities will be utilized within the systems' operational, maintenance, and logistics contexts, but also requires a more critical assessment of how the CBM technologies can be expected to perform, both now and in the future (Byer, Hess and Fila, 2001), (Wilmering and Ramesh, 2005). Which component failure modes are detectable? What are the false alarm, and missed detection rates? What is the detection sensitivity? Is damage classification, localization or progression monitoring possible? Answering these questions is nearly impossible for a cost analyst, and even for the average engineer, unless they happen to be specifically knowledgeable in the developing field of diagnostics and prognostics. Even then, the answers are incredibly dependent on the specific implementation, and the actual performance capability of a well-developed solution may not be known until a variety of testability analyses have been undertaken (Keller, et al, 2001). Yet, without answers to these questions, it is impossible to begin drawing accurate connections to the larger impact on items and processes that can be more directly related to quantifiable costs. An understanding of the performance capability will determine how the system can be best integrated into each context (operational, maintenance, logistic, etc.) as well as determining the nature and potential extent of specific benefits. This will allow some general assumptions to be made regarding how the system will actually be used in the field under typical operational conditions.

CBA development efforts for CBM-related programs are also complicated by the fact that it is not possible to concentrate on a single primary benefit, which means that individual benefits need to be accurately considered and their cumulative effects assessed in order to make an effective business case for the program[2]. This is compounded by the fact that most of the proposed benefits are not easily quantified because they are types of process improvements, or because it is difficult to establish cost factors that relate them to quantifiable costs. This leads to a need to creatively account for, and compare, costs-benefits that cannot be reduced to dollar estimates (or any other common metric). Typically, in such scenarios, the cost analysts' only recourse is to include a detailed explanation of these costs within a final report.

There are other factors that must also be considered before approaching a cost-benefits analysis. One of the key steps is to determine a well-defined scope for the analysis, and to understand the desired purpose. Beyond any initial ground rules communicated by the decision-makers', any additional decisions made by the cost analyst are effectively an assumption on the decision-makers' behalf. These decisions and assumptions are intrinsically affected by the perspective of the analyst. In many scenarios, the person preparing the analysis has only limited knowledge of the decision-makers' decision criteria, preferences, and general thought process. As a result, some pertinent information may inadvertently be omitted, or less thoroughly identified in the analysis, which may bias the decision-makers' conclusion. Attempting to capture the desired considerations and criteria of the decision-makers is a difficult task, and typically cannot be avoided since it is necessary to focus the CBA in order to allow it to be thorough, and able to be completed in a reasonable amount of time. Performing a broader analysis that takes into account detailed cost-factors and relationships for numerous design alternatives often are not feasible. But it is still desirable to present as much relevant cost-benefit details and assumptions to the decision-makers so that they can take on the responsibility of making inferences and decisions about the analysis, as opposed to the cost analyst making simplifying assumptions in order to reasonably balance the depth of the analysis with the practical limitations. (This is especially important for CBM-related analyses because of the number of benefits, and the indirect links between the system performance and any directly quantifiable benefits.) By presenting decision-makers with more of the un-interpreted data, there is less risk of errors that can lead to poor decisions, and a better understanding of the entire space of design alternatives. The general approach to most CBA's is to document all assumptions made in the analysis so that these missteps are avoided. However, if the decision-makers do not agree with the assumptions, or if they respond with "what if…" scenarios, a large portion of the analysis often must be redone.

3 APPROACH

In light of the various challenges associated with performing a CBA for an integrated health monitoring effort, an attempt has been made to introduce less conventional methodologies for analyzing the cost-benefit problem. The initial approach toward a suitable methodology involved the examination of the CBA task from a systems engineering perspective, as a design problem. The intent was to develop a tool/methodology that allows the comparison of a wide range of alternative designs, while accommodating the use of a large number of dissimilar parameters (possessing different metrics, units, etc.). This was desirable in order to allow for a more thorough exploration of the design space than what is typically possible within traditional CBA methodologies, which tend to examine only a very small number of alternatives. To facilitate such an analysis, an intuitive means of displaying and exploring this large collection of data would also be necessary.

The ARL Trade Space Visualizer (ATSV, an ARL-developed data visualization tool) was selected as a graphical interface for this analysis because of the need to explore large amounts of disparate data. The ATSV had also been previously applied to engineering design problems, where it was used in conjunction with models that defined relationships between design parameters. The exploration of design considerations using the data visualization tool allowed engineers to better understand dependencies within the trade space. As an example, if one were designing a new combat vehicle, a design relationship would exist between the vehicle's gross payload and its engine requirements to meet a given performance specification (max speed and acceleration). However, the engine specification would affect the size and weight of the required transmission components. This could result in less interior cabin space for crew or equipment, or result in larger exterior dimensions, which might make the vehicle too wide for certain types of cargo transports. It is easy to see that there are numerous interdependent design parameters one could think of, stemming from this simple example. As a consequence, it is extremely difficult to understand exactly what designs are possible and which aren't, based on a given set of design criteria without a suitable analysis tool.

The approach taken in this research was to create a set of models that created relationships between both the design parameters, and the cost factors, that would allow for exploration of the design space in the ATSV. Spreadsheet-based models were developed for dollar quantifiable costs, and benefits. This approach requires knowledge of cost factor relationships, identification of the various dependent variables, and the anticipation of near-term changes that might affect the cost relationship. In addition to dollar quantifiable parameters, there are numerous benefits associated with improvements to the operational, maintenance and logistics processes that are extremely difficult to translate into equivalent dollar amounts. A unique process simulation, which modeled relevant aspects of the vehicles' operational and repair processes was developed to quantify these improvements.

4 VHMS PRODUCT CONFIGURATOR

The product configurator tool was used to generate all of the potential VHMS designs using the list of components described within the degrader analysis, and their proposed solutions. Each configuration is then processed through the cost, benefit, and operational models to assess the financial and non-monetary, costs and benefits. These outputs populate the VHMS design trade space. Figure 2 shows a block diagram of the trade space models.

The degrader analyses describe multiple solutions for each candidate component, based on desired performance capabilities: current fault monitoring coverage with software modifications only, a diagnostic solution, a predictive diagnostic solution, and a prognostic solution (if technically viable). The product configurator then generates all of the potential combinations of these solutions. For example, the product configurator generates 172,186,884 unique designs for the Bradley platform that consists of 18 different candidate components, and differing levels of implementation. For example, one possible VHMS configuration for the Bradley could use the diagnostic solution for the PT fuel pump, the advanced diagnostic solution for the transmission, the current diagnostic capabilities on the generator, etc. One benefit of describing potential solutions by performance capability is that it makes it slightly more straightforward to estimate the process improvements. Diagnostic capability will result in greatly reduced MTTD (mean time to diagnose), predictive capability will translate into reduced probability of on-mission failures, etc. While estimating the actual process improvements is still difficult, this methodology provides a capability to intuitively generalize the benefits of each solution according to its performance capability.

A predictive diagnostic solution has the ability of providing an advanced warning of a failure without specifying the anticipated remaining useful life until failure. Whereas, a prognostic solution would require the identification of the developing failure mode in order to track fault development and predict the remaining useful life. Few fully prognostic solutions currently exist, and in many cases they are simply not feasible to develop because of the unpredictable nature

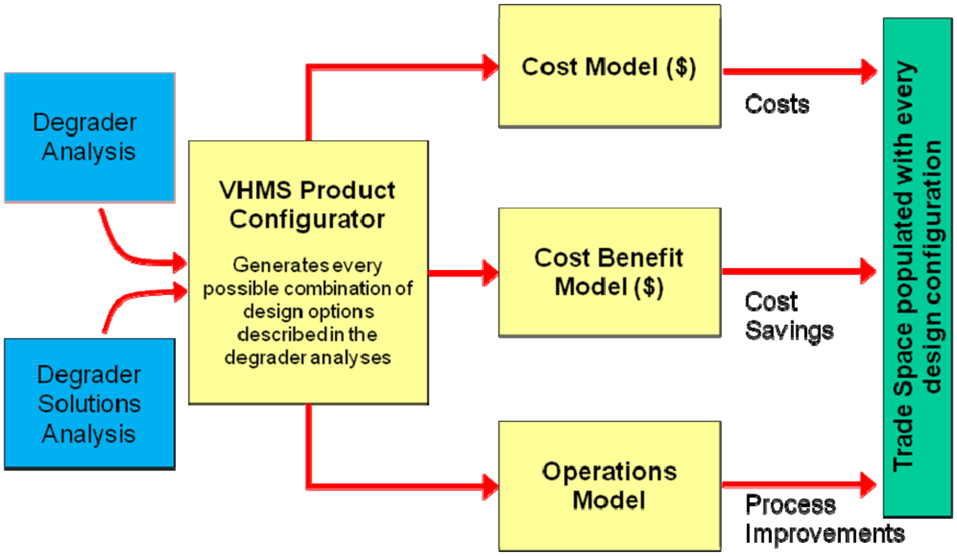


Figure 2 Block Diagram of VHMS Trade-Space Development Process

of some failures (for example, when cables are pinched or stepped on). In these types of failures, there is no progression from fault to failure, and thus there is no opportunity to implement prognostics. The batteries are the only components within this study that are considered to currently have a prognostic solution. The software modification scenario reflects what improvements could be made without making any hardware modifications. The majority of current technologies employed by the Army, whether via DSESTS or on-board BIT/FIT tests, generally fall under the category of diagnostic solutions. However, within this analysis, diagnostic capability is defined as the real-time automatic detection and identification of a component failure. It should be noted that the majority of BIT/FIT capabilities do not identify faults in real time, as they generally require sensors and processing that are otherwise required for control purposes during operation. While some tests do run continuously in the background, the majority can only be performed during system start-up, or from within maintenance-mode.

