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WHOLE SYSTEM TRADES ANALYSIS TOOL FOR THE HIGH MOBILITY MULTIPURPOSE WHEELED VEHICLE

Marissa Ballantine[1], Alex Dessanti[1], Adam Pierson[1], Yang Ho[1], Michael Dinunzio[2], Tera Cardinale[3], Laura Costa[3], Daniel Hopkinson[3], Nathan Pykor[3]

[1]Sandia National Laboratories, Albuquerque, NM
[2]TACOM Cost & Systems Analysis, Warren, MI
[3]Booz Allen Hamilton, Troy, MI

ABSTRACT

The Product Director Light Tactical Vehicles (PdD LTV) is responsible for the Army's High Mobility Multipurpose Wheeled Vehicle (HMMWV) family of vehicles. Due to the large number of variants found throughout the Army plus the continued need for their service into the foreseeable future, the Army has conducted extensive depot recapitalization programs and continues to explore modernization options to sustain enduring requirements. Because competing performance requirements exist and budget constraints demand careful design choices, PdD LTV commissioned the development of a Whole System Trades Analysis Tool (WSTAT) specified for the HMMWV family of vehicles to help gain an analytic understanding of the key performance, cost, risk, and growth tradeoffs inherent within their potential designs. The WSTAT provides a holistic framework for modeling and understanding these tradeoffs. In this paper, the overarching WSTAT methodology is presented along with the specific implementation for HMMWV. Several example results are then provided to demonstrate the types of decision support enabled by the WSTAT capability.

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1. INTRODUCTION

The Product Director Light Tactical Vehicles (PdD LTV), a division of the United States Army Program Executive Office Combat Support and Combat Service Support (PEO CS&CSS), is responsible for providing American war fighters with superior and comprehensive program management services, world-class light tactical vehicles and trailer systems, and responsive life cycle support. PdD LTV achieves this by developing, acquiring, producing, fielding, and sustaining safe, reliable, effective and supportable light tactical vehicles and trailer systems for the joint war fighting community. As such, PdD LTV must carefully consider a complex and vast array of design tradeoffs and interdependencies in order to maximize effectiveness to the warfighter, minimize long-term maintenance and sustainment needs, maximize reliability, minimize overall costs to the taxpayer, and balance many other goals. These important and competing design considerations require an unbiased analytic approach that presents decision makers with multiple optimal system alternatives, a spectrum of options that best balance all design considerations.

Such an analytic approach can be provided by the Whole System Trades Analysis Tool (WSTAT), developed by Sandia National Laboratories in collaboration with the U.S. Army. The WSTAT model developed for PdD LTV's primary platform, the High Mobility Multipurpose Wheeled Vehicle (HMMWV), was created in partnership with PdD LTV and involved significant contributions from the U.S. Army Tank-automotive and Armaments Command (TACOM) Cost & Systems Analysis Organization, Sandia National Laboratories, Booz Allen Hamilton, and the U.S. Army Combat Capabilities Development Command Data and Analysis Center (CCDC DAC). This group of organizations is collectively referred to as the "WSTAT Development Team" in the remainder of this document.

This paper introduces WSTAT and provides an overview of PdD LTV's HMMWV design effort. The capability needs for this program and the modeling approaches taken to cast the HMMWV design architecture into the WSTAT framework are described. Finally, example results that elucidate the variety of analyses enabled by WSTAT are presented.

2. WSTAT OVERVIEW

The Whole System Trades Analysis Tool (WSTAT) is a holistic system design and tradeoff exploration tool that uses a multi-objective optimization [1] to find system configurations that best balance competing design criteria as specified by formal requirements documents and subject matter expert (SME) guidance. These design criteria typically include, but are not limited to, performance, cost, schedule risk, and growth potential, which become WSTAT's optimization dimensions. In general, design criteria cannot all be satisfied simultaneously (e.g., while increased performance and decreased cost are both desirable, greater performance generally requires a greater investment). WSTAT then serves to provide decision makers with a variety of possible designs, each balancing the competing design criteria in different ways, rather than give a single optimized design. The WSTAT framework is generalizable and has been successfully applied to a diverse range of systems such as the Ground Combat Vehicle [2], the Armored Multi-Purpose Vehicle family, the Maneuver Support Vessel (Light) aquatic landing craft, Contingency Base camp Infrastructure design, and the Squad Multipurpose Equipment Transport autonomous ground vehicle [3].

