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# Capability portfolio analysis tool (CPAT) verification and validation report

Ewing, Lee; Dell, Robert F.; MacCalman, Molly; Whitney, Laura

NPS-OR-13-001

# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

**CAPABILITY PORTFOLIO ANALYSIS TOOL (CPAT) VERIFICATION AND VALIDATION REPORT**

by

Lee Ewing, Robert F. Dell, Molly MacCalman, Laura Whitney

January 2013

**Approved for public release; distribution is unlimited**

Prepared for: Program Executive Office for Ground Combat Systems
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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ADA | Air Defense Artillery |
| ALT | Acquisitions Logistics and Technology |
| AMEDD | Army Medical Department |
| AMOD | Abrams Modernization |
| AMSAA | Army Materiel Systems Analysis Activity |
| AMPV | Armored Multi-Purpose Vehicle |
| AoA | Analysis of Alternative |
| APUC | Average Procurement Unit Cost |
| ARFOGEN | Army Force Generation |
| AR&A | Acquisition Resources and Analysis |
| ASA | Assistant Secretary of the Army |
| AT&L | Acquisitions, Logistics and Technology |
| ATGM | Anti-Tank Guided Missile |
| BCT | Brigade Combat Team |
| BDE | Brigade |
| BFSB | Battlefield Surveillance Brigade |
| BFV | Bradley Fighting Vehicle |
| BMOD | Bradley Modernization |
| C2 (H) | Command and Control (HBCT) |
| C2 (S) | Command and Control (SBCT) |
| CASCOM | Combined Arms Support Command |
| CBRN | Chemical, Biological, Radiological, and Nuclear |
| CDD | Capability Development Document |
| CPAT | Capability Portfolio Analysis Tool |
| CAV | Cavalry |
| DA | Department of the Army |
| DASA-CE | Deputy Assistant Secretary of the Army Cost and Economics |
| ECP | Engineering Change Proposal |
| Eng | Engineer |
| ESV | Engineering Squad Vehicle |
| FCoE | Fires Center of Excellence |
| FD | Force Development |
| FIST | Fire Integrated Support Team |
| FOV | Family of Vehicles |
| FSP | Field Studies Program |
| FSV | Fire Support Vehicle |
| FTL | Far Target Location |
| FY | Fiscal Year |
| GCS | Ground Combat Systems |
| GCV | Ground Combat Vehicle |
| GP | General Purpose |
| GUI | Graphical User Interface |
| HBCT | Heavy Brigade Combat Team |

| | |
|---|---|
| IBO | Industrial Base Office |
| ICV | Infantry Carrier Vehicle |
| IED | Improvised Explosive Device |
| IFV | Infantry Fighting Vehicle |
| M-ATV | MRAP All-Terrain Vehicle |
| MBT | Main Battle Tank |
| MCoE | Maneuver Center of Excellence |
| MCV | Mortar Carrier Vehicle |
| Med | Medical |
| MEV | Med Evac Vehicle |
| MGS | Mobile Gun System |
| MILPRS | Military Personnel |
| MILCON | Military Construction |
| MODA | Multiple Objective Decision Analysis |
| MRAP | Mine Resistant Ambush Protected |
| MRL | Multiple Rocket Launcher |
| MtrCr | Mortar Carrier |
| NBCRV | Nuclear, Biological, & Chemical Reconnaissance Vehicle |
| NPS | Naval Postgraduate School |
| O&S | Operation & Support |
| OIF | Operation Iraqi Freedom |
| OPL | Open Programming Language |
| OPS | Operations |
| OPTEMPO | Operational Tempo |
| OR | Operations Research |
| ORD | Operational Requirement Document |
| ORF | Operational Readiness Float |
| OSD | Office of the Secretary of Defense |
| OTOE | Objective Table of Organization and Equipment |
| PAE | Program Analysis and Evaluation |
| PEO | Program Executive Office |
| PIM | Paladin Integrated Management |
| PM | Project Manager |
| POC-V | Paladin Operation Command Vehicle |
| RDTE | Research, Development, Test and Evaluation Funds |
| RFT | Research Facilitation Team |
| RPG | Rocket Propelled Grenade |
| RV | Reconnaissance Vehicle |
| SBCT | Stryker Brigade Combat Team |
| SEP | System Enhancement Package |
| SME | Subject Matter Expert |
| SMOD | Stryker Modernization |
| SPA | Self-Propelled Artillery |
| TACOM | Tank-automotive and Armaments Command |
| Tank KE | Tank Kinetic Energy |
| TARDEC | Tank Automotive Research, Development and Engineering Center |

| | |
|---|---|
| TCM | Training and Doctrine Command Capabilities Manager |
| TRAC-WSMR | Training and Doctrine Command Analysis Center-<br>White Sands Missile Range |
| TRADOC | Training and Doctrine Command |
| TUSK | Tank Urban Survival Kit |
| V&V | Verification and Validation |

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# EXECUTIVE SUMMARY

This technical review of the Capability Portfolio Analysis Tool (CPAT) was conducted by the Naval Postgraduate School (NPS) at the request of the Program Executive Office (PEO) Ground Combat Systems (GCS). The CPAT is intended to support Department of the Army portfolio resourcing and capabilities decisions for the ground combat fleet. The tool is designed to identify the optimum courses of action (cost, schedule, and performance) for portfolio investment.

The development of CPAT was a multiagency collaboration consisting of researchers and analysts from PEO GCS; Army Materiel Systems Analysis Activity (AMSAA); Sandia National Labs; Booz Allen; and Tank Automotive Research, Development and Engineering Center (TARDEC). Other contributing agencies included Maneuver Center of Excellence (MCoE), Fires Center of Excellence (FCoE), Army Medical Department (AMEDD), Combined Arms Support Command (CASCOM), Training and Doctrine Command Analysis Center-White Sands Missile Range (TRAC-WSMR), and Project Managers (PMs) for the Abrams, Bradley, Field Studies Program (FSP), M113, Ground Combat Vehicle (GCV), and Stryker.

This validation and verification report provides a technical review of CPAT's performance and optimization model. At its core, CPAT is an optimization model; however, the CPAT objective function is derived using multiattribute decision-analysis techniques. Therefore, our assessment focuses first on the validity of the value (or performance) model used to determine the objective function coefficients. Secondly, we verify the CPAT optimization formulation and the Open Programming Language (OPL) code implementation. Third, we validate the CPAT model by varying the most sensitive parameters and observe the changes to the CPAT solutions.

The assessment of the value model includes a qualitative examination of the model's structure and a synthesis of the quantitative components of the model. Additionally, the performance evaluation assessment includes a sensitivity analysis of the weights and a quantitative analysis of the value function range usage.

The optimization model assessment includes a thorough examination of the optimization formulation and implementation tests on model parameters using a reduced data set of three roles: the Main Battle Tank (MBT), Infantry Fighting Vehicle (IFV), and Cavalry (CAV) vehicle variants. This reduced set enables an examination of many excursions in a limited time and easier implementation of the results. Conclusions concerning particular weapons systems should be avoided.

Overall, the results of our analysis indicate that the performance model provides robust results, primarily due to the small number of alternatives considered for a given role. Moderate changes to the attribute weight or the shape of the value function affect a small number of vehicle alternatives for a given role. Our analysis also highlights that the model contains many attributes that are not relevant or do not contribute to the differentiation among alternatives. For example, the actual range of the data for Maximum Speed in the CAV role utilizes just 2% of the possible range allowed for the value function. In other cases, all the alternatives receive the same value level for a qualitative measure or only one or two alternatives receive any value from a binary measure. Additionally, attributes should be weighted globally across all roles. Currently, the weighting structure results in 20 different models, with one model corresponding to each role. Due to this current limitation, alternative values from one model should not be directly compared to values of another model.

The graphical user interface (GUI) on the optimization model does allow CPAT to be used by novice users not accustomed to running optimization models. Therefore, with little training, the PMs should be able to use CPAT to examine fielding and modernization issues as long as custom output is not required.

It is also important to highlight that in the optimization model the alternatives compete across roles; unlike in the value model, where they compete amongst each other within a role. Therefore, the value trade-offs are critical in a reduced budget environment. The sensitivity tests of the optimization model also indicate that CPAT results are highly sensitive to research, development, test and evaluation (RDTE) funding profiles for different vehicle alternatives and to maximum purchases allowed on the fielding schedule.

Our review identifies two main recommendations that can be addressed within the current model in the near term. First, study the effects of removing ineffective value measures. This would include measures that do not use the full range of the scale as well as qualitative and binary measures that show little variation in scale. Second, aggregate CPAT at the brigade-set level. Currently, all fielding and modernization decisions are being made at the brigade-set level, implying that all production decisions must also be made at the brigade-set level. This aggregation would allow for the removal of the complicating constraint (1.27), permitting quicker solution times and smaller optimality gaps.

In the longer term, we recommend determining a "single" objective value model by reducing the number of attributes and reweighting across all roles. This will allow users to make direct value comparisons between roles and strengthen the additive assumptions implied by the optimization. Secondly, develop *CPAT Version 2* to consider separate decisions for production and allow inventory to be carried from one period to the next. This next-generation CPAT will then decouple the fielding of Brigade (BDE) sets from the vehicle production decisions and provide for lower cost, long-run solutions with greater fleet performance.