5 COST MODEL

The cost model is a parametric model that uses a set of rules and defined relationships to generate cost estimates for a VHMS design based on the required hardware, software, labor, etc. The model determines the required quantity and type of sensors, data acquisition, processing cards, and software development effort for individual VHMS designs. The resulting cost estimate is a bottoms up ROM that includes labor hour estimates for assembly, integration, and testing, as well as overhead rates (profit and fee), and initial sparing costs. The material costs include sensors, cables and intelligent nodes (data acquisition and processing computers). Material cost estimates were generated from manufacturer quotes and from previous cost estimates for similar efforts. The labor costs consist of the effort to build, install and test the intelligent nodes, as well as install and test the sensors, portable maintenance aid, and other components. Other costs that were considered are updates to the technical manuals, and adding new NSN's. A 15% discount was assumed for bulk purchase of sensors. A 110% labor overhead rate, 10% material overhead, 25% general and administrative rate, and a 10% profit rate were assumed in this model. The initial spares cost was estimated at 15% of the system cost.

The development and production cost categories were developed by ARL using mainly prototype cost estimates available from only a few comparable programs. Future feedback from the government and OEM's will help refine these cost estimates. This input and validation is particularly important because of the scarcity of historical cost estimates for CBM related programs, and the difficulty in projecting program costs from prototype efforts.

Currently, there are several cost parameters that are independent of the overall design configuration, which are not currently included in the model. The initial emphasis has been on identifying and including those cost parameters that vary between different configurations because they are necessary for accurately comparing designs. Those costs that are common to all designs will be necessary for more accurately computing ROI, total life cycle costs, etc. Eventually, it is desirable to add this level of detail to the model, which would allow for more accurate computation of life cycle costs, ROI and break-even estimates.

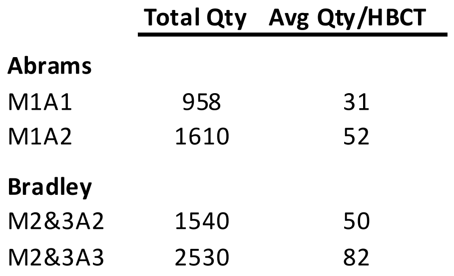
6 BENEFITS MODEL

Performing cost-benefits analyses for programs that involve the implementation of CBM technology has traditionally been difficult because the anticipated benefits are very difficult to accurately estimate. This is generally due to the nature of the benefits as process improvements, but it is also complicated by the difficulty in projecting a new technology's impact on maintenance and support operations. In many cases, the required information does not exist, or is not readily available (Balling, 1999). This poses a significant challenge for the development of a cost-benefit design tool for CBM applications because it requires estimates of specific benefits in order to allow for a comparison of alternative designs.

Even if the benefits of CBM technology are difficult to estimate, they are generally well understood by industry. These include extended inspection and overhaul periods, reduced downtimes, the ability to schedule downtime when it is most convenient (avoiding costly and inopportune downtime), reduced collateral damage, reduced repair costs, and reduced spares inventory, among others. For this effort, there are other unique benefits, such as reduced instances of no evidence of failure (NEOF's), reduced use of recovery vehicles (M88A2's), and fewer aborted missions due to component failures.

The benefits model developed for this effort is a parametric model that estimates the cost benefits of each VHMS design. The benefits associated with collateral damage reduction, reduced part order errors and reduced repair costs were estimated as a percentage of total annual operating and support costs. In most instances, these estimates are based solely on expert opinion because of a lack of comparable programs, which is common when implementing new technology.

The benefits model does not yet take financial credit for NEOF reductions, extended service life between overhauls, reductions in contractor and FSR man-hours, reduced inventory of spare parts, reduced M88A2 usage due to fewer in-field failures, and some logistics benefits (reduced fuel usage, for example, etc.). These benefits have not yet been included due to a lack of requisite information. As the program progresses, more of the necessary information will be available, and these benefits can be included. The ability to reduce vehicle downtime by improving the efficiency of various maintenance tasks through VHMS is assumed. Ideally, it would be desirable to quantify this in terms of a decrease in the rate of on-mission failures, as an increase in the mean service life between overhauls, or as the reduction of repairs requiring multiple part order cycles (just as a few examples). It is difficult to estimate these, however, because of the complex nature of the operation and maintenance processes. Factors such as OPTEMPO, location, maintainer availability, maintainer experience, number of FSR's, availability of repair tools, support structure, and even budget restrictions, all significantly affect the maintenance process. Properly accounting for these factors is extremely difficult without a detailed model. One such model has been developed by LIA, and would be appropriate for estimating these benefits. However, due to run time requirements the LIA simulation could not be used for this analysis. In order to process the millions of simulations (corresponding to each of the potential VHMS solutions) in a reasonable amount of time, it was necessary to develop a less detailed model that was tailored to this effort. It has been recommended that the LIA process model be used for obtaining more refined estimates of benefits once a design (or set of designs) has been determined.



	Total Qty	Avg Qty/HBCT
Abrams		
M1A1	958	31
M1A2	1610	52
Bradley		
M2&3A2	1540	50
M2&3A3	2530	82

Figure 3 Average HBCT Vehicle Quantities

7 MAINTENANCE OPERATIONS MODEL

A discrete event simulation model of the maintenance process was created using the Flexsim process modeling software to estimate the impact of VHMS on weapon system operation and support processes. The model simulates a brigade sized element for each weapon system, and assumes mission profiles consistent with high OPTEMPO (67% on-mission). An average brigade structure was estimated from figures provided by TACOM, based on fleet plans and an assumption of 31 HBCT's. This is shown in Figure 3. These figures are not necessarily representative of each brigade, but are instead an average across all brigades.

For the purposes of this analysis, it was possible to combine the M1A1 AIM and M1A2 SEPv2 into a single model, because all of the components currently being considered are common to both platforms. The Bradley variants were also examined in a single model to simplify the analysis.

The model simulates maintenance and operation activities over time, with tasks modeled as statistical distributions and probabilities. For example, the time to perform each specific task is modeled as a probabilistic distribution that was estimated from AMSAA SDC records and from maintainer interviews. This was done in order to more accurately capture the variability in process times that occur due to differences in maintainer experience, training, parts availability, and availability of tools (to name a few factors). Component failure rates associated with non-mission capable (NMC) events are estimated from historical records, and are used to drive the simulation. The maintenance process is broken down into specific tasks: in-field recovery operations, fault diagnosis, parts order and logistics delay, repair (actual wrench-turning), and additional delays due to misdiagnosis or incomplete diagnosis. The recovery scenario allows for the possibility of self evacuation to the forward operating base (FOB) when failures occur on-mission. The probabilities and process times to conduct these specific actions are modeled individually for each of the candidate components identified in the degrader analyses (see Appendix A). Each candidate component has different sets of parameters correlating to the different VHMS solutions (i.e., the different scenarios: as-is, diagnostic, predictive, etc.). An "other" category was used to capture the effects of failures of components not included in the degrader analyses that remain constant throughout the analysis. A high level view of the maintenance and operations process for HBCT combat vehicles is shown in Figure 4 for demonstrating the effect of predictive monitoring. A more detailed schematic is included in Appendix B.

The benefits of potential VHMS solutions were modeled individually based on results of the degrader analyses and expert opinions provided by subject matter experts. While the benefits are uniquely modeled for each component, there are some generalizations that can be made. Benefits of diagnostic capability include increased fault coverage, reduced MTTD, and reduced probability of misdiagnosis. In addition to these benefits, predictive coverage has reduced MLDT and reduced probability of collateral damage. In order to simulate predictive capabilities, an alarm time distribution was generated for each component that allows the diagnosis and part ordering process to begin prior to the platform becoming NMC.