When the WSTAT process is applied to a new program, it begins with establishing a thorough understanding of the program needs and requirements, typically guided by a Capability Development Document (CDD) or Operational Requirements Document (ORD) and discussions with SMEs. These needs and requirements are then mapped to Functional Objectives (FOs), which are quantitative or qualitative measures of capability comparable to the system's requirements. In the context of ground vehicles, example FOs might include payload capacity, off-road speed, and protection against under-vehicle attack. The FOs are then aggregated into major optimization dimensions (e.g., performance, cost, risk, and growth potential); if an FO should not be aggregated, it is considered as its own optimization dimension. Next, the system is conceptually decomposed into its constituent subsystems (collectively referred to as the "Product Structure"), with each subsystem having multiple potential Technology Options (TOs) with inherent advantages and disadvantages. For a TO to be considered, it must be a component of the system for which there exists current or potential technology alternatives with different tradeoffs relative to the design criteria (performance, cost, schedule risk, etc.). TOs typically considered, in the case of a ground combat system, for example, would typically include subsystems such as engine, transmission, hull, armor, and weapon system.

Once the FOs and Product Structure are defined, an iterative refinement of the calculations used to measure the FOs ensues based on further discussion with SMEs, individuals with technical, operational, and programmatic expertise, and data availability for the TOs. Also during this phase of development, a panel of system users (typically soldiers who have operated similar systems in the field) is assembled to provide priority weightings of the FOs that are aggregated into each optimization dimension. This user elicitation follows the Swing Weight Matrix approach [4] to capture FO priority, giving highest weights to FOs that have both 1) greater tactical importance, and 2) require larger performance improvements from the current state to meet threshold requirements.

Once these major modeling elements are finalized, the system configurations are optimized by a multi-objective genetic algorithm in which the decision variables consist of the choice of TO for each subsystem in the Product Structure. By mixing the various subsystem TOs, many millions of system configurations can be evaluated by the genetic algorithm, learning from and evolving consecutive populations of configurations to generate ever-improving sets of designs. The final set of solutions that best balances the competing optimization dimensions is then presented to decision makers by WSTAT, enabling a holistic trade-space examination across multiple measured of interest to stakeholders. The WSTAT results engine provides dozens of different filters and views with which to interrogate the resulting trade space. A more detailed overview of WSTAT's methodology and capabilities may be found in [5] and [6].

3. HMMWV OVERVIEW

PdD LTV is responsible for the Army's High Mobility Multipurpose Wheeled Vehicle (HMMWV, pronounced "Humvee") family of vehicles. The large number of HMMWV variants found throughout the Army and the continued need for their service into the foreseeable future has prompted the Army to conduct extensive depot recapitalization programs and continue to explore modernization options to sustain enduring requirements. As a result, four variants have been prioritized for performance upgrades: the non-armored M1097A2, and the up-armored M1151A1, M1152A1, and M1165A1.

Central to the desired performance for the upgraded fleet of HMMWV's are survivability and air assault transportability. As with any government procurement, initial investment cost must also be considered, and because the performance upgrade design decisions will characterize the HMMWV fleet for years to come, the long-term operation and sustainment cost impacts inherent in these decisions must also factor into the analysis that compares design options. The complexity introduced by the myriad of technology options that impact both survivability and air assault transportability, along with the constraints imposed by budget limitations and schedule requirements are what drove PdD LTV to employ the WSTAT approach to support the HMMWV performance upgrade design.

4. HMMWV REQUIREMENTS AND CAPABILITIES

The first step in creating a WSTAT model is a distillation of system requirements into the FOs that will be used by the optimization algorithm to measure the "goodness" of a configuration. The WSTAT model for HMMWV gathered requirements from the 2004 ORD, official addendums to the ORD, and PdD LTV engineers, and these requirements were distilled into FOs by the WSTAT Development Team.

The project started with an exhaustive list of Performance FOs, which was gradually reduced by about 50%; the FO's that were not considered were either deemed non-tradeable (i.e., the FO had no associated product structure elements) or not measurable under the project schedule and funding constraints. Among the most prominent FOs deferred were those related to lethality and non-air transportability; the FOs retained did thoroughly cover performance related to detection avoidance, mobility, power generation, survivability, and air transportability.