# 1. BACKGROUND

The Capability Portfolio Analysis Tool (CPAT) was developed following a request by Program Executive Office (PEO) Ground Combat Systems (GCS) for a tool to support Department of the Army (DA) portfolio resourcing and capabilities decisions for the ground combat fleet.

Under the sponsorship of Mr. Scott Davis, the development of CPAT was a multiagency collaboration consisting of researchers and analysts from PEO GCS, Army Materiel Systems Analysis Activity (AMSAA), Sandia National Labs, Booz Allen, and Tank Automotive Research, Development and Engineering Center (TARDEC). Other contributing agencies included Maneuver Center of Excellence (MCoE), Fires Center of Excellence (FCoE), Army Medial Department (AMEDD), Combined Arms Support Command (CASCOM), Training and Doctrine Command Analysis Center-White Sands Missile Range (TRAC-WSMR), and Program Managers (PMs) for the Abrams, Bradley, Field Studies Program (FSP), M113, Ground Combat Vehicle (GCV), and Stryker.

The CPAT team launched Phase I of development in Fiscal Year (FY) 2010. Booz Allen Hamilton took the lead role on the performance evaluation component—with data availability input from AMSAA—while Sandia National Labs led the optimization analysis. The cost analysis was provided by the Tank-automotive and Armaments Command (TACOM) Cost and Systems Analysis Office. Cost data was provided by the PM cost teams using the annual weapons systems reviews. The schedule was provided by the individual PM offices.

To date, CPAT has been reviewed and accepted the following senior leadership within the analytical community (Edwards, 2011b).

| | |
|---|---|
| LTG Walker | Training and Doctrine Command |
| Dr. Crain | Army Materiel Systems Analysis Activity |
| Dr. Markowitz | Army headquarters staff (G3/5/7) |
| MG Spoehr | G8-Program Analysis and Evaluation |
| BG Dyess | G8-Force Development |
| LTG Phillips | ASA-Acquisitions, Logistics, and Technology |
| Mr. Bagby | DASA-Cost and Economics |
| Mr. Ahern | OSD-Acquisition, Technology, and Logistics |
| Dr. Spruill | Acquisition Resources and Analysis |

## 1.1 VERIFICATION AND VALIDATION (V&V) METHODOLOGY

We recognize for our analysis that CPAT is an optimization model that is characterized by mathematical constraints and a mathematical objective function. To determine the parameters or *fixed data* of the objective function, a second model is analyzed that we refer to as the CPAT performance model. The performance model provides the objective function coefficients for the optimization model's objective function.

Our intent for this report is two-fold. The first is to provide a verification of CPAT. The second is to provide model stakeholders with the means to validate CPAT. The official Army definitions of V&V follow (Headquarters, Department of the Army, 2005, p. 8):

> Verification is the process of determining if the M&S accurately represents the developer's conceptual description and specifications and meets the needs stated in the requirements document. The verification process evaluates the extent to which the M&S has been developed using sound and established software engineering techniques, and establishes whether the M&S logic and code correctly perform the intended functions.
>
> Validation is the process of determining the extent to which the M&S adequately represents the real-world from the perspective of its intended use.

We believe the Army's V&V definitions are inadequate for the CPAT technical evaluation. Therefore, we rely on the definitions from the National Research Council (2012, p. 8) to frame the CPAT V&V:

> Verification: The process of determining how accurately a computer program ("code") correctly solves the equations of the mathematical model. This includes code verification (determining whether the code correctly implements the intended algorithms) and solution verification (determining the accuracy with which the algorithms solve the mathematical model's equations for specified quantities of interest).
>
> Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

The NRC includes a third category not commonly recognized by the military—the Uncertainty Quantification, which asks, how do the various sources of error and uncertainty feed into uncertainty in the model-based prediction of the quantities of interest? Figure 1 shows our view of how CPAT represents the true system through the equations of the optimization formulation and the Excel/Visual Basic for Applications (VBA) implementations of the performance model. We verify that the computational models are correct, i.e., they are implemented according to the qualitative value model and the optimization equations.

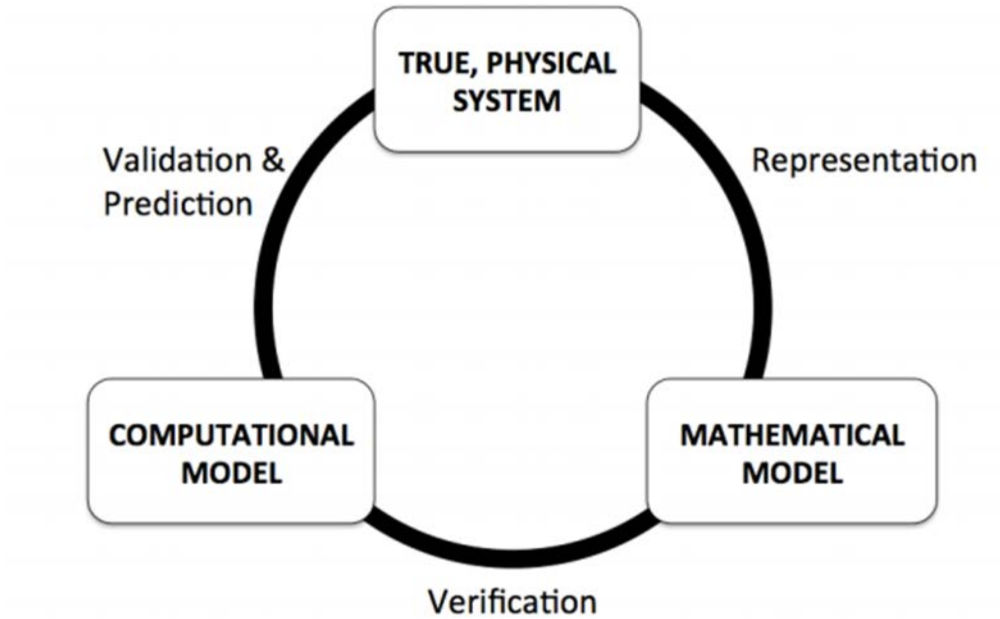


Figure 1. Verification, validation, and prediction as they relate to the true, physical system, the mathematical model, and the computational model. (Adapted from AIAA [1998] and the NRC [2012]).

For the validation, our focus is on the technical aspects of the model. We exercise the model to provide results that are useful to model stakeholders so that they may better understand the limitations of CPAT. Our intent for validation is not to determine if the answers provided given our input data make sense from a policy view. We leave that analysis to many others who have the subject matter expertise and data to make those evaluations. We also do not attempt to conduct an uncertainty quantification on CPAT for this report.

In the end, our CPAT verification should answer the question, "How accurately does the computation solve the underlying equations of the model for the quantities of interest?" Our hope is that the CPAT validation provides enough data and analysis for model stakeholders to answer the question, "How accurately does the model represent reality for the quantities of interest?"

## 1.2 CAPABILITY PORTFOLIO ANALYSIS TOOL (CPAT) OVERVIEW

CPAT is an acquisition tool designed to identify the optimum courses of action (cost, schedule and performance) for portfolio investment. CPAT provides transparent and replicable analysis, evaluating courses of action within a given budget. It was designed to complement the formal Analysis of Alternative (AoA) process and support the transformation and modernization of the combat vehicle fleet (Edwards, 2011a).

The CPAT performance model determines a *value* for 47 vehicles across 20 roles using 49 attributes.[1] However, not all vehicles are considered for all roles and, in most cases, no more than four to six vehicles are considered for a given role. For example, the Turretless GCV in the CAV role will not be considered for the Infantry Fighting Vehicle (IFV) role. Table 1 lists the Heavy Brigade Combat Team and Stryker Brigade Combat Team (HBTC/SBCT) vehicle alternatives by role.

Table 1. Vehicle alternatives.