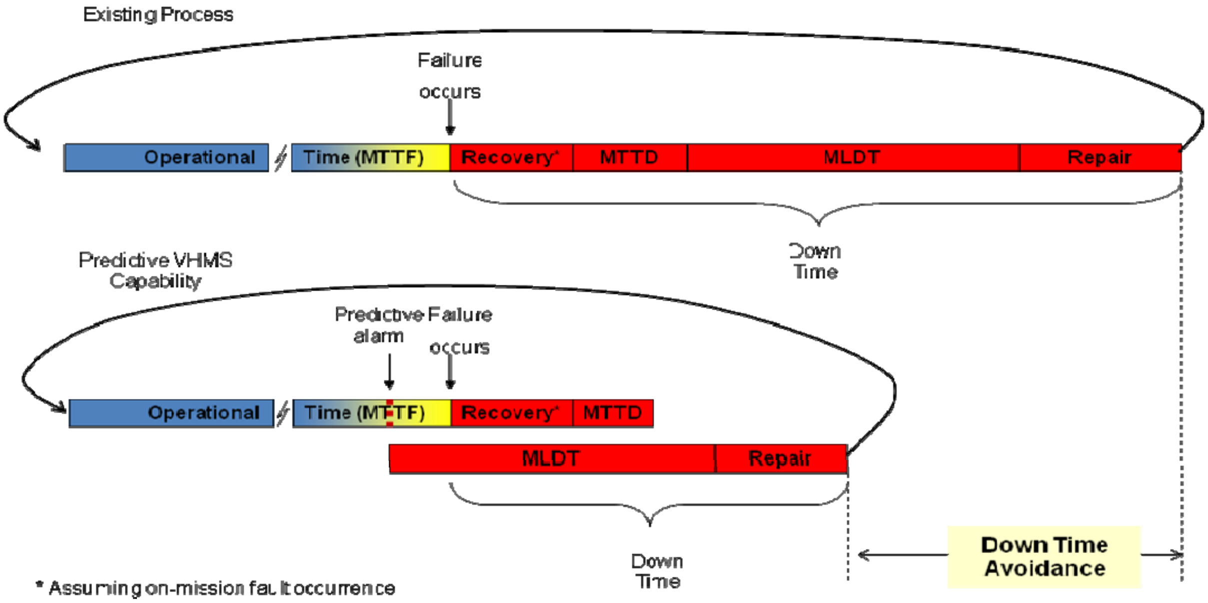
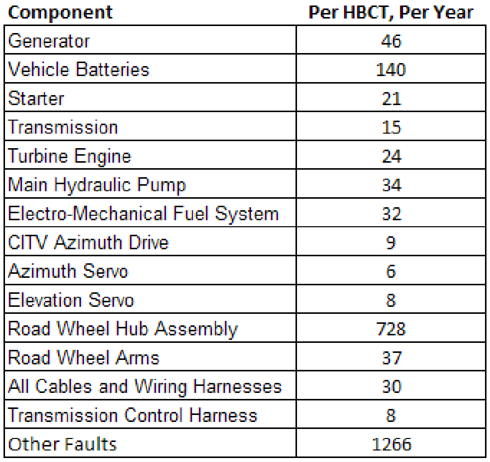


Figure 4 – Modeled Effect of Predictive Diagnostics on Downtime

Many of these benefits (reduction in MTTD, MTTR, and MLDT for example) ultimately result in improvements to A_O, however, this is a difficult parameter to estimate because of how it is computed in practice. Mission critical component failures do not always result in downtime that counts against A_O, but for the purpose of this model it is assumed that they do. This results in A_O estimates that are lower than reported rates, but which more accurately reflect the process improvements. This also highlights an important clarification that should be made concerning A_O. Current assessments of readiness that are 95% or greater provide an impression that there is no opportunity or need for improvement. However, this doesn't accurately represent the full picture, due to the guidelines for reporting vehicles down. For instance, repairs that can be completed by the end of the day are not required to be included in daily deadline reports. For instance, the ability to reduce the average downtime for unreported repairs from 8 hours to 2 hours would not result in a change in A_O, despite its obvious impact. This is most significant during combat operations, where such "minor" NMC failures can be critical force degraders. For these reasons, every mission critical failure counted against A_O for the purpose of this simulation.

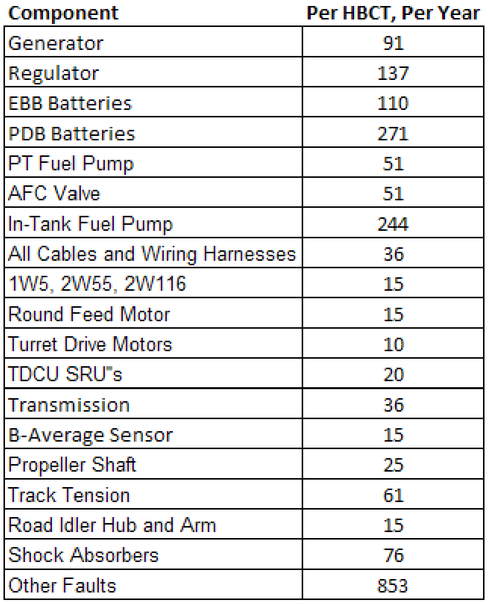
One limitation of the model is that it does not consider the effects of limited manpower resources for maintenance and logistics, which in reality restricts the amount of work that could occur at any given time. In addition, the maintenance and logistics associated with the non-NMC repairs (which aren't modeled) will absorb some of the available manpower resources as well. These shared manpower resources are a relevant cross-link between platforms. For example, an improvement to the A_O of one platform would have a carry-over effect on the A_O of other platforms because maintainers would have increased availability. There are some other nonlinear effects that would be captured in a more detailed model (which are modeled in the LIA simulation) that could not be included due to difficulty in acquiring the necessary data and the need to limit simulation run times. While these modeling aspects would improve the accuracy of the simulations, they are not necessarily required because the platforms are modeled individually (owing to the sheer number of unique designs), and because the effects would be generally consistent across all designs.

Another benefit that was extracted from the simulation was the percentage of on-mission faults that provide an alarm time greater than 8 hours, which assumes that 8 hours is sufficient time to avoid a mission interrupt (implying that a vehicle on mission would have sufficient time to self-evac to a nearby FOB for repair, or avoid leaving on a mission entirely).



Component	Per HBCT, Per Year
Generator	46
Vehicle Batteries	140
Starter	21
Transmission	15
Turbine Engine	24
Main Hydraulic Pump	34
Electro-Mechanical Fuel System	32
CITV Azimuth Drive	9
Azimuth Servo	6
Elevation Servo	8
Road Wheel Hub Assembly	728
Road Wheel Arms	37
All Cables and Wiring Harnesses	30
Transmission Control Harness	8
Other Faults	1266

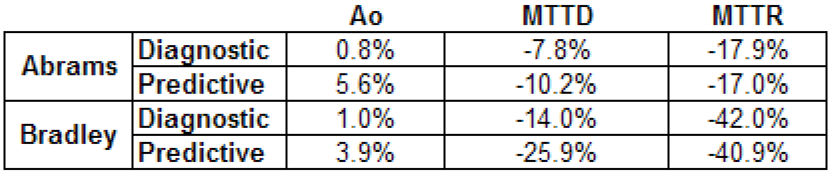
Figure 5 – M1A1 and M1A2 Failure Estimates



Component	Per HBCT, Per Year
Generator	91
Regulator	137
EBB Batteries	110
PDB Batteries	271
PT Fuel Pump	51
AFC Valve	51
In-Tank Fuel Pump	244
All Cables and Wiring Harnesses	36
1W5, 2W55, 2W116	15
Round Feed Motor	15
Turret Drive Motors	10
TDCU SRU"s	20
Transmission	36
B-Average Sensor	15
Propeller Shaft	25
Track Tension	61
Road Idler Hub and Arm	15
Shock Absorbers	76
Other Faults	853

Figure 6 – M2A2 and M2A3 Failure Estimates

The input data for this simulation was compiled from a variety of resources. Annual quantities of parts demanded from supply were used to estimate failure rates, and were validated against first-hand accounts from maintainers in the field. Logistics records from item managers, the OSMIS database, and from the AMSAA SDC analysis were additional sources of information. Due to numerous issues pertaining to the interpretation of the logistics data, first-hand accounts were given preference when estimating



		Ao	MTTD	MTTR
Abrams	**Diagnostic**	0.8%	-7.8%	-17.9%
	Predictive	5.6%	-10.2%	-17.0%
Bradley	**Diagnostic**	1.0%	-14.0%	-42.0%
	Predictive	3.9%	-25.9%	-40.9%

Figure 7 – Maintenance and Operations Simulation Results: Percent Change in Process Model Parameters

failure rates. These interviews were conducted with FSR's, CWO's, and motor pool mechanics from Ft. Hood, Ft. Carson, Ft. Sill and Aberdeen Proving Grounds. Estimates of MTTD, MTTR and MLDT for specific components were obtained from maintainer interviews. Estimates of MTTR were also taken from the AMSAA SDC analysis. These times were modeled as distributions because of the variability in circumstances that occur in the field. The estimated number of failures per HBCT per year for Abrams and Bradley are shown in Figures 5 and 6, respectively. The estimates for the batteries and in-tank fuel pumps are for the number of failures, not the quantity of items replaced.