All Performance FO's are aggregated into a single Performance score, which is one of the six optimization dimensions analyzed in this study. The other five dimensions, which are entirely independent of the Performance FOs, are Commonality, Growth, Investment Cost, Operations and Sustainment (O&S) Costs, and Schedule Risk. For the analysis presented here and at the direction of PdD LTV, each of these dimensions were weighted equally. The HMMWV assessment dimensions are described as follows:

- Commonality – A measure of how many product structure elements are shared among variants; applies to up-armored variants only. When a HMMWV optimization is performed including the Commonality dimension, all solutions represent three distinct configurations corresponding to the three up-armored variants.
- Growth – A combination of Electrical Power Margin and Mechanical Power Margin. Electrical Power Margin is measured as the generation capacity of the alternator/generator minus peak power draw of all subsystems; Mechanical Power Margin is measured as peak power output of the final drive minus the larger of power needed to achieve threshold dash speed and power needed to achieve threshold sustained hard surface road speed.
- Investment Cost – The average acquisition cost per HMMWV, which includes the new purchase price of all upgraded parts minus the trade-in value of these parts, plus the integration cost. This is commonly referred to as the Average Unit Manufacturing Cost, or AUMC.
- O&S Costs – The overall expenses incurred for repairing, maintaining, and fueling an HMMWV throughout its operational lifetime.
- Performance – A single score derived from the weighted average of the 25 performance FOs.
- Schedule Risk – The relative technology and manufacturing maturity, as indicated by the current technology readiness level (TRL), of the subsystems employed in the HMMWV configuration.

In addition to the FOs for each optimization dimension, WSTAT can also track a wide range of supplementary metrics for each configuration. For HMMWV, there are over a dozen metrics related to various configuration weights, component weight limits, speeds, fuel efficiency, and costs. These metrics are often employed as intermediate steps for many FO calculations, but they also provide important diagnostic information for analyzing the trade space and understanding the underlying rationale for high-level design choices.

5. HMMWV ARCHITECTURE

Broadly speaking, WSTAT operates by scoring a candidate configuration based on its selection of subsystems, eventually finding those solutions that best balance the optimization dimensions. Therefore, it is important to properly decompose the system into its constituent subsystems, as these form the fundamental decision variables of the optimization. It is this decomposition architecture, or Product Structure, that forms the basis for WSTAT's conceptualization of a configuration. In other words, all FOs and metrics are calculated based on parameters of the subsystems chosen for each configuration.

Generally, when designing a WSTAT Product Structure, the objective is to balance the granularity of detail. With too much information, the optimization can be impeded by choices about subsystems that do not impact the trade space; too little information can result in insufficient detail on the FOs to capture a rich set of design tradeoffs. In addition, the Product Structure is heavily influenced by the availability of data for each subsystem and by the ability to freely "mix and match" the subsystems. For example, if there is no reliable source of data for a given subsystem, including it in the Product Structure is of limited value. Similarly, if two parts cannot be independently selected due to heavily interrelated design restrictions, then the Product Structure should not be decomposed to that level; instead those parts should be aggregated into a single subsystem. All of these considerations were taken into account to define the final HMMWV Product Structure shown in Figure 1.

The light gray boxes represent a subsystem in the HMMWV architecture, each of which has a variety of TO choices that WSTAT can explore (the dark gray boxes are subsystem groupings made for organizational purposes and do not impact the optimization). Note that some of the subsystems are systems of subsystems and therefore necessitate a "None" TO selection for those subsystems (i.e., a configuration that chooses an Integrated Starter Generator will have "None" options for Alternator, Inverter and Starter, while a configuration that chooses a Complete Mobility System will have "None" options for Suspension, Transfer Case, and Frame Rails). Also note that many subsystems are optional (e.g., Frag Kit 1, Frag Kit 2, Frag Kit 5, Frag Kit 7, and Inverter), hence a HMMWV configuration may not include every subsystem. Finally, the non-armored variant cannot choose any of the armor options. With all of these considerations in mind, the WSTAT HMMWV model results in a trade space of 10^{16} possible configurations; when the up-armored variants are considered as a family of vehicles, there are upwards of 10^{51} possible configurations.