| **HBCT Roles** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Main Battle Tank** | **Infantry Fighting Vehicle** | **Cavalry** | **Fire Integrated Support Team** | **Engineer** | **Self-Propelled Artillery** | **Mortar Carrier** | **Command and Control** | **Med** | **General Purpose** |
| M1A2 SEP Tusk | M2A3 OIF | M3A3 OIF | M3A3 BFIST | M2A2 ODS-E | M109A6 | M1064A3 | M1068A3 | M113A3 Medical | M113A3 General Purpose |
| M1ECP | M2A3 ECP | M3A3 ECP | M3A3 BFIST ECP | M2A2 ODS-E ECP | PIM | Bradley Derivative | Bradley Derivative | Bradley Derivative | Bradley Derivative |
| M1ECP II | M2A3 ECP II | M3A3 ECP II | M3A3 BFIST ECP II | M2A2 ODS-E ECP II | PIM ECP | GCV Derivative | GCV Derivative | GCV Derivative | GCV Derivative |
| M1ECP III | M2A3 ECP III | M3A3 ECP III | M3A3 BFIST ECP III | M2A2 ODS-E ECP III | | MCV OIF | MRAP Caiman | MRAP Caiman | MRAP-M-ATV |
| M1 AMOD | M2A3 BMOD | M3A3 BMOD | M3A3 BFIST BMOD | M2A3 (E) BMOD | | MCV SWaP Recovery/ FP Upgrade | POC-V | POC-V | MRAP-MaxxPro |
| | GCV | Turretless Bradley | Armored Knight | Turretless Bradley | | MCV SMOD | C2 OIF | MEV-OIF | ICV OIF |
| | | Turretless GCV | Turretless Bradley | Turretless GCV | | | C2 SMOD | MEV SWaP Recovery/ FP Upgrade | ICV SWaP Recovery/ FP Upgrade |
| | | | Turretless GCV | EVS OIF | | | | MEV SMOD | ICV SMOD |
| | | | FSV OIF | ESV SMOD | | | | | |
| | | | FSV SMOD | | | | | | |
| **SBCT Roles** | | | | | | | | | |
| **Infantry Carrier** | **Anti-Tank Guided Munitions** | **Command and Control** | **Reconnais-sance** | **Mortar Carrier** | **Fire Support** | **Engineering Squad** | **Medical Evacuation** | **Nuclear, Biological & Chemical Reconnais-sance** | **Mobile Gun System** |
| OIF | OIF | OIF | OIF | OIF | OIF | OIF | OIF | OIF | OIF |
| SWaP Recovery/ FP Upgrade | SWaP Recovery/ FP Upgrade | SWaP Recovery/ FP Upgrade | SWaP Recovery/ FP Upgrade | SWaP Recovery/ FP Upgrade | SWaP Recovery/ FP Upgrade | SWaP Recovery/ FP Upgrade | SWaP Recovery/ FP Upgrade | SWaP Recovery/ FP Upgrade | SWaP Recovery/ FP Upgrade |
| System Digitization | System Digitization | System Digitization | System Digitization | System Digitization | System Digitization | System Digitization | System Digitization | System Digitization | System Digitization |
| Full SMOD | Full SMOD | Full SMOD | Full SMOD | Full SMOD | Full SMOD | Full SMOD | Full SMOD | Full SMOD | Full SMOD |

The 49 attributes in the performance model were selected through analysis of the most recent and relevant requirement documents, a subject matter expert (SME) panel, and input from AMSAA.

[1] The analysis was conducted on 49 attributes, rather than the full 52 in the hierarchy, due to lack of available data for three of the sustainability attributes.

The results of the performance evaluation are combined with the cost analysis and scheduling analysis in the optimization model. The optimization model embedded in CPAT is designed to provide the ability to understand the trade space between cost, schedule, and performance in order to assist in planning for the overall Combat Vehicle portfolio and fleet modernization.

## 1.3 INTENDED USE

CPAT is intended to identify optimum courses of action (cost, schedule, and performance) for the PEO GCS portfolio investment (Edwards, 2011b).

The PEO GCS Operations (OPS) are currently executing a comprehensive assessment of their modernization initiatives. CPAT is intended to provide the analytical underpinnings that support an achievable and affordable Combat Vehicle Modernization Strategy.

As a decision-making tool, CPAT is also intended to provide PEO with rapid assessments of "bang for buck" alternative questions. CPAT is intended to support the user community in requirements development for CBA-type analysis.

The longer-term objective is for CPAT to be utilized for annual updates and to support PMs, PEO, and DA in making future investment decisions. It is intended that the Optimization Model's Graphical User Interface (GUI) will help the PM analyze possible future "what if" scenarios. In the future, it is also intended that PEO GCS will continue to develop the tool and conduct detailed data collection using the same methodology in support of the PMs' technology trade assessments (Edwards, 2011b).

## 1.4 CPAT ASSUMPTIONS

For the development of CPAT, the CPAT team outlined the following list of assumptions (Edwards, 2011b):

1. The timeframe of analysis is 2013-2040
2. Will modernize its fleet
3. HBCT and SBCT will maintain current objective table of organization and equipment (OTOE) levels—but these can be integrated
4. There will be two brigade types: (1) HBCT with 24 brigades and 10 missions; each can be upgraded separately; (2) SBCT with 9 brigades. SBCT must be upgraded in entire brigade quantities. As a result, multiple missions are modeled as a single SBCT mission
5. The alternatives for each mission role are the same as the alternatives in the upcoming AoA
6. In the performance evaluation it is assumed that the attributes selected are robust enough to provide trade space between alternatives
7. Performance evaluation value functions were derived using Full Spectrum Operation
8. Field schedules are fixed inputs

9. The minimum sustaining rate for production is one Brigade per year
10. Modernization plans are limited to what is currently proposed by the individual PMs
11. M113 must be divested from fleet by 2030
12. When production ceases on the modernization program the line will not restart
13. Cost Assumptions—
    a. Base year of analysis is 2012
    b. Period of comparison is FY2013-FY2028
    c. Weapon system populations are limited to Brigade Combat Team assigned assets, Operational Readiness Floats (ORFs), TRADOC assets and Research Facilitation Team (RFT) assets
    d. Starting weapon system populations within each BCT mission role will remain constant
    e. Only modification and replacement configurations as defined in the systems book will be studied
    f. Costs do not account for schedule delays or Industrial Base Office (IBO) uncertainty
    g. RDTE expenditures prior to FY2013 are not included
    h. Modified or replacement systems will be fielded to Active Army brigades followed by Prepositioned Stock and Reserve/National Guard units
    i. Costs are modeled assuming a Peacetime OPTEMPO
    j. Required RDTE prior to FY2013 will be completed for all alternatives

## 1.5 CPAT LIMITATIONS

The CPAT team identified several current limitations. First, in the area of performance evaluation, only a single SME-user panel has been conducted. Therefore, it is recommended that the team conduct an additional two panels. Second, the performance evaluation does not account for the synergistic effects of technology. Third, the cost analysis does not account for step-function average per unit cost (APUC)—this is scheduled to be implemented in FY2012. The cost analysis also does not account for military personnel (MILPRS) and military construction (MILCON). Fourth, the schedule does not penalize cost or performance for schedule slip (Edwards, 2011b).

# 2. CPAT REQUIREMENTS

## 2.1 GENERAL REQUIREMENTS

At the highest level, CPAT is required to fulfill the following requirements:

1. Identify optimal courses of action for PEO GCS fleet investment
2. Be analytically credible and repeatable
3. Be auditable and transparent
4. Include holistic perspective of key stakeholders: analytical community, headquarters, OSD

## 2.2 MODELING REQUIREMENTS

The following lists the CPAT modeling requirements:

1. Trained analysts (Sandia currently) must run the model to determine parameter sensitivity and typical output requirements for development
2. Very large input performance data requirements; ~620+ attributes
3. Software installation is self-contained and does not require external load of CPLEX or Open Programming Language (OPL)
4. Standardized output and GUI to allow for PM use of CPAT for final version
5. Consider for future development to other Army equipment portfolio

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# 3. CPAT V&V

## 3.1 V&V SCOPE

The purpose of this technical review is to determine whether CPAT performs its intended functions correctly and, to a lesser extent where possible, to ensure that CPAT performs no unintended functions and to measure its quality of solutions. The verification of CPAT focuses on the performance model structure, the formulation of CPAT, and the OPL implementation. The verification includes an evaluation of documents, code, requirements, and specifications. The validation of CPAT investigates the quality of the solutions represented for the data given to test the robustness of the model to small changes in the model's parameters, and to investigate the correctness of the solutions given. We do not conduct exhaustive sensitivity analysis by trying to duplicate what the sponsor has already done, nor do we attempt to evaluate the data given or the "qualitative" correctness of the solution from a policy perspective.

To conduct a review of the CPAT model we use the database, Unrestricted_4.0B_b30.cpat. The technical review also utilizes the following supplied documentation:

1. L. Andrade, G. Kao, C. Lawton, D. Melander, and R. Rice. Working Paper. *Fleet Management Planning Decision Analysis: A Mixed Integer Linear Program Formulation*
2. Program Executive Office (PEO) Ground Combat System (GCS). "PEO GCS Capability Portfolio Analysis Tool (CPAT)." August 23, 2011
3. PEO GCS. "PEO GCS Capability Portfolio Analysis Tool (CPAT)." November 15, 2011
4. PEO GCS. "PEO GCS Capability Portfolio Analysis Tool (CPAT)." December 9, 2011
5. Sandia National Laboratories. "CPAT Sensitivity Analysis." November 29, 2011
6. Sandia National Laboratories. "CPAT Objective Function Studies." November 30, 2011

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# 4. V&V OF THE VALUE MODEL

## 4.1 PERFORMANCE MODEL OVERVIEW

The CPAT performance evaluation uses a Multiple Objective Decision Analysis (MODA) approach for assessing the value of vehicle modernization in the HBCT and SBCT combat fleets. The MODA approach provides insight to decision makers who are faced with a problem that has multiple competing objectives. Figure 2 shows the general qualitative value hierarchy framework that the CPAT team used to decompose the problem into the subobjectives concerning each role's objective.[2] Every subobjective has a set of attributes that measure the achievement of a subobjective's performance intent. Value functions are used to transform the raw vehicle performance data from each attribute into a normalized scale ranging from 0 to 1, and to measure the returns to scale for a given attribute.