Sample output of the maintenance and operations simulation is shown in Figure 7, for the cases of all diagnostic, and all predictive diagnostic implementation on the proposed components. The simulation results show an improvement in A_O as a result of VHMS implementation. As expected, predictive capabilities provide a greater increase in A_O than diagnostic capabilities. Because the simulation models failure events by the mean time to failure, any reduction in downtime will translate into an increase in the number of failures per year. The simulation results point toward a 1% increase in failures with diagnostic capabilities, and 4-6.5% increases in failures with predictive capabilities. These results assume that increased A_O translates directly into increased usage. In reality, this is only true for HBCT's with high OPTEMPO's (namely, those operating in theatre). Units operating in CONUS, where there is not consistent usage, will be less likely to see an increase in failure rates because of the intermittent nature of their use for training and maneuvers. Whereas vehicles operating in theatre have mission profiles such that any unscheduled downtime for repair necessarily results in less use. As a result, the estimated Ao benefit for low OPTEMPO units would be much greater than the figures generated by the simulation.

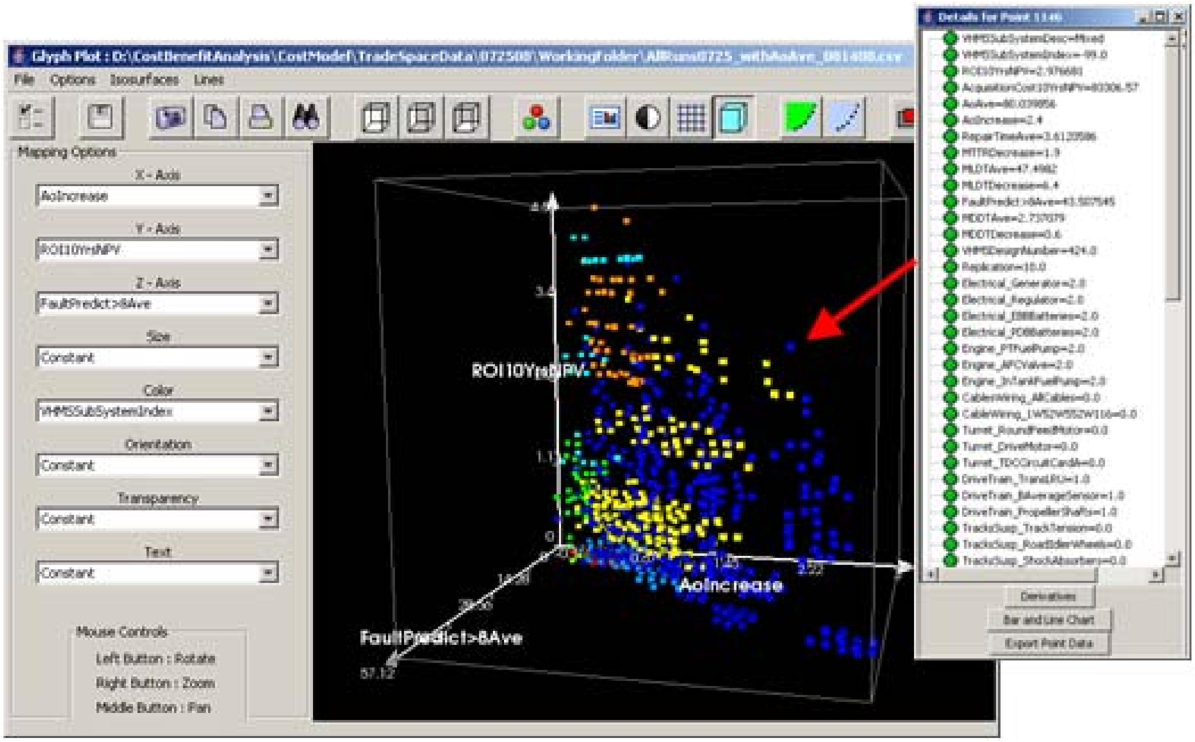
8 QUALITATIVE RISK SCORECARD

The consideration of risk within this analysis was incorporated by using a qualitative scorecard approach. This approach allows risk to be loosely quantified using qualitative definitions of risk severity levels. Such an approach helps to differentiate between acceptable and unacceptable levels of risk. Five different risk areas were identified: schedule, development, performance, reliability, and supply. Schedule risk is the risk that a VHMS solution for a particular vehicle subsystem might require development efforts that exceed the allowable timetable. Development risk is the risk that the required technical development of a suitable solution is not technically possible, even given extended timeframes and maximum resource allocation. Performance risk is the risk that the developed solution will experience high rates of false alarms, missed detections, or otherwise fails to perform at an acceptable level. Reliability risk is the risk of frequent failure of physical components of the VHMS hardware, with consideration for environmental and operational effects related to the locations of VHMS hardware on the vehicle. Supply risk is the risk that manufacturing capabilities of certain unique items may suffer from inefficiencies, unpredictable resource scarcities, production bottlenecks, etc., that could affect reliable supply. The qualitative definitions of risk levels and the assigned scores for each of the described areas are shown in Appendix C and D, for reference. The cumulative sum of these scores for alternative designs can be utilized as a comparison metric, either as a total score across all risk areas, or as individual scores for each risk area. These scorecards allow less concrete information to be integrated into the analysis in a way that helps decision-makers understand aspects of the design that could not be captured quantitatively.

9 TRADE SPACE TOOL

The ARL Trade Space Visualizer (ATSV) is a data visualization tool that was selected for analyzing the cost-benefits data of the different VHMS designs because of its unique ability to graphically explore multidimensional design trade spaces. It employs a design by shopping paradigm (Balling, 1999), (Stump, et al, 2002) that enables a decision-maker to form a preference after having viewed the multi-dimensional trade space of possible designs (*a posteriori*). This is in contrast to most optimization procedures that require *a priori* specification of optimization criteria. An *a priori* approach to the design process blindly assumes that the chosen optimization criteria will lead to the best design. However, there may exist more preferable design possibilities that were unforeseen by the decision-maker, and thus are not discovered. With an understanding of the design trade space using the ATSV, the decision-maker can select an optimal design without being limited by *a priori* assumptions.

The ATSV is a JAVA-based software package that utilizes multi-dimensional visualization techniques and optimization algorithms to compare design trades (Stump, et al, 2002), (Stump, et al, 2007). The tool is useful for identifying relationships between design variables, and has a variety of tools that enable the user to identify an optimal design(s). The visualization techniques include glyph plots, histograms, parallel coordinate plots, scatter matrices, brushing and linked views. A glyph plot represents each design as an individual data point, and multivariate information is represented in the position, size, shape, color, orientation and transparency of the icon. Brushing allows user-defined filter settings to be implemented, which removes designs from the trade space that fall outside the designated bounds of selected variables. This can be useful for applying a maximum acquisition cost limit, or a minimum return on investment, etc. Preference shading can be used to graphically reflect the rankings (or weights) applied to selected variables. This is useful for comparing dissimilar benefits, such as A_O, ROI, and Total Life Cycle Cost, where decision-makers may have different opinions of which benefits are more important. The preference weightings can also be used to identify the Pareto frontier, which defines the maximum potential benefits that can be achieved from the selected variables. The ATSV user-interface, with a sample dataset is shown in Figure 8.



Mapping Options

X - Axis: AoIncrease

Y - Axis: ROI10YrsNPV

Z - Axis: FaultPredict>8Ave

Size: Constant

Color: VHMSSubSystemIndex

Orientation: Constant

Transparency: Constant

Text: Constant

Mouse Controls

Left Button : Rotate

Right Button : Zoom

Middle Button : Pan

VHMSSubSystemDesc=Mixed
VHMSSubSystemIndex=-99.0
ROI10YrsNPV=2.976681
AcquisitionCost10YrsNPV=80306.57
AoAve=80.039856
AoIncrease=2.4
RepairTimeAve=3.6120586
MTTRDecrease=1.9
MLDTAve=47.4982
MLDTDecrease=6.4
FaultPredict>8Ave=43.507545
MDDTAve=2.737079
MDDTDecrease=0.6
VHMSDesignNumber=424.0
Replication=10.0
Electrical_Generator=2.0
Electrical_Regulator=2.0
Electrical_I588Batteries=2.0
Electrical_FO8Batteries=2.0
Engine_PTFuelPump=2.0
Engine_APCValve=2.0
Engine_InTankFuelPump=2.0
CableWiring_AllCables=0.0
CableWiring_1W52W552W116=0.0
Turret_RoundFeedMotor=0.0
Turret_DriveMotor=0.0
Turret_TDCCircuitCards=0.0
DriveTrain_TransLRU=1.0
DriveTrain_BAverageSensor=1.0
DriveTrain_PropellerShafts=1.0
TracksSusp_TrackTension=0.0
TracksSusp_RoadIdlerWheels=0.0
TracksSusp_ShockAbsorbers=0.0

Figure 8 – ATSV Interface with Sample Dataset

The data describing each VHMS design configuration generated by the cost, benefit and maintenance operations models are displayed with the Trade Space Visualizer software. Due to the large number of unique designs that are possible for each platform, it was necessary to develop a surrogate model of the trade space. It would not be feasible to display and analyze hundreds of millions of points at once. The surrogate modeling process involves mapping the trade space, and then re-sampling with fewer data points (Ligetti, 2003). This makes it more manageable to analyze the data, but also results in hidden data points. At any point it is possible to examine all the data points within a specific area of the trade space, but it simply is too cumbersome to examine the entire trade space at once (Stump, et al, 2007).