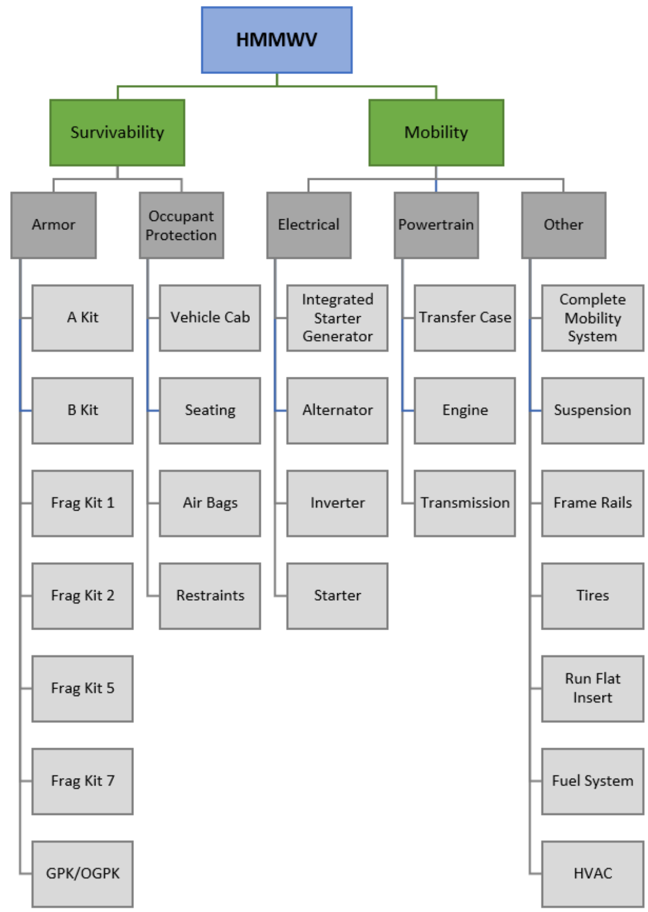

Figure 1: WSTAT HMMWV Product Structure.

6. UTILITY SCORES AND USER PRIORITY WEIGHTS

The penultimate step in the WSTAT development process (prior to running the optimization) maps each "raw" FO value into a unitless utility score, then takes a weighted sum of these scores for each optimization dimension. As mentioned earlier, the Performance dimension consists of a diverse set of 25 FOs, each with unique units of measure such as, miles per hour for speed-related FOs and pounds for weight-related FOs. Mapping these raw FO units into utility scores allows: 1) an apples-to-apples comparison between different FO scores and 2) a means by which to take a weighted sum to aggregate the multiple FOs into a single Performance score.

Utility score mapping is done via analyst-specified walkaway, threshold, and objective values (taken from the CDD or ORD when appropriate) where the raw walkaway value translates to a utility score of 1, raw threshold translates to 70, and raw objective translates to 100 (usually with linear interpolation between these values). Thus, WSTAT has the freedom to explore below-threshold trades for individual FOs in order to find good overall performance or to find solutions that excel in other optimization dimensions.

User priority weights for HMMWV were elicited from over two dozen HMMWV experts and users, all with an equal voice, during an in-person panel. The user panel employed the Swing Weight Matrix method [4] and consisted of a survey followed by a facilitated discussion. Each FO was ranked based on 1) how important it is to HMMWV usability in the field, and 2) how much improvement was needed over the current performance level. FOs having the greatest importance and needing the most performance improvement are given the highest weight, while those with the least importance and requiring relatively little performance improvement are given the lowest. User weights were elicited for each variant separately, as they each fulfill different roles. The final priority weights resulting from the HMMWV user panel were entered into WSTAT and used for each optimization run. If different priorities want to be considered in the future, these weights can be readily updated and the optimization rerun.

7. CONSTRAINTS, LIMITATIONS, AND ASSUMPTIONS

The WSTAT HMMWV project was not subject to any constraints, limitations, or assumptions that hindered development of the model. There are, as is true with most research projects, some areas that could be improved as data availability allow. For this project, improvements could be made in terms of armor technology option attribute data and maintenance cost data. Regarding armor data, at the time of WSTAT HMMWV development, the several armor technology options that were available for A Kit, B Kit, Frag Kit 1, Frag Kit 2, Frag Kit 5, Frag Kit 7, and GPK/OGPK were not highly differentiable, leading to a trade space that similarly preferred all armor options of the same type (e.g., protection level). Developing armor technology options that are clearly distinct and/or improving on existing technology options to enhance their distinctiveness will lead to more diverse configurations in the optimal result set. For the maintenance cost data, estimates were made for each subsystem based on historical expenditures; while this is a reasonable approximation and treats all subsystems similarly, it might overestimate the 20-year O&S cost for new or future technology options.