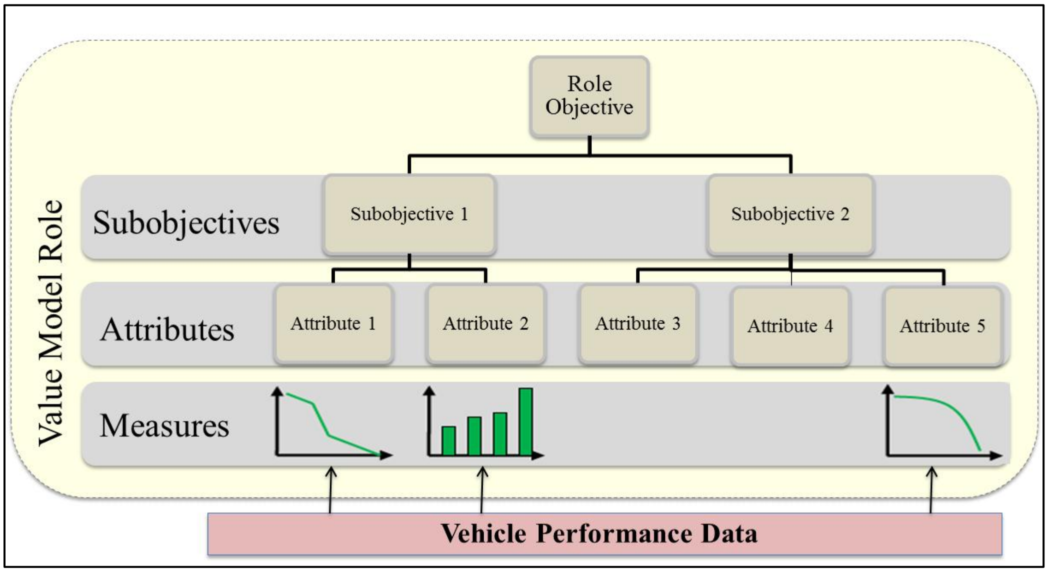


Figure 2. The CPAT Value Hierarchy decomposes the problem into subobjectives concerning each role. Attributes indicate each subobjective's performance and value functions are used to measure the returns of scale for a given attribute.

The MODA approach promotes buy-in from multiple stakeholders. The CPAT team held an SME panel with key stakeholders in Fort Benning, Georgia, from November 30 to December 2, 2010. The SME panel consisted of 16 individuals drawn primarily from the MCoE TRADOC Capability Manager (TCM) Heavy Brigade Combat Team (HBCT), TCM Battlefield Surveillance Brigade (BFSB), TCM Stryker Brigade Combat Team (SBCT), along with representatives from FCoE, CASCOM, and AMEDD. The panel focused on refining the attributes and their trade space bounds, generating value functions for each of the attributes, developing weights using the swing weight

[2] NPS Operations Research analysts have adapted the terminology in the hierarch slightly changing major attributes to sub-objective, measures to attributes, and value functions to measures for our analysis.

matrix technique, and establishing role weights using pair-wise comparisons (Edwards, 2011b).

## 4.2 PERFORMANCE MODEL CONSTRAINTS, LIMITATIONS, AND ASSUMPTIONS

In order to adhere to the timeline, the attributes were selected using as much existing data and studies as possible (see Table 2 for attribute data sources).

Table 2. CPAT data sources.

| Role | Source Documents |
|---|---|
| Direct Fire Infantry Fighting Vehicle (IFV); Fire Integrated Support Team (FIST); Engineer (Eng); Cavalry (CAV) | BFV FOV CDD Block II - 16 Apr 2010<br>GCV FOV CDD - 10 Mar 2010 |
| Indirect Fire Self-Propelled Artillery (SPA) | M109 FOV CPD |
| Mortar; C2 Vehicle; Medical; General Purpose | AMPV CDD 31 AUG 10; (w/INC 1, 2)<br>M113A3 Specification<br>MRAP FOV CPD v1.1 Draft 2009-04-10 |
| Direct Fire Main Battle Tank (MBT) | Abrams CDD 1 JUN 10 |
| Stryker Family of Vehicles (FOV) | Stryker ORD (w/Block 1, 2, 3) |

The performance model has several key limitations:

1. The value model does not capture potential performance synergies across roles in the overall performance of a vehicle. For example, the added value of a better thermal sight for an IFV may also affect other roles in the same formation (Edwards, 2011b).
2. The value model does not account for potential performance synergies based on vehicle quantities in each role. Meaning each vehicle in a type is assumed to provide the same performance (Edwards, 2011b).
3. Trade-offs among the roles is not considered, which results in 20 separate performance models.

The primary performance evaluation assumption is that all vehicles in a role are configured similarly and role weightings represent trade-offs in the full spectrum of operations.

## 4.3 CHARACTERISTICS OF THE CPAT PERFORMANCE MODEL

### 4.3.1 CPAT Value Hierarchy

The CPAT team uses a value hierarchy to assess the value of each vehicle alternative within each role. A total of 47 vehicles are analyzed by CPAT. Each of the 20 roles has its own hierarchy composed of the six subobjectives: survivability, growth, lethality, personnel payload, mobility, and sustainability. Each subobjective has a unique set of attributes that collectively assess a vehicle's value. Table 3 shows the CPAT Qualitative Value Hierarchy with the 49 possible attributes used within each role. Some of the attributes in value hierarchy can be grouped such as "Occupant Protection" against

Small Arms and Medium Caliber, Rocket Propelled Granade (RPG), Anti-Tank Guided Missile (ATGM), Tank KE, Top Attack, Undervehicle, and Improvised Explosive Device (IED). We refer to this grouping of “subattributes” as *categories*. The same is true for the survivability attribute. We classify the following as categories of “Survivability” against Small Arms and Medium Caliber, RPG, ATGM, Top Attack, Undervehicle, IED. These categories are reflected in Table 3.

Table 3. CPAT Qualitative Performance Model below is represented by the six primary subobjectives in the columns and 49 attributes shown in the rows. For example, the survivability objective has four attributes: Occupant Protection, CBRN Operation, Survivability, and Silent Watch. The Occupant Protection and Survivability attributes are each described by seven category measures.

| **Survivability** | | **Growth** | **Lethality** | **Personnel Payload** | **Mobility** | **Sustainability** |
|---|---|---|---|---|---|---|
| Occupant Protection (Qualitative) | Protection against Small Arms & Medium Caliber (Category) | Available Electrical Power (Linear) | Effective Range vs. Tanks (Linear) | Personnel Carry (Linear) | Soft Soil Mobility (Qualitative) | Operational Availability – Initial (Linear) |
| | Protection against RPG (Category) | Exportable Electrical Power (Linear) | Effective Range vs. IFVs (Linear) | Litter Carry (Linear) | Max Speed (Linear) | Operational Availability – Worst Case (Linear) |
| | Protection against ATGM (Category) | Information System Growth (Qualitative) | Effective Range vs. Light Armor (Linear) | | Turning Diameter (Linear) | Sustainment Availability (Linear) |
| | Protection against Tank KE (Category) | | Effective Range vs. Personnel (point target) (Linear) | | Static Stability Factor (Qualitative) | Port Commonality* (Linear) |
| | Protection against Top Attack (Category) | | Effective Range vs. Personnel (area target) (Linear) | | Vehicle Width (Linear) | Embedded Diagnostics* (Linear) |
| | Protection against Undervehicle (Category) | | Efficiency vs. Air Defense Artillery (ADA) site (Linear) | | Dash Speed (Linear) | Mean Time Between Essential Function and Failure* (Linear) |
| | Protection against IED (Category) | | Efficiency vs. Artillery Platoon (Linear) | | Air Transportability (Qualitative) | |
| Chemical, Biological, Radiological, and Nuclear (CBRN) Operation (Qualitative) | | | Efficiency vs. Mech Platoon (Linear) | | Cruising Range (Linear) | |
| Survivability (Qualitative) | Survivability against Small Arms & Medium Caliber (Category) | | Efficiency vs. Multiple Rocket Launcher (MRL) (Linear) | | | |
| | Survivability against RPG (Category) | | Efficiency vs. Dismounted Crew (Linear) | | | |
| | Survivability against ATGM (Category) | | Missile Capability (Qualitative) | | | |
| | Survivability against Tank KE (Category) | | ATGM Fire Control (Binary) | | | |

| Survivability | | Growth | Lethality | Personnel Payload | Mobility | Sustainability |
|---|---|---|---|---|---|---|
| | Survivability against Top Attack (Category) | | Mast Mounted Sensor (Binary) | | | |
| | Survivability against Undervehicle (Category) | | Target Designation (Binary) | | | |
| | Survivability against IED (Category) | | Far Target Location (FTL) Targeting (Binary) | | | |
| Silent Watch (Linear) | | | Weapon Stabilization (Binary) | | | |
| | | | Transition from Firing to Moving (Linear) | | | |

(*) *Data currently unavailable for these attributes; they are not used in the analysis.*

Many of the attributes are the same across all of the qualitative models, but in some instances not all of the quantitative characteristics of the attributes are identical. Table 4 provides a breakdown of the number of attributes used in each role hierarchy as well as the mean, median, and standard deviation. The number of attributes used in each of the 20 role value hierarchies ranges from 31 to 41. When considering all roles, the average number of attributes used is 37.1, with a standard deviation of 3.5.