The sheer number of potential design configurations also justifies the need for a more efficient CBA analysis methodology. For this analysis there were in excess of one hundred million possible scenarios for each platform, based on the selected design options. Whereas a traditional CBA considers only a few broad alternatives, there are in actuality, a large number of engineering design alternatives that must be compared during the design and development. Some design decisions are formally examined as they are identified, but many are considered ad hoc, without any formal methodology or approach. The ability to examine all (or at least a majority) of the pertinent design alternatives would allow for a more thorough design analysis, and could result in the discovery of advantageous designs that would not otherwise be known.

10 ATSV MODEL RESULTS

The developed ATSV models are intended to be used interactively by decision-makers and program stakeholders to explore the design space. By selectively applying weights to different metrics, and discriminating alternative designs with user-configurable limits, it is possible to analyze the design space from a variety of perspectives. For instance, a stake-holder from the logistics community might have different preferences concerning the benefits that should be maximized, than a company commander or chief warrant officer. Bringing these decision-makers together, and allowing them to explore the data in a manner that lets them collectively work towards a mutually agreeable optimum design (or set of designs), provides a unique design capability that integrates cost-benefit relationships into the systems engineering process.

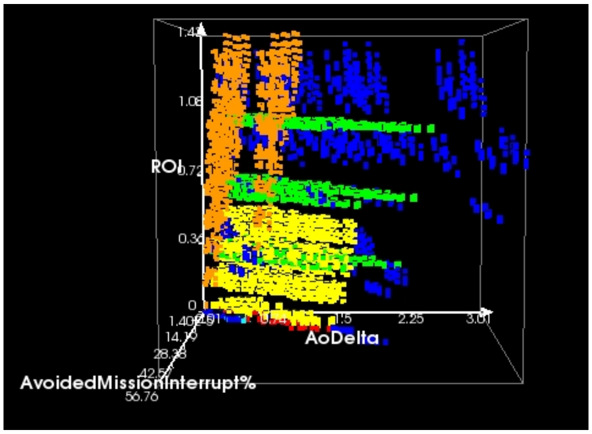


Figure 9 – Bradley Model, Color linked to Subsystem Grouping

Sample views of the Bradley CBA trade-space are shown in Figures 9 and 10. The color scheme in Figure 9 is used to group components from similar vehicle subsystems. The color scheme in Figure 10 is linked to the cumulative risk scores, which helps to understand which design configurations are most feasible.

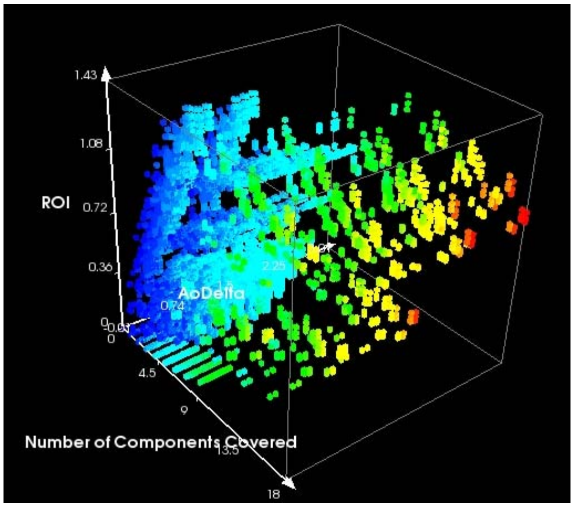


Figure 10 – Bradley Model, Color linked to Risk

While the tool does not lend itself to a single authoritative conclusion as to the optimum design, some general observations can be made from the Abrams and Bradley VHMS models. The results of the model generally point towards an optimum VHMS configuration that implements improved diagnostic solutions for items in the engine, drivetrain and electrical power subsystems. Even though track and suspension components have high replacement rates, and are critical components, the cost and risk associated with developing adequate VHMS solutions is relatively high. More precise results would rely upon the preferences of decision-makers. Are cost savings more important than improvements to operational availability? Is the avoidance of mission interruption due to failures a greater benefit than minimizing parts storage? Questions like these dictate an understanding of current needs and awareness of the future Army vision. For example, more emphasis has been placed in recent years on having smaller units of action that can be increasingly more operationally independent. From this perspective, reducing spare parts requirements may be more critical than achieving process improvements. Selection of an optimum VHMS design is thus dramatically dependent upon the decision-makers' perspective and decision criterion.

The ATSV tool has a variety of other applicable capabilities for examining the data sets. By selecting weighting factors for different cost and benefit metrics, it is possible to develop a Pareto frontier of optimum designs, as shown in Figure 11. The tool makes it possible to link the color, size, shape, transparency and visibility of data points to specific parameters. In this way it is possible to examine multidimensional data in a 3-dimensional view.

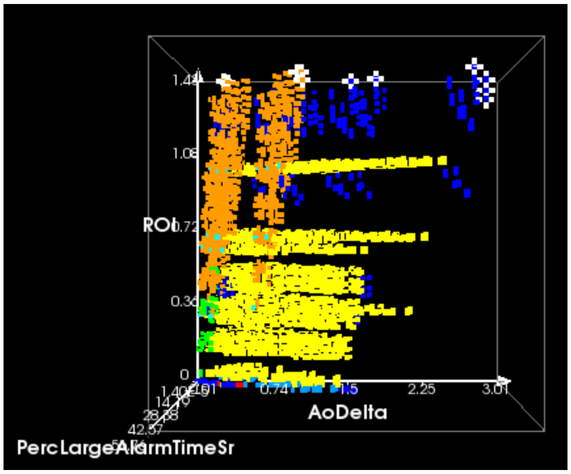


Figure 11 - Sample Bradley model, after filtering and application of a Pareto frontier

Another useful capability of the ATSV is in identifying trends within the design space. In the Abrams model, trends were identified between the benefits and the level of diagnostic implementation on the EMFS and turbine engine, as shown in Figures 12 and 13. This indicates that the resulting benefits are more significantly affected by the contributions of these components.

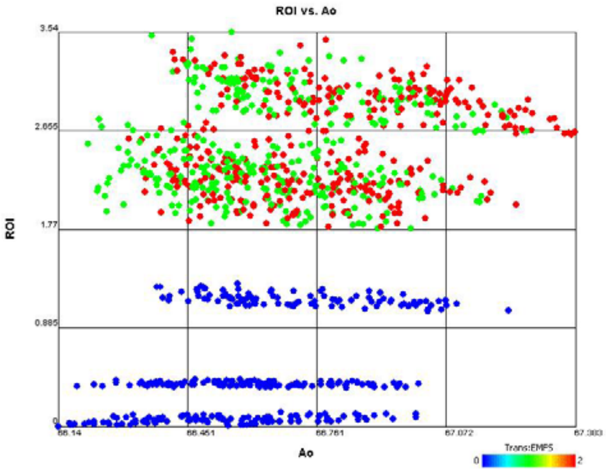


Figure 12 – Effect of Abrams EMFS Diagnostic Implementation Level on ROI and A_O

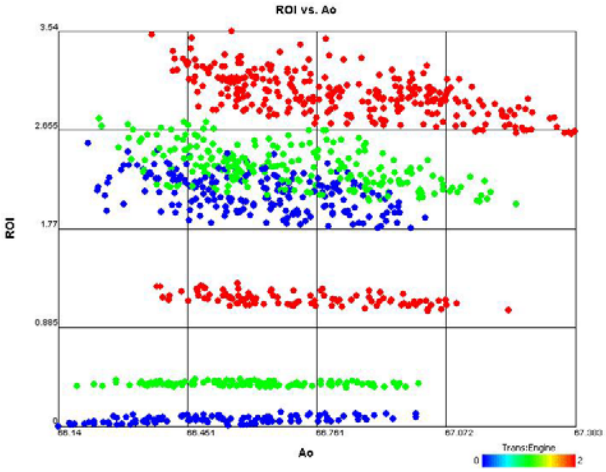


Figure 13 – Effect of Abrams Engine Diagnostic Implementation Level on ROI and Ao

11 CONCLUSION

The developed models were used to successfully integrate large amounts of dissimilar cost and design parameters in an intuitive way that allows for a more thorough cost-benefit/design analysis than what is typically possible using a traditional CBA methodology. This is particularly important due to its applicability to health monitoring efforts in general, where insufficient quantitative cost information is available to make an adequate business case. The incorporation of a discrete-event simulation of the system operation and support processes was a critical component of this analysis, and allowed for the inclusion of many difficult to estimate process improvements. The simulation development was performed in cooperation with LIA, using a very detailed process-flow model that LIA had developed for previous Army analyses. Owing to a variety of factors (including simulation run times), it was necessary for ARL to develop a more simplified simulation for this effort that was tailored specifically to the health monitoring CBA task. The LIA simulation remains a more thorough, and more flexible simulation that would be preferable if additional detail and accuracy is desired. The primary distinction between the ARL developed simulation, and the LIA model, is that the LIA model accounts for limited resources (manpower, special maintenance equipment, etc.), which can have significant impact on the repair process. However, for a first-order analysis, the ARL simulation provides more than enough detail for a relative comparison of designs, but may not be sufficiently accurate to capture the precise magnitudes of these benefits. The simplified model was also advantageous for this effort, in order to process the millions of simulations in a reasonable amount of time.