Neither of the aforementioned data realities were seen to hinder the current WSTAT HMMWV analysis. Furthermore, the WSTAT HMMWV model that was delivered to PdD LTV can be readily modified (i.e., technology option attribute data can be updated, and new technology options can be added) at any time by PdD LTV, the optimizations rerun, and trade space reassessed.

8. HMMWV TRADE STUDY RESULTS

Once all preceding modeling activities were complete, WSTAT was run for each variant to obtain a representative sample of the Pareto trade space of optimal configurations. WSTAT was also run for all three armored variants together in order to utilize the Commonality assessment dimension. WSTAT run time varies from problem to problem, depending on the size of the search space and the number of problem constraints, and usually requires between one hour and one day to achieve satisfactory convergence, which is a subjective measure assessed by a WSTAT analyst using several diagnostic tools provided by the "Confidence Analytics" feature of WSTAT. The HMMWV results presented in this section are gathered from runs of various durations that all started with a population of 2,000

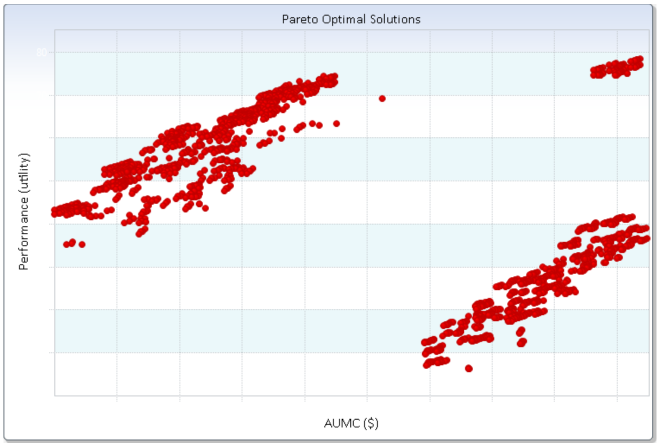

Figure 2: Pareto frontier of optimal M1097A2 solutions.

randomly-generated configurations and used a Maximum Generation criterion to determine when the run would stop; each run was examined to ensure satisfactory convergence.

Figure 2 shows a plot of Average Unit Manufacturing Cost (AUMC) measured in dollars ($) on the x-axis vs. Performance measured in utility score on the y-axis for the Pareto frontier of optimal solutions, each point representing an optimal HMMWV design. Less expensive solutions appear on the left of the graph, followed by more expensive solutions towards the right; similarly, lower performing solutions are near the bottom of the graph while higher performing solutions are near the top. Note that only two of the five optimization dimensions are shown here; this detail will be further discussed below. A similar plot is shown for the armored variants in Figure 3. Again, only two of the optimization dimensions are shown; however, in this case, there are six total dimensions that were explored because the Commonality dimension is included.

It is readily noticeable that the Pareto frontier for the non-armored M1097A2 (Figure 2) is distinguishable from that for the armored variants (Figure 3) due to a substantial (845 of 1989 solutions) group of points in the lower right corner of the plot. This is one instance where it is important to remember that only two of five optimization dimensions are being shown and understand that the low-performing solutions are

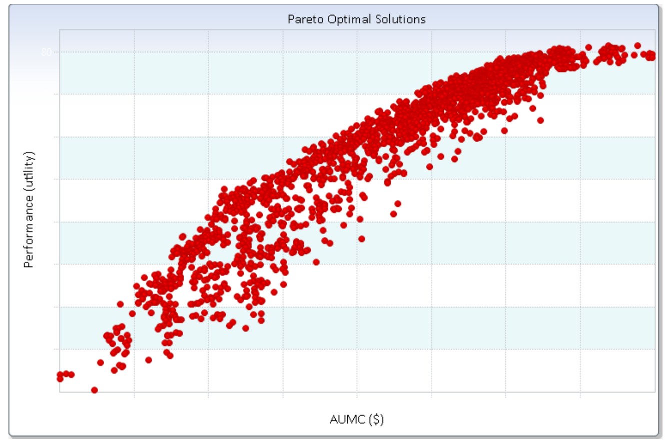

Figure 3: Pareto frontier of optimal armored solutions (M1151A1, M1152A1, and M1165A1).

part of the optimal set because they must be scoring high in some other dimension.

To determine what dimension this is, it is useful to figure out what technology option(s) dominate this cloud of points. Using WSTAT's "Highlight by Alternatives" feature, it becomes readily clear that there is a single tech option driving this phenomenon: the Vehicle Cab selection (Figure 4). The next question to ask is, why?