Table 4. Number of attributes used for HBCT and SBCT roles.

| **HBCT** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Role** | **MBT** | **IFV** | **CAV** | **FIST** | **Eng** | **SPA** | **MtrCr** | **C2 (H)** | **Med** | **GP** |
| No. Attributes | 38 | 40 | 40 | 40 | 37 | 36 | 35 | 31 | 31 | 31 |
| | | | | | | | | | **Mean** | **35.9** |
| | | | | | | | | | **Median** | **36.5** |
| | | | | | | | | | **Standard Deviation** | **3.8** |
| **SBCT** | | | | | | | | | | |
| **Role** | **ICV** | **ATGM** | **C2 (S)** | **RV** | **MCV** | **FSV** | **ESV** | **MEV** | **NBCRV** | **MGS** |
| No. Attributes | 41 | 41 | 35 | 39 | 39 | 39 | 41 | 34 | 34 | 40 |
| | | | | | | | | | **Mean** | **38.3** |
| | | | | | | | | | **Median** | **39.0** |
| | | | | | | | | | **Standard Deviation** | **2.9** |
| **HBCT/SBCT** | | | | | | | | | | |
| | | | | | | | | | **Mean** | **37.1** |
| | | | | | | | | | **Median** | **38.5** |
| | | | | | | | | | **Stand Deviation** | **3.5** |

Thirty of the 49 attributes are used by all 20 roles, which include all attributes in the Survivability, Growth, Mobility, and Sustainability subobjectives. However, nine attributes are used in four or fewer of the qualitative value hierarchies. These include Transition from Firing to Moving (used in one role), Litter Carry (two roles), Efficiency versus ADA site, Efficiency versus artillery platoon, Efficiency versus Mech Platoon, Efficiency versus MRL, Efficiency versus Dismounted Crew, ATGM Fire Control (three roles), and Mast Mounted Sensor (four roles). The Descriptive Statistics Summary Table in Appendix A displays the attribute-role mapping.

### 4.3.2 Value Functions

The model uses value functions to transform the raw vehicle data from each attribute into a normalized scale ranging from 0 to 1. The shape of the value function defines the returns of scale for a particular attribute.

Each attribute has a value function associated with it. The hierarchy includes a mix of 20 attributes with constructed scales, 24 attributes that have piecewise linear scales with at least one inflection point, and 5 attributes that have binary (yes/no) scales. The constructed scales consist of *bins* that indicate the lowest to highest impact levels. For example, the Information System Growth attribute has a constructed scale with bins ranging from none (low) to a combination of radio suites (high).

### 4.3.3 Weighting the Attributes

Attribute weights assess the trade-off among the different subobjectives within a role. A significant finding of this review is that attributes within a role were assessed using the swing weight matrix. However, attributes across roles where not assessed. Therefore, it is not advised to compare vehicle performance values outside a given role because the trade-offs among the different roles have not been determined.

Each of the 49 possible attributes within the CPAT value hierarchy is assessed a weight with a possible range from 0 to 1. The sum of all weights within each qualitative hierarchy is equal to 1. The maximum weight recorded for an attribute is 0.055,[3] with 90% of the attributes across all roles ranging from 0 to 0.039. The average weight across all attributes is 0.027.

The structure of the qualitative value model is additive by design. Therefore, the weights for all attributes supporting a given objective are additive and when aggregated, the subobjective relative weights are obtained. The weights for each of the six subobjectives across the 20 roles are shown in Figure 3.

---

[3] A weight of 0.055 is used for seven attributes including Occupant Protection against Small Arms & Medium Caliber, Occupant Protection against IED, Survivability against Small Arms & Medium Caliber, Cruising Range, Survivability against Undervehicle, Survivability against IED, and Soft Soil Mobility.

| | HBCT | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **MBT** | **IFV** | **CAV** | **FIST** | **Eng** | **SPA** | **MtrCr** | **C2 (H)** | **Med** | **GP** |
| **Survivability** | 0.488 | 0.432 | 0.411 | 0.464 | 0.499 | 0.434 | 0.454 | 0.518 | 0.489 | 0.548 |
| **Growth** | 0.068 | 0.072 | 0.070 | 0.075 | 0.086 | 0.089 | 0.060 | 0.146 | 0.112 | 0.042 |
| **Lethality** | 0.211 | 0.225 | 0.252 | 0.207 | 0.053 | 0.205 | 0.185 | 0.000 | 0.000 | 0.000 |
| **Personnel Payload** | 0.000 | 0.031 | 0.032 | 0.007 | 0.039 | 0.000 | 0.000 | 0.026 | 0.044 | 0.032 |
| **Mobility** | 0.151 | 0.162 | 0.151 | 0.164 | 0.219 | 0.180 | 0.190 | 0.193 | 0.235 | 0.250 |
| **Sustainability** | 0.081 | 0.078 | 0.083 | 0.083 | 0.104 | 0.091 | 0.111 | 0.117 | 0.119 | 0.127 |
| | **SBCT** | | | | | | | | | |
| | **ICV** | **ATGM** | **C2 (S)** | **RV** | **MCV** | **FSV** | **ESV** | **MEV** | **NBCRV** | **MGS** |
| **Survivability** | 0.394 | 0.411 | 0.469 | 0.395 | 0.410 | 0.398 | 0.383 | 0.481 | 0.504 | 0.399 |
| **Growth** | 0.074 | 0.077 | 0.115 | 0.094 | 0.076 | 0.096 | 0.072 | 0.125 | 0.094 | 0.064 |
| **Lethality** | 0.247 | 0.248 | 0.078 | 0.211 | 0.219 | 0.206 | 0.239 | 0.042 | 0.073 | 0.247 |
| **Personnel Payload** | 0.034 | 0.014 | 0.039 | 0.034 | 0.032 | 0.034 | 0.034 | 0.036 | 0.010 | 0.010 |
| **Mobility** | 0.165 | 0.163 | 0.193 | 0.178 | 0.169 | 0.175 | 0.180 | 0.201 | 0.211 | 0.190 |
| **Sustainability** | 0.086 | 0.088 | 0.105 | 0.087 | 0.094 | 0.091 | 0.091 | 0.115 | 0.107 | 0.090 |

Figure 3. Subobjective weights for each HBCT and SBCT role.

*Note: Highest overall weight is shown in green, the lowest overall weights are shown in red, and nonweighted subobjectives are shown in gray.*

The Survivability subobjective makes up approximately 55% (shown in green) of the total weight for the GP role, while Lethality receives no weight and Personnel Payload receives only 3.2% of the total weight for the GP role. For the FIST role, Survivability receives only 46% of the weight and provides less the 0.7% of its total weight toward Personnel Payload (shown in red). In general, Survivability is weighted the highest across all roles and Personnel Payload the lowest across all roles (see Figure 4). The weights for Growth and Sustainability range between 4.2% and 14.6% for all roles, and the Mobility subobjective weights range from 15.1% to 25% for all roles. The Lethality weights range from 4.2% to 25.2% for all roles except C2(H), Med, and GP, which receive no weight for the underlying attributes. The Personnel Payload weights range from 0.7% to 4.4% with no weights for the MBT, SPA, and MtrCr roles.

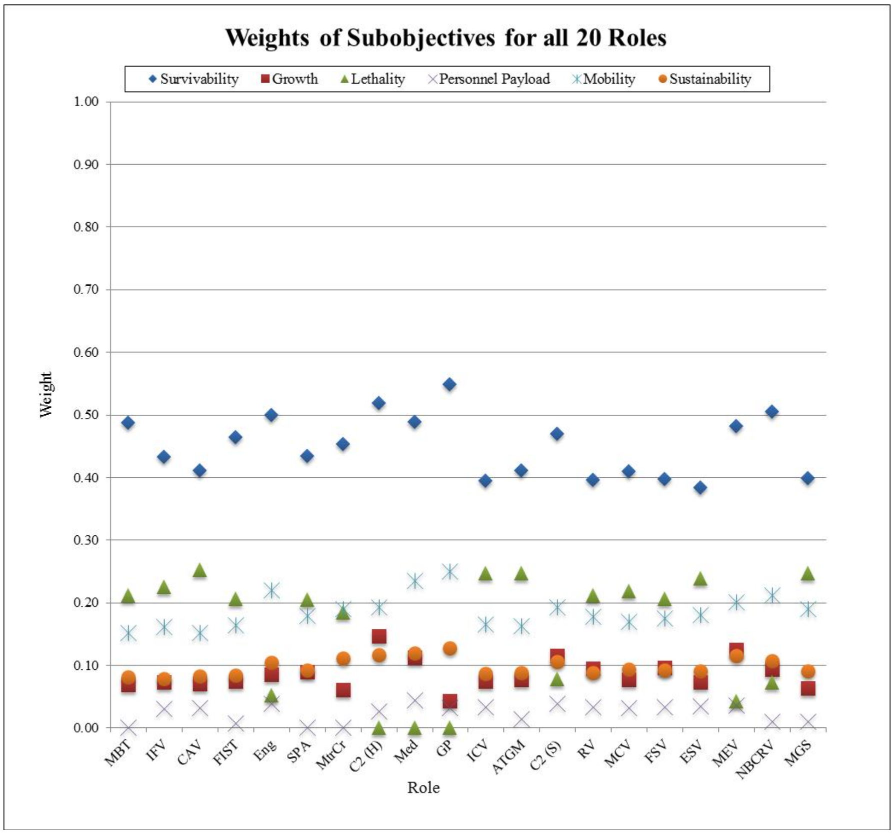


Figure 4. Weighting of Subobjectives for all 20 roles. Survivability is weighted the highest for each role and Personnel Payload is the lowest in all but three roles.