There are a number of additional cost categories and factors that could be included in the trade-space model that would allow for a more thorough analysis. LRU's could not be included in this analysis due to the inability to obtain applicable historical cost estimates. Without these estimates, the return on investment and total life cycle cost metrics are not reflective of the entire VHMS program. The cost estimates used in this analysis are rough estimates based on comparable programs, using industry standard cost estimating assumptions. The estimates can, and should be refined as better information becomes available. This will allow the tool to be utilized for making informed engineering design decisions as the program moves forward. In addition to existing cost estimates, there will also be a more detailed understanding of the cost relationships and interdependencies that should be reflected in the cost model in order to make it more accurate.

There are significant benefits that have not yet been added to the cost benefit models because of difficulty in assessing the necessary cost relationships. NEOF's were not included in the model because there is relatively little uncontested information available on what causes them, how many occur, and what impact they have on operations. Logistics benefits related to reduced support vehicle usage and fuel consumption were not included either because of the difficulty in relating VHMS benefits to the logistics operations. The modeling accuracy of the ARL operations model is probably insufficient for estimating these secondary benefits, and government cost analysts at TACOM have recommended against quantifying monetary benefits related to logistics improvements.

The elimination of DSESTS is the primary benefit of VHMS, but as it is associated with the LRU's, it is not included in this analysis. This benefit is both financial and process oriented. The financial benefits come from the elimination of the recurring support of the DSESTS equipment and vans, as well as the elimination of related FSR and OEM technical support. The process improvements result from a quicker diagnosis time and diagnosis accuracy that ultimately improve A_O. The operations model does not include LRU's, but the conducted interviews clearly point towards LRU fault diagnosis as a significant degrader of vehicle uptime. This benefit could be estimated using the operations model provided that subject matter experts could provide estimates of various process times associated with each LRU, and that necessary cost factor relationships and estimates are available.

The trade-space model does not currently take advantage of the various government cost models, such as Visual SESAME, LCET, CASA and COMPASS. Integrating these tools into the trade-space model would allow for a more detailed analysis. However, these software packages cannot be automated to perform multiple simulations. Thus, the integration of some of these tools would require significant effort to develop surrogate or meta-models. Cost relationships and calculations from CASA are available, and could be more readily incorporated into the model. However, the development of a more detailed model is particularly dependent on the availability of necessary data, which is exceedingly difficult to obtain. Any future work would require further cooperation from the government and from the OEM's.

ACKNOWLEDGEMENT

Special thanks are extended to the VHMS program management including Gerald Biolchini, Chuck Smithson and Joe Delfrate from U.S. Army TACOM, Andy Lee from TARDEC, and Brian Van De Wal from Benet Laboratories. The authors would also like to thank the Logistics Innovation Agency, with particular appreciation to Don Bates and Chris Ogburn, who provided invaluable assistance in the development of the maintenance and operational model. This work was supported by the NAVSEA Contract Number N00024-D-02-D-6604, Delivery Order Number 0356. The content of the information does not necessarily reflect the position or policy of NAVSEA, and no official endorsement should be inferred.

REFERENCES

(Banks and Merenich, 2007) Banks, J., and Merenich, J. “Cost Benefit Analysis for Asset Health Management Technology,” *Annual Reliability and Maintainability Symposium (RAMS ’07),* 2007, pp. 95-100.

(Byer, Hess and Fila, 2001) Byer, B., Hess, A., and Fila, L. “Writing a Convincing Cost Benefit Analysis to Substantiate Autonomic Logistics,” *IEEE Aerospace Conference Proceedings*, vol. 6, pp. 63095-63103, 2001.

(Wilmering and Ramesh, 2005) Wilmering, T., and Ramesh, A. “Assessing the Impact of Health Management Approaches on System Total Cost of Ownership,” *IEEE Aerospace Conference Proceedings*, pp. 3910-3920, 2005.

(Keller, et al, 2001) Keller, K., Simon, K., Stevens, E., Jensen, C., Smith, R., and Hooks, D., “A Process and Tool for Determining the Cost/Benefit of Prognostic Applications,” *Proceedings of IEEE AUTOTESTCON*, 2001, pp. 532-544.

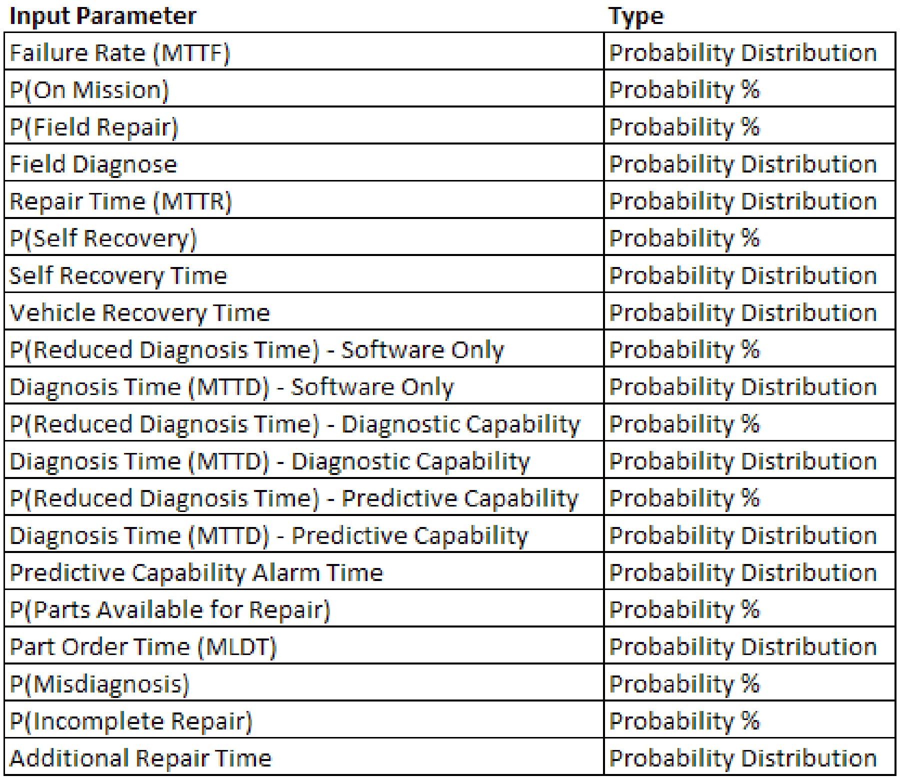
(Balling, 1999) Balling, R., 1999, “Design by Shopping: A New Paradigm,” *Proceedings of the Third World Congress of Structural and Multidisciplinary Optimization (WCMSO-3)*, Buffalo, NY, pp. 295-297.

(Stump, et al, 2002) Stump, G., Simpson, T., Yukish, M., and Bennett, L., “ Multidimensional Visualization and its Application to a Design By Shopping Paradigm,” 9th Annual *AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2002. Washington, DC.

(Stump, et al, 2007) Stump, G., Lego, S., Yukish, M., Simpson, T., and Donndelinger, J. “Visual Steering Commands For Trade Space Exploration: User Guided Sampling with Example,” *Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2007*, Sept. 4-7, Las Vegas, NV.