Leaving the alternatives highlighted, then changing the y-axis selection to O&S Costs (utility) gives the plot shown in Figure 5.

The AUMC vs. O&S Costs plot with the Vehicle Cab alternatives highlighted shows that Cab Upgrade 1 (purple points) scores better than all

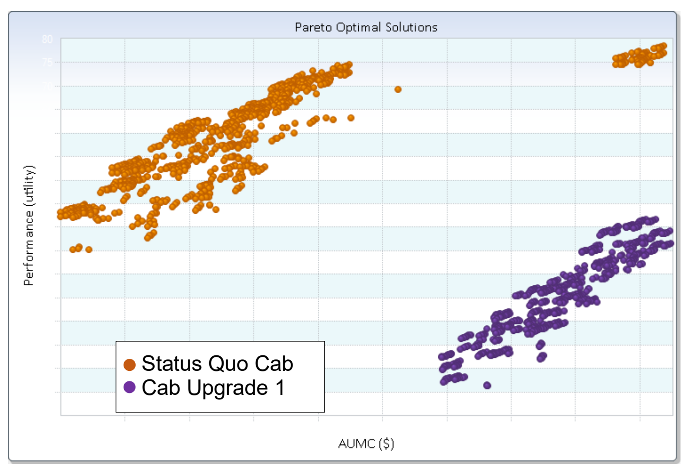

Figure 4: M1097A2 optimal solutions colored by vehicle cab selection.

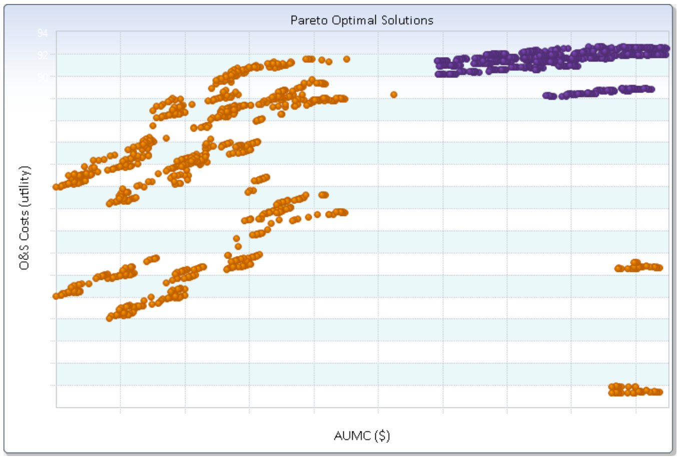

Figure 5: Solutions shown in Figure 4 plotted as AUMC vs. O&S Costs.

other solutions in the O&S Costs dimension. Recall that the O&S Costs are being displayed as a utility score rather than raw cost (i.e., a lower raw cost equates to a higher utility). Examination of the technology option attribute data reveals that this technology option has the lowest Maintenance Cost when compared to all other options.

The Highlight by Alternatives feature is useful not only for interrogations like the one described above, but also to determine which technology options are dominating at different price points and performance levels.

Doing this same exercise for the armored variants (Figures 6 and 7) shows that Cab Upgrade 1 also appears frequently in this set of solutions; however,

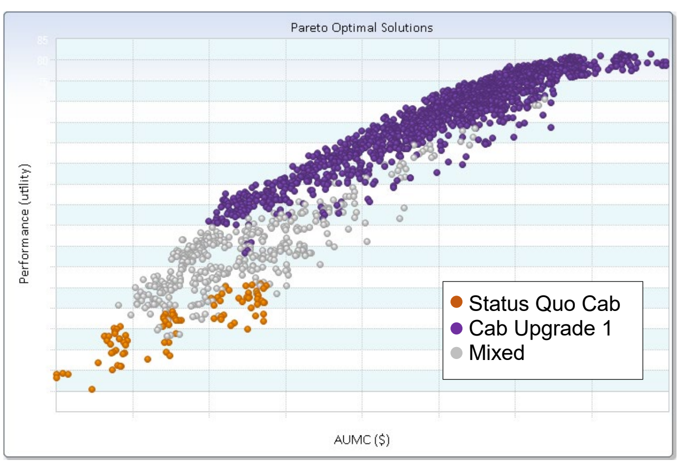

Figure 6: M1151A1, M1152A1, and M1165A1 optimal solutions colored by vehicle cab selection.