We did not attempt to make a judgment based on the resulting subobjective weights. However, it is important for leadership and users of CPAT to understand the underlying emphasis a given role places on a given subobjective in terms of the value trade-offs. Therefore, a subject matter expert review should ensure that the weight for a given subobjective and for a given role is verified. If it is found later that the weights for the subobjectives require an adjustment then we suggest a revision beginning with the value model's subobjectives and supporting attributes, followed by a reassessment of the attribute weights.

## 4.4 PERFORMANCE MODEL VALIDATION

For the performance model validation, we examine the impact of changes to the major model parameters to evaluate robustness. Specifically, we examine how changes to swing weights and value function shape affect alternative selection. We also look at how influential a value function is in terms of evaluating the return to scale of an attribute.

### 4.4.1 Swing-Weight Sensitivity Analysis

We use one-way sensitivity analysis to determine the impact of changes in the weights on the ranking of vehicles. Ideally, we would perform one-way sensitivity analysis on all possible 49 attributes used in the value model; however, because most attributes represent less than 3% of the total trade space available, changing only one attribute at a time would likely not impact the results. Therefore, we opt to conduct changes of the weights for each of the six subobjectives, one objective at a time.

The sensitivity analysis is conducted for all 47 vehicles within the 20 roles to test the robustness of the CPAT model. It is important to remind the reader that only a small number of alternatives are considered in each role, typically only four to six vehicles. The weights for each role in the green (unclassified) and red (classified) versions of the model are the same. Therefore, the analysis performed on the green (unclassified) model is representative of results, which would be derived from the red model.

Figure 5 illustrates the sensitivity analysis conducted for the seven vehicles considered within the CAV role. The seven lines on the graph show how each vehicle's performance changes as we vary the weight on the lethality objective from 0 to 1. When lethality is weighted from 0.0 to 0.650 the Turretless GCV is selected as the highest value alternative. At 0.650 the highest-value alternative changes to the M3A3 BMOD. We define this inflection point as a *breakpoint*. The graph also shows the distance between the originally assigned weight and the breakpoint. If the distance between the assigned weight and the breakpoint is large, the weight is not sensitive to change, but a weight that is close to the breakpoint is sensitive to change. For the Lethality subobjective in the CAV role, the assigned weight is 0.252 and the distance to the nearest breakpoint 0.398. In other words, it would take an increase of over 150% in the underlying attributes supporting the lethality subobjective before the model would select a different alternative. In this case, we say that the Lethality subobjective for the CAV role is very insensitive to changes in the 17 attributes that add up to the Lethality subobjective weight.

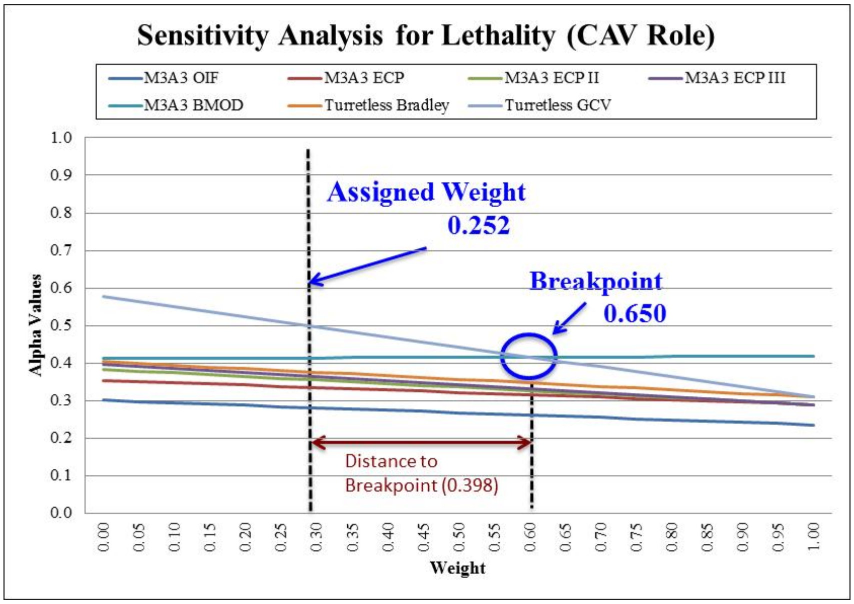


Figure 5. Sensitivity Analysis conducted for the seven vehicles considered within the CAV role illustrating the breakpoint. Turretless GCV is the highest-value alternative when lethality is weighted from 0.0 to 0.650. For weights greater than 0.650, the highest-value alternative changes to the M3A3 BMOD.

In general, the results of the sensitivity analysis suggest that the value model is very robust to changes in attribute swing-weights. Table 5 illustrates the percentage weight change required before the model would select a different alternative. Cells with a dash (-) do not have a breakpoint. The cells highlighted in red show that the lowest-percentage weight change required to alter the preferred vehicle alternative is 76% for the Lethality subobjective in the MBT role and the Survivability subobjective for the CAV role. All other subobjectives across the 20 HBCT roles require greater than a 100% change in weight for the model to select a different alternative.

Table 5. Percent increase change in swing-weight required for change in alternative selection (assuming one change at a time at the objective level). A dash indicates that no change can be made for the role and objective indicated.

| **HBCT** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **MBT** | **IFV** | **CAV** | **FIST** | **Eng** | **SPA** | **MtrCr** | **C2 (H)** | **Med** | **GP** |
| **Survivability** | - | - | 76% | - | - | - | - | - | - | 91% |
| **Growth** | 923% | - | 1257% | - | - | - | - | - | - | - |
| **Lethality** | 76% | - | 158% | 286% | - | - | - | - | - | - |
| **Personnel Payload** | - | - | - | - | - | - | - | - | - | - |
| **Mobility** | - | 395% | - | 419% | - | - | 348% | 263% | 219% | 220% |
| **Sustainability** | - | - | - | 801% | - | - | 573% | 585% | 572% | - |
| | | | | | | | | | | |
| **SBCT** | | | | | | | | | | |
| | **ICV** | **ATGM** | **C2 (S)** | **RV** | **MCV** | **FSV** | **ESV** | **MEV** | **NBCRV** | **MGS** |
| **Survivability** | - | - | - | - | - | - | - | - | - | - |
| **Growth** | - | - | - | - | 816% | 524% | 1145% | 181% | 648% | 369% |
| **Lethality** | - | - | - | - | - | - | - | - | - | - |
| **Personnel Payload** | - | - | - | - | - | - | - | - | - | - |
| **Mobility** | - | - | - | - | - | - | - | - | - | - |
| **Sustainability** | - | - | 658% | 990% | - | 938% | - | - | - | - |

### 4.4.2 Value Function Relevance Analysis

Ideally, we want the quantitative value functions of a model to have a scale that is just large enough to contain the minimum and the maximum score of the alternatives being measured, and no more. In practice, this may be impossible for a variety of reasons. For example, many of the value functions for the CPAT performance model were assessed before the ranges of the actual data were known. When time is available, it is ideal to go back and reassess the value function for the "actual" range of the data, but this was not possible with the current version of CPAT. As a result, it is possible to have a model with many measures that are not influential or do not discriminate between alternatives. In other words, we would describe these value measures as nonrelevant to a particular decision context. The intent of this section is to identify those measures that do not utilize the full scale range and also those whose alternatives all receive the same value because there is no variation across the alternatives for a given role (or across roles, in some cases). The identified measures are prime candidates for elimination with the intent of achieving a more parsimonious model.

For this analysis, we define the *possible range* as the minimum and maximum on the value function scale and the *actual range* as the minimum and maximum values of the data that is input into the model. For example, the possible range used for the Silent Watch attribute is the same for all 20 roles (0 to 12 hours). In fact, the possible range is the same across all 20 roles for 27 of the 49 attributes. See Appendix B, Attribute Summary Table, for more information on range variation among attributes.

Our analysis shows that the actual range of the data often does not utilize the full possible range of the value functions. For example, Figure 6 shows that the actual range of the data for Max Speed in the CAV role utilizes just 2% of the possible range. It is important to note here that the function is piecewise linear, but the data will only show constant returns to scale for value increments of the same size over the actual range. This function may not be measuring at the correct level of resolution and capturing the correct returns of scale, and, as a result, the measure does not discriminate properly among alternatives in the CAV role.

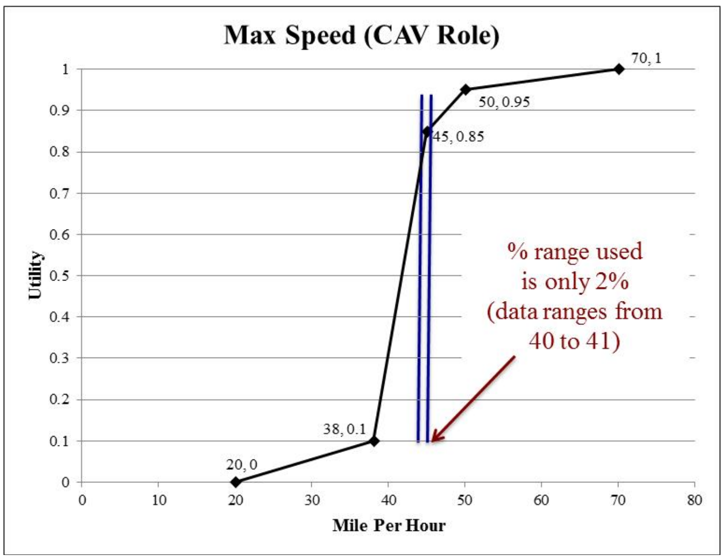


Figure 6. Max Speed (CAV Role) utilizes just 2% of the possible range.