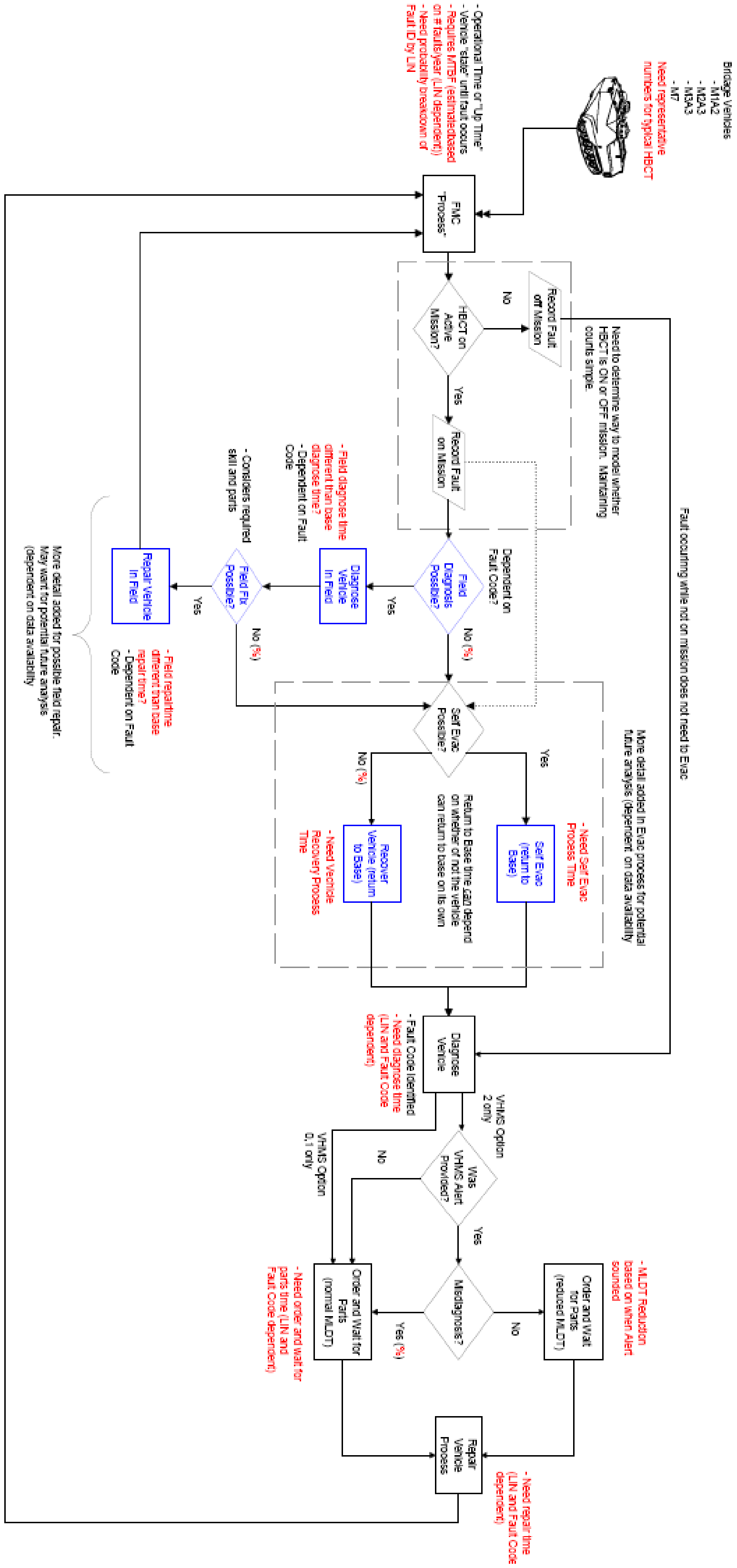
(Ligetti, 2003) Ligetti, C.B., “Metamodel-Driven Visualization in Engineering Design: Studies on Design Efficiency and Effectiveness Using Graphical Design Interfaces,” M.S. thesis, 2003, Dept. of Industrial and Manufacturing Engineering, Pennsylvania State University, University Park, PA.

APPENDIX A – MAINTENANCE AND OPERATIONS MODEL PARAMETERS

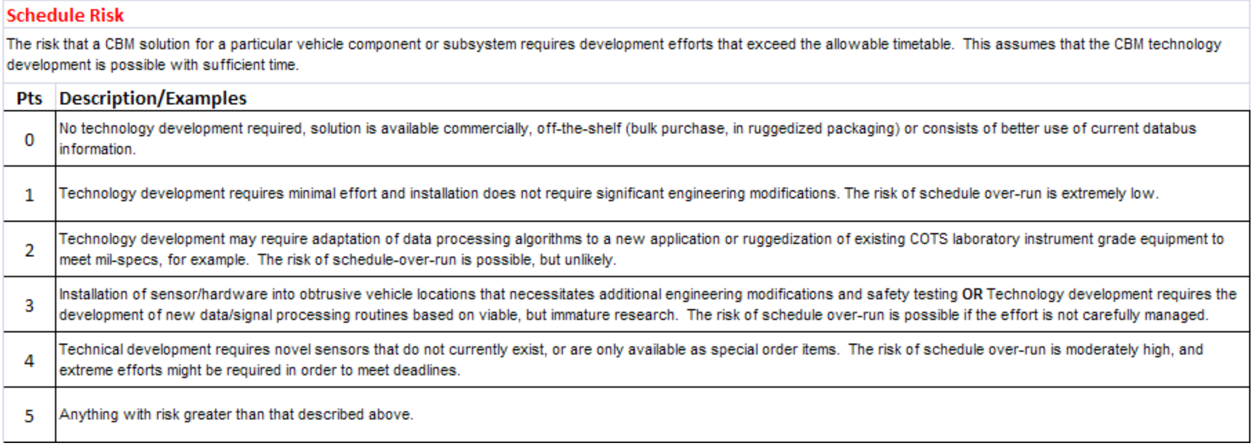


Input Parameter	Type
Failure Rate (MTTF)	Probability Distribution
P(On Mission)	Probability %
P(Field Repair)	Probability %
Field Diagnose	Probability Distribution
Repair Time (MTTR)	Probability Distribution
P(Self Recovery)	Probability %
Self Recovery Time	Probability Distribution
Vehicle Recovery Time	Probability Distribution
P(Reduced Diagnosis Time) - Software Only	Probability %
Diagnosis Time (MTTD) - Software Only	Probability Distribution
P(Reduced Diagnosis Time) - Diagnostic Capability	Probability %
Diagnosis Time (MTTD) - Diagnostic Capability	Probability Distribution
P(Reduced Diagnosis Time) - Predictive Capability	Probability %
Diagnosis Time (MTTD) - Predictive Capability	Probability Distribution
Predictive Capability Alarm Time	Probability Distribution
P(Parts Available for Repair)	Probability %
Part Order Time (MLDT)	Probability Distribution
P(Misdiagnosis)	Probability %
P(Incomplete Repair)	Probability %
Additional Repair Time	Probability Distribution

APPENDIX B – MAINTENANCE AND OPERATIONS MODEL (GENERAL MODEL PROCESS FLOW)



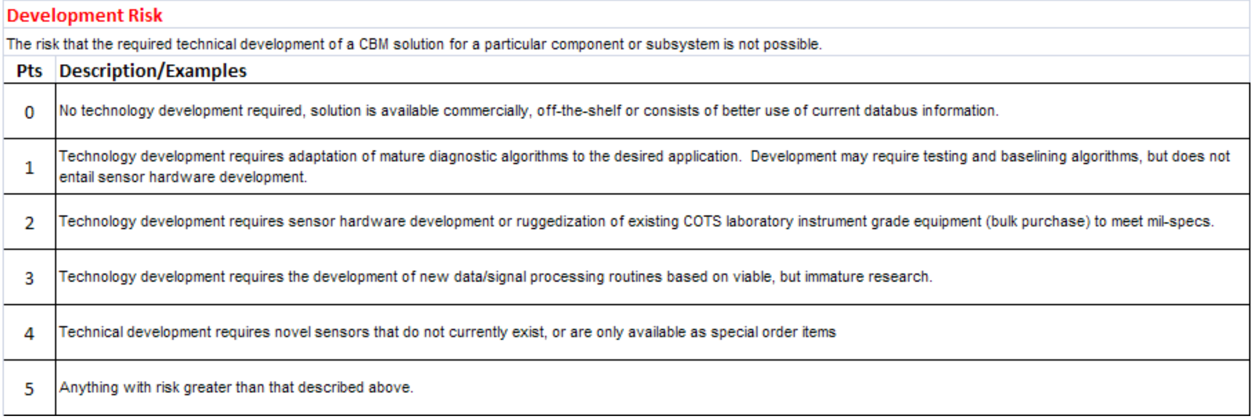
APPENDIX C – RISK SCORECARD GUIDELINES



Schedule Risk

The risk that a CBM solution for a particular vehicle component or subsystem requires development efforts that exceed the allowable timetable. This assumes that the CBM technology development is possible with sufficient time.

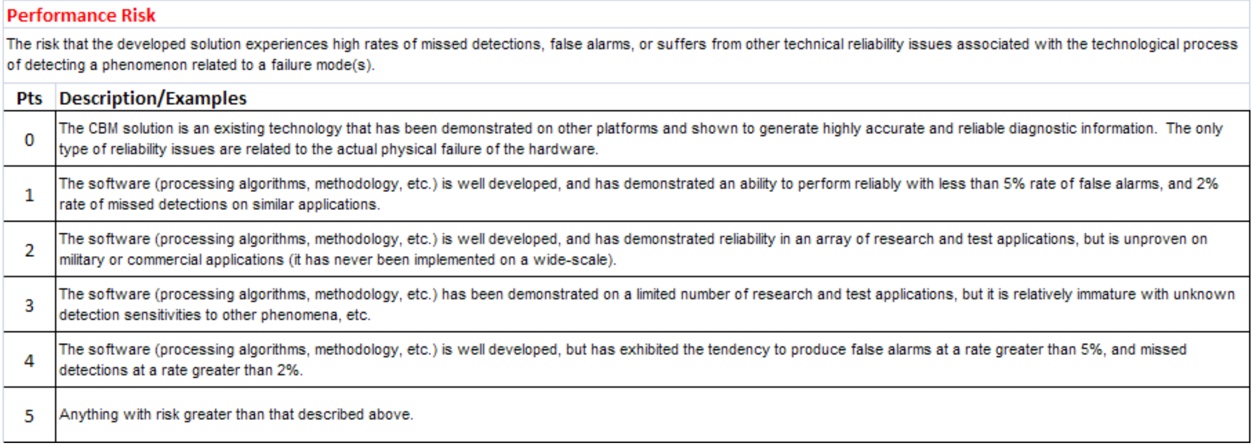
Pts	Description/Examples
0	No technology development required, solution is available commercially, off-the-shelf (bulk purchase, in ruggedized packaging) or consists of better use of current databus information.
1	Technology development requires minimal effort and installation does not require significant engineering modifications. The risk of schedule over-run is extremely low.
2	Technology development may require adaptation of data processing algorithms to a new application or ruggedization of existing COTS laboratory instrument grade equipment to meet mil-specs, for example. The risk of schedule-over-run is possible, but unlikely.
3	Installation of sensor/hardware into obtrusive vehicle locations that necessitates additional engineering modifications and safety testing **OR** Technology development requires the development of new data/signal processing routines based on viable, but immature research. The risk of schedule over-run is possible if the effort is not carefully managed.
4	Technical development requires novel sensors that do not currently exist, or are only available as special order items. The risk of schedule over-run is moderately high, and extreme efforts might be required in order to meet deadlines.
5	Anything with risk greater than that described above.