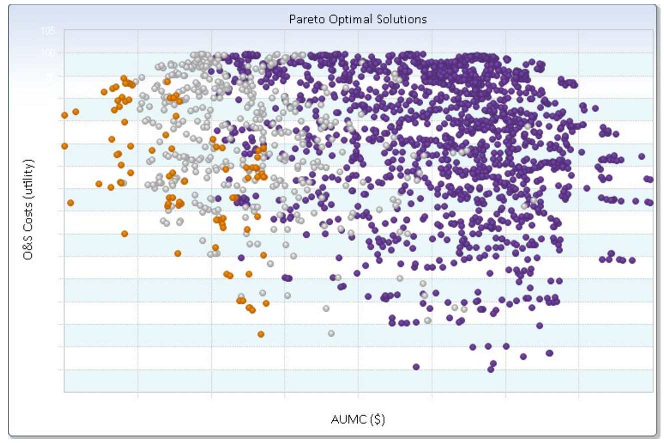

Figure 7: Solutions shown in Figure 6 plotted as AUMC vs. O&S Costs.

it does not only appear in solutions with higher O&S Costs utility as it did for the non-armored variant. Note that the set of solutions for the armored variants includes a third vehicle cab solution titled “Mixed”; these gray dots indicate that the configurations in this solution subset do not have a common Vehicle Cab (e.g., the M1151A1 might have the upgraded cab, while the M1152A1 and M1165A1 have the Status Quo cab).

Comparing Figures 5 and 7 suggests that while the Vehicle Cab selection is a significant driver for long-term O&S Costs of the M1097A2, it is not such for the armored variants, likely because of the impact that armor and other high-cost, high-weight technologies only applicable to the M1151A1, M1152A1, and M1165A1 have on lifetime maintenance and fuel costs.

In addition to the three assessment dimensions discussed up to this point, it is worthwhile to consider the remaining assessment dimensions of Commonality, Growth, and Risk. Commonality does not have a corresponding illustrative graphic in this model, but it is still an important dimension for the genetic algorithm to explore: for every set of three configurations that is built (comprised of an M1151A1, M1152A1, and M1165A1), it is just as important to achieve a high Performance score (along with low AUMC, low O&S Costs, low Risk, and high Growth Potential) as it is to achieve a high

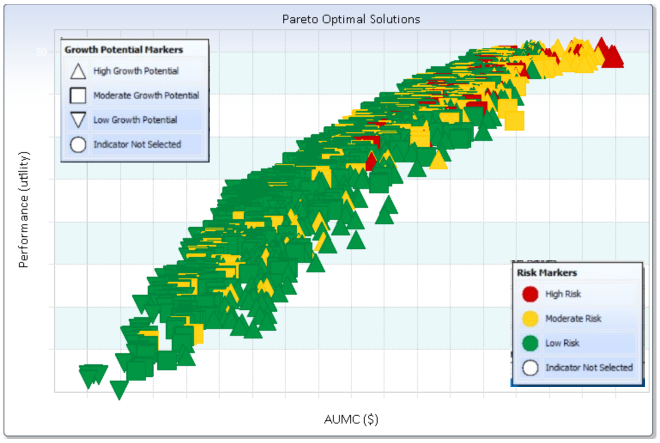

Figure 8: Pareto frontier of optimal armored solutions (M1151A1, M1152A1, and M1165A1 considered together) displayed with markers for Growth Potential and Risk.

Commonality score, meaning that every configuration in a solution will have at least one, if not many, of the same technology options selected across subsystems. While Commonality is most usefully interpreted by examining technology options selections, Growth and Risk can be seen by turning on WSTAT's "Custom Markers" option (Figure 8).

The plot shown in Figure 8 now displays four of the six assessment dimensions: AUMC ($) is plotted on the x-axis, Performance (utility score) is plotted on the y-axis, Growth Potential (utility score) is shown as a shape (Triangle = High, Square = Moderate, Upside down triangle = Low), and Risk (utility score) is indicated by a color (Red = High, Yellow = Moderate, Green = Low). Turning on the O&S Costs marker adds 20-year O&S Cost, measured in millions of dollars, to the center of each point (enabling the user to visualize five dimensions simultaneously); when viewing these results in the WSTAT tool itself, individual points or groups of points can be zoomed in on and these data considered in more detail. Note that any assessment dimension or metric can be plotted on the x- or y- axis; custom markers are only available for Growth, Risk, and O&S Costs. In the view shown in Figure 8, the following high-level trends are readily visible: high Performance and AUMC correspond to high Growth Potential and high Risk, while low Performance and AUMC correspond to low Growth Potential and low Risk, with midrange Performance and AUMC seeing a mix of Growth Potential and Risk scores.