For the 24 quantitative attributes used in the model, only 10% of the data's actual range utilizes more than 50% of the possible value function range. Approximately half (51%) of the value function data use 0% of the range, which means there is no variability and all vehicle data within the role are the same. This happens when all alternatives score the same for a given attribute in a role or the attribute is not used for a particular role. Additionally, 7% of the value function data extend beyond the established range. See Appendix C for a table of the percent range used for all quantitative attributes.

In addition to the quantitative measures, there are five binary attributes in the model. The binary attributes, however, are not considered for all vehicles within the SBCT/HBCT roles. For example, Target Destination is considered for four vehicle types within the HBCT role and seven vehicle types within the SBCT role. The highlighted portions of Tables 6 and 7 show where 100% of the data is either yes or no for a given binary attribute. For the binary measures, we want to identify those that have little or no influence on the outcomes. For example, the Target Designation attribute provides a nice discriminatory effect among HBCT roles, but little effect on outcomes for SBCT roles. The Mast-Mounted Sensor attribute, however, provides no value for any attributes in any HBCT role and very little in the SBCT role.

Table 6. HBCT Binary Attribute – Percentage of Yes/No for each role.

| | | HBCT | | | |
|---|---|---|---|---|---|
| **Attribute** | | **MBT** | **IFV** | **CAV** | **FIST** |
| **ATGM Fire Control** | Yes | - | - | - | - |
| | No | - | - | - | - |
| **Mast-Mounted Sensor** | Yes | - | - | 0% | 0% |
| | No | - | - | 100% | 100% |
| **Target Designation** | Yes | 40% | 33% | 14% | 100% |
| | No | 60% | 67% | 86% | 0% |
| **FTL Targeting** | Yes | 40% | 0% | 0% | 20% |
| | No | 60% | 100% | 100% | 80% |
| **Weapon Stabilization** | Yes | 100% | 100% | - | - |
| | No | 0% | 0% | - | - |

Table 7. SBCT Binary Attribute – Percentage of Yes/No for each role.

| | | SBCT | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Attribute** | | **ICV** | **ATGM** | **C2 (S)** | **RV** | **MCV** | **FSV** | **ESV** | **MEV** | **NBCRV** | **MGS** |
| **ATGM Fire Control** | Yes | 0% | 25% | - | - | - | - | 0% | - | - | - |
| | No | 100% | 75% | - | - | - | - | 100% | - | - | - |
| **Mast-Mounted Sensor** | Yes | - | - | - | 25% | - | 0% | - | - | - | - |
| | No | - | - | - | 75% | - | 100% | - | - | - | - |
| **Target Designation** | Yes | 0% | 0% | 0% | 0% | - | 100% | 0% | - | - | 0% |
| | No | 100% | 100% | 100% | 100% | - | 0% | 100% | - | - | 100% |
| **FTL Targeting** | Yes | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | No | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| **Weapon Stabilization** | Yes | 100% | 25% | 25% | 25% | 25% | 25% | 25% | 0% | 0% | 100% |
| | No | 0% | 75% | 75% | 75% | 75% | 75% | 75% | 100% | 100% | 0% |

The ranges for attributes with qualitative scales are generally constructed with well-defined criteria for the different levels that can be obtained. There are six qualitative attributes included in the model: CBRN Operation, Information System Growth, Missile Capacity, Soft Soil Mobility, Static Stability Factor, and Air Transportation. There are also two qualitative attributes—Occupant Protection and Survivability—that have seven “additive” categories each, which are discussed later in this section.

A qualitative scale is characterized by using a scale that is constructed with discrete scale increments, or nonoverlapping *bins*, and with well-defined criteria associated with each of the bins or scale increments. The number of bins for the six qualitative attributes range from 3 to 10. For example, the CBRN scale has three bins with the associated criteria: (1) None; (2) Mask with threat-specific filter system; and (3) Contains over pressure systems to protect against CBRN threats. For the CBRN attribute in the HBCT role, 86% of the alternatives score in bin 2 and 14% in bin 3. No alternatives scored in bin 1. Figure 7 illustrates the alternative histogram for the HBCT role.

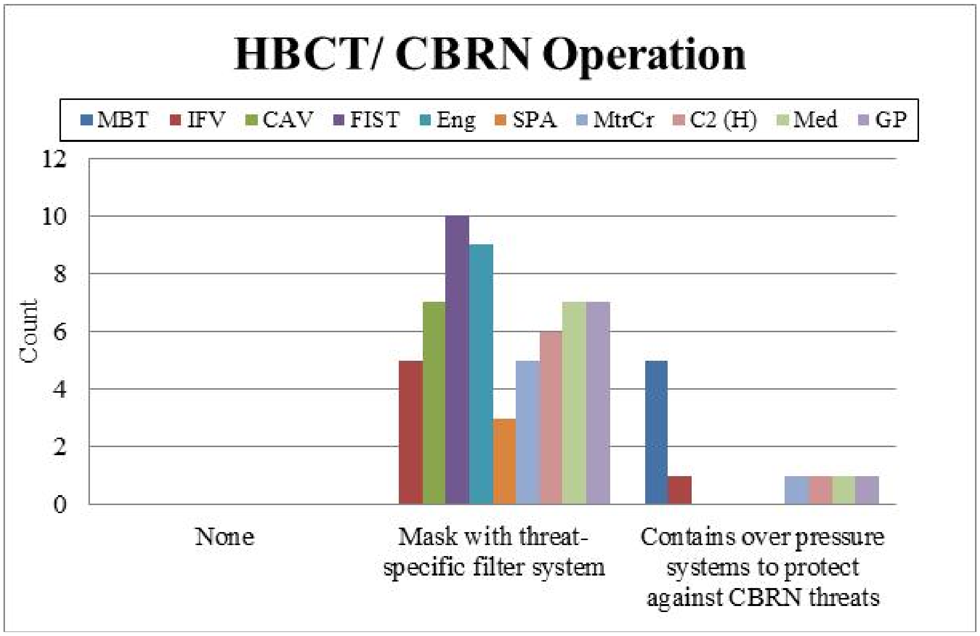


Figure 7. HBCT data for CBRN Operation fall within two bins: Mask with threat-specific filter system (86%) and Contains over pressure systems to protect against CBRN threats (14%).

When we evaluate CBRN Operation for the SBCT role, we observe that all alternative scores are in bin 2 (Mask with threat-specific filter system). See Appendix D for table of percentage alternative scores by bin.

The last two qualitative attributes (Occupant Protection and Survivability) have constructed scales or bins, referred to as bins A through D. The attributes are each comprised of seven categories (Small Arms, RPG, ATGM, Tank KE, Top Attack, Undervehicle, and IED). Some of the categories include multiple levels, as shown in Table 8.

Table 8. Number of levels used for each Occupant Protection and System Survivability Category.

| Category | # Levels |
|---|---|
| Occupant Protection against Small Arms | 6 |
| Occupant Protection against RPGs | 3 |
| Occupant Protection against ATGMs | 3 |
| Occupant Protection against Tank KE | 1 |
| Occupant Protection against Top Attack | 3 |
| Occupant Protection against Undervehicle | 4 |
| Occupant Protection against IEDs | 3 |
| System Survivability against Small Arms | 6 |
| System Survivability against RPGs | 3 |
| System Survivability against ATGMs | 3 |
| System Survivability against Tank KE | 1 |
| System Survivability against Top Attack | 3 |
| System Survivability against Undervehicle | 4 |
| System Survivability against IEDs | 3 |

For Occupant Protection against Small Arms, the HBCT MtrCr role data includes 16 data points within bin A, 2 bin B, 5 bin C, and 13 bin D. However, in order to prevent categories with more levels from dominating the results, the data are normalized by dividing by the number of vehicle alternatives for a given role; in this case, six vehicles are considered for the MtrCr role. This normalization allows for comparison across roles. Figure 8 shows the normalized count for the MtrCr role. Data in bins A through D sum to six because there are six levels for the Occupant Protection Against Small Arms category.

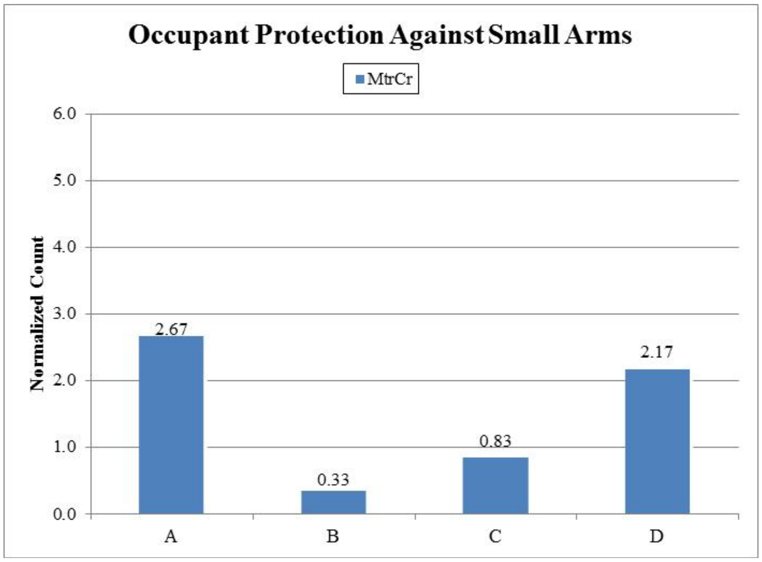


Figure 8. MtrCr data for Occupant Protection Against Small Arms, showing that the majority of the data fall within bins A and D.