Development Risk

The risk that the required technical development of a CBM solution for a particular component or subsystem is not possible.

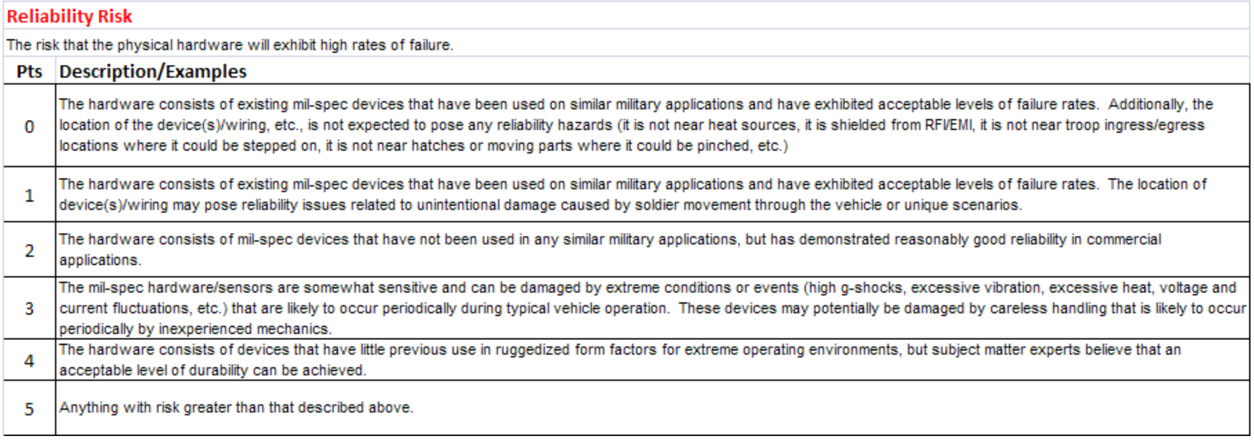
Pts	Description/Examples
0	No technology development required, solution is available commercially, off-the-shelf or consists of better use of current databus information.
1	Technology development requires adaptation of mature diagnostic algorithms to the desired application. Development may require testing and baselining algorithms, but does not entail sensor hardware development.
2	Technology development requires sensor hardware development or ruggedization of existing COTS laboratory instrument grade equipment (bulk purchase) to meet mil-specs.
3	Technology development requires the development of new data/signal processing routines based on viable, but immature research.
4	Technical development requires novel sensors that do not currently exist, or are only available as special order items
5	Anything with risk greater than that described above.



Performance Risk

The risk that the developed solution experiences high rates of missed detections, false alarms, or suffers from other technical reliability issues associated with the technological process of detecting a phenomenon related to a failure mode(s).

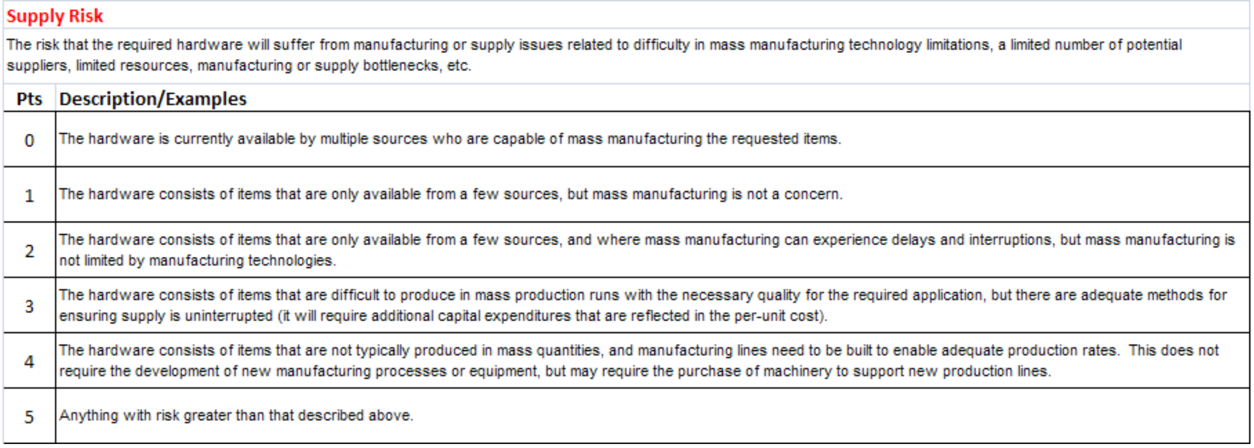
Pts	Description/Examples
0	The CBM solution is an existing technology that has been demonstrated on other platforms and shown to generate highly accurate and reliable diagnostic information. The only type of reliability issues are related to the actual physical failure of the hardware.
1	The software (processing algorithms, methodology, etc.) is well developed, and has demonstrated an ability to perform reliably with less than 5% rate of false alarms, and 2% rate of missed detections on similar applications.
2	The software (processing algorithms, methodology, etc.) is well developed, and has demonstrated reliability in an array of research and test applications, but is unproven on military or commercial applications (it has never been implemented on a wide-scale).
3	The software (processing algorithms, methodology, etc.) has been demonstrated on a limited number of research and test applications, but it is relatively immature with unknown detection sensitivities to other phenomena, etc.
4	The software (processing algorithms, methodology, etc.) is well developed, but has exhibited the tendency to produce false alarms at a rate greater than 5%, and missed detections at a rate greater than 2%.
5	Anything with risk greater than that described above.



Reliability Risk

The risk that the physical hardware will exhibit high rates of failure.

Pts	Description/Examples
0	The hardware consists of existing mil-spec devices that have been used on similar military applications and have exhibited acceptable levels of failure rates. Additionally, the location of the device(s)/wiring, etc., is not expected to pose any reliability hazards (it is not near heat sources, it is shielded from RFI/EMI, it is not near troop ingress/egress locations where it could be stepped on, it is not near hatches or moving parts where it could be pinched, etc.)
1	The hardware consists of existing mil-spec devices that have been used on similar military applications and have exhibited acceptable levels of failure rates. The location of device(s)/wiring may pose reliability issues related to unintentional damage caused by soldier movement through the vehicle or unique scenarios.
2	The hardware consists of mil-spec devices that have not been used in any similar military applications, but has demonstrated reasonably good reliability in commercial applications.
3	The mil-spec hardware/sensors are somewhat sensitive and can be damaged by extreme conditions or events (high g-shocks, excessive vibration, excessive heat, voltage and current fluctuations, etc.) that are likely to occur periodically during typical vehicle operation. These devices may potentially be damaged by careless handling that is likely to occur periodically by inexperienced mechanics.
4	The hardware consists of devices that have little previous use in ruggedized form factors for extreme operating environments, but subject matter experts believe that an acceptable level of durability can be achieved.
5	Anything with risk greater than that described above.



Supply Risk

The risk that the required hardware will suffer from manufacturing or supply issues related to difficulty in mass manufacturing technology limitations, a limited number of potential suppliers, limited resources, manufacturing or supply bottlenecks, etc.

Pts	Description/Examples
0	The hardware is currently available by multiple sources who are capable of mass manufacturing the requested items.
1	The hardware consists of items that are only available from a few sources, but mass manufacturing is not a concern.
2	The hardware consists of items that are only available from a few sources, and where mass manufacturing can experience delays and interruptions, but mass manufacturing is not limited by manufacturing technologies.
3	The hardware consists of items that are difficult to produce in mass production runs with the necessary quality for the required application, but there are adequate methods for ensuring supply is uninterrupted (it will require additional capital expenditures that are reflected in the per-unit cost).
4	The hardware consists of items that are not typically produced in mass quantities, and manufacturing lines need to be built to enable adequate production rates. This does not require the development of new manufacturing processes or equipment, but may require the purchase of machinery to support new production lines.
5	Anything with risk greater than that described above.