The WSTAT HMMWV tool itself is replete with many more analytic capabilities than can be shown here, including tools to examine particular solution points, functionality to add manually-created solutions and plot them against the optimal solution set, detailed information on each point accessible by double-clicking it, detailed information on all solutions exportable to Excel, and filtering of the solution set by FO scores and/or Metrics. The final analytic capability to be presented in this paper is the ability to view and explore multiple Pareto frontiers. Figure 9 shows the optimal solution sets for the armored variants, where each set was generated by a separate optimization run, then the solutions sets were merged.

The merged solution sets can be interrogated using all of the same features as described so far; however, when looking at the three distinct armored variants, it likely will prove more instructive to examine the optimization run of all three together, with Commonality included as an assessment dimension. The merge feature available in WSTAT could also be used for the individual

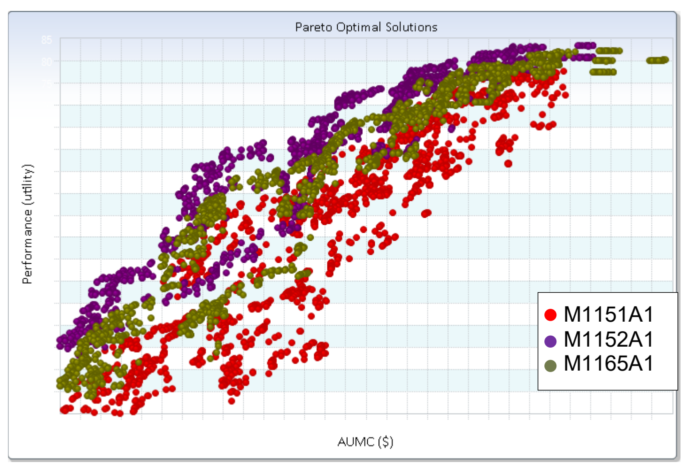

Figure 9: Pareto frontier of optimal M1151A1 (red), M1152A1 (purple), and M1165A1 (green) solutions. All three variants were run separately (i.e., without the consideration for Commonality).

variants run with different priority weighting sets, say those of the users and those of programmatic officials, or with different threshold and objective requirements for critical FOs.

9. SUMMARY

Making design decisions that will upgrade the enduring HMMWV fleet involves a complex intertwining of competing requirements and technology options. The complexity inherent in upgrade design decisions can be informed by the analytic and visualization capabilities provided by the WSTAT HMMWV model. Understanding the relationships and tradeoffs between requirements and technologies is of critical importance to the success of the HMMWV program and, as such, the general WSTAT process that enables holistic insights into these tradeoffs, along with the specific modeling approaches utilized to cast the HMMWV architecture within the WSTAT framework and the insights that result from the ensuing analysis should be leveraged to the greatest extent possible.

10. DISCLAIMER

This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy, the Department of the Army (DoA), or the United States Government; Furthermore, the views and opinions expressed in this paper shall not be used for advertising or product endorsement purposes.

11. REFERENCES

[1] J.P. Eddy, “JEGA - A Tool for Multi-objective Optimization”, SAND2006-6659C, Sandia National Laboratories, Albuquerque, NM, 2006.

[2] S. Edwards, et al., “Whole Systems Trade Analysis”, NDIA Ground Vehicle Systems Engineering and Technology Symposium, Systems Engineering Technical Session, Novi, MI, 2014.

[3] S.M. Henry, L.A. Waddell, and DiNunzio, M.R., “The Whole System Trades Analysis Tool for Autonomous Ground Systems,” Proceedings of the 2016 NDIA Ground Vehicle Systems Engineering and Technology Symposium, 2016.

[4] G.S. Parnell and T. Trainor, “Using the Swing Weight Matrix to Weight Multiple Objectives”, INCOSE International Symposium, vol 19, issue 1, pages 283-298, 2009.

[5] S. Edwards, et al., “Whole Systems Trade Analysis”, INCOSE International Symposium, vol 25, issue 1, pages 1133-1146, 2015.

[6] M.J. Hoffman, S.M. Henry, and B.M. Thompson, “Whole System Trades Analysis Tool (WSTAT) Overview”, SAND2014-20604PE, Sandia National Laboratories, Albuquerque, NM, 2014.