Figure 9 illustrates the breakdown of the data across all vehicles in the HBCT role for the Occupant Protection Against Small Arms category. The histogram graphic illustrates that the majority of the scores fall in bins A and D.

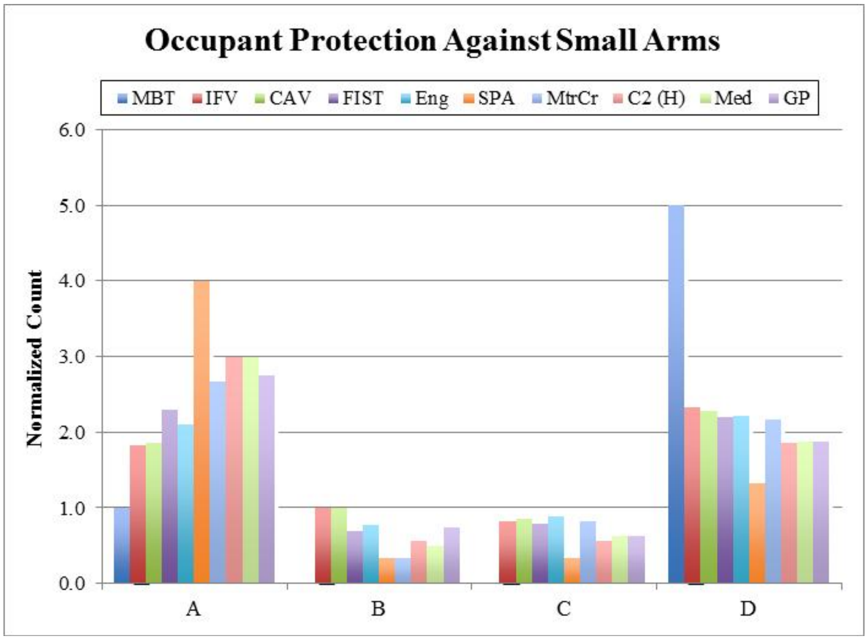


Figure 9. A breakdown of Occupant Protection Against Small Arms for HBCT roles showing that the majority of the data fall in bins A and D.

#### *4.4.2.1 Performance Model Summary*

For future versions of the CPAT performance model, we suggest several improvements:

1. Conduct further analysis of the value function sensitivity and relevancy analysis in order to identify attributes that can be eliminated. Currently, the model contains many attributes that do not measure anything; meaning, the attribute is only relevant for one to three alternatives or the data for the attribute is the same for all alternatives. A reduction in the number of attributes will allow for greater ease of data collection, higher quality of value function and weight assessments, and facilitate design and weighting of a global performance model.
2. Simplify the protection and lethality attributes by developing only the relevant categories that influence results. Weight the categories locally for these two attributes, not globally against all of the other attributes in the model. This change will greatly simplify global weighting assessments and provide a much more transparent and defendable value increment assessment of the two value functions, which is not done in the current model. This change will also enforce the integrity of the value increment.
3. Weight all attributes across all roles globally. Currently, this is not done and results in 20 different models, one corresponding to each role. Due to

this current limitation, alternative values from one model should not be directly compared to those of another model.

In general, the performance model provides robust results. This is primarily due to the partitioned structure of the model. In other words, a small number of alternatives are considered for a given role, so changes in weights or the shape of the value function only affect a small number of alternatives in a given role. Given that each of the 20 role models is independent, changes in one model do not affect the alternative ranking in another. This may not be the case when all alternatives are considered in the optimization and are evaluated in the next chapter of this report.

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# 5. OPTIMIZATION REVIEW

## 5.1 REVIEW OF OPTIMIZATION FORMULATION

The optimization model presented in the *Fleet Management Planning Decision Analysis: A Mixed Integer Linear Program Formulation* working paper by Andrade, Kao, Lawton, Melander, and Rice (2011) is an integer linear program that prescribes yearly procurement and upgrades 47 vehicles, across 20 roles. Not all vehicles are considered for all roles (see Section 1.2). There are several possible objective functions (maximize overall fleet performance, maximize final fleet performance, minimize Operations and Support (O&S) cost, and minimize total cost) used in different combinations. The impact of using these different objective functions was reported by Sandia (Sandia National Laboratory, 2011). However, only one of the objective functions, maximize overall fleet performance, has been used to obtain results for senior leadership review. Overall fleet performance is defined by the total value of the all vehicles in service over all periods of the time horizon, subject to a minimum number of brigades filled by the last time period (constraints 1.38 and 1.39) (Andrade et al., 2011). Other constraints limit yearly upgrades, procurement, and budgets.

Overall, this is a good application for optimization. Several examples of similar optimization models can be found in the military operations research literature (see, for example, Brown, Dell, & Newman, 2004). The following section enumerates observations from our review of the formulation from Andrade et al. (2011).

1. Several parameters could be made more general, as in other similar applications (Brown et al., 2004). For example,

   (i) $MissionReq_m$ could vary by year. As written, the value must remain the same for every year of the planning horizon. Clearly, the need for vehicles in a specific mission area could increase or decrease over time and allowing this parameter to vary by year would be a simple fix.

   (ii) $MaxBDE_m$ could also vary by year. Again, allowing this parameter to vary by year would be a simple way to permit changes over time and could better account for the ARFOGEN cycle.

2. The penalty should not be the same for all deviations (elastic variables) as written in Equation (1.10) of the Andrade et al. (2011) report, and should potentially vary by year. As we understand it, the elastic variables were not implemented for the results reported for senior leadership review. That said, they are available in the implementation (shown below) and this implementation does not match the documentation.

```
dexpr float objFunValNew =
 sum(r in setSupportedRoles, t in setTimePeriodID)
  Alpha[r] * NumVehInService[r][t]
 -   1000000000000.1*sum(tx   in   setSupportedTransitions,   t   in   setTimePeriodID)
iExcessTransition[tx][t]
 - 1000000.1*sum(t in setTimePeriodID)(fExcessbudget[t])
 - 100000000.1*sum(t in setTimePeriodID)(fExcessOSbudget[t])
 - 1000000.1*sum(t in setTimePeriodID)(fExcessRDTEbudget[t])
 - 1000000.1*sum(t in setTimePeriodID)(fExcessTotalbudget[t]);

maximize objFunValNew;
```

From the implementation, we see the penalty values are not parameter values that can be changed outside of the implementation. Furthermore, the values themselves appear to be somewhat arbitrary and unrelated to other objective function coefficients. The orders of magnitude differences used for the penalties above together with numerical precision and any allowed optimality gaps could make some of these terms meaningless.

Allowing these penalty parameters to vary by year will help solution time and reinforce the importance of near-term decisions relative to decisions closer to the end of the horizon (see Brown et al., 2004, for more details).

The requirement constraint (Equation [1.11]; in Andrade et al. [2011]) has several issues as written.

$$\forall m,t \sum_{i \in VehSupported(m)} NumInService_{i,m,t} + \sum_{j \in VehSupported(m), t^* \leq t} ExcessTransition_{j,i,m,t} - \sum_{j \in Transition(i,m), t^* \leq t} ExcessTransition_{i,j,m,t} = MissionReq_m$$

i) $ExcessTransition_{j,i,m,t}$ is written as $ExcessTransitions_{j,i,m,t}$ elsewhere in the document.

ii) As written, the same penalty per unit exists for being over and under the mission requirement level. Being able to satisfy mission requirements, but being over is arguably far better than being under or not being able to satisfy mission requirements. Put as a simple question, would you rather be 10 vehicles short or 10 vehicles over? The above formulation assumes there is no difference.

iii) Summing $t^* \leq t$ implies the variable should be indexed by $t^*$. Summing over $t^*$, however, implies that the measured deviation from the desired mission requirement in any year is included as part of the measured deviation in all subsequent years. Clearly, this is not desired. One would certainly prefer being short just one year and not in subsequent years. As written, there is no incentive for eliminating shortages in future years.

iv) As written, the index (*i*) is not controlled in the expressions. The value must be summed again in the expressions.

$$\sum_{j \in VehSupported(m), t^* \leq t} ExcessTransition_{j,i,m,t} - \sum_{j \in Transition(i,m), t^* \leq t} ExcessTransition_{i,j,m,t} .$$

3. In Andrade et al. (2011), Equation (1.14) has many of the same issues as previously described in Equation (1.11). As implemented, all of the *Excess Transition* variables are set to zero as the default configuration and this is the only way the constraints will work properly. Clearly, this should be revised. It is too easy to be given a goal that would cause infeasibility and without the use of this variable it is impossible to tell how much the goal needs to be reduced without performing additional model runs.

4. In Andrade et al. (2011), Equation (1.27) is a complicating constraint that can make this model more difficult to solve. A reformulation should be considered to determine brigade lot sizing or change the data so that the decisions are aggregated at the brigade-set level.

5. It is assumed that what is produced must be fielded in the current period plus some delay (usually two years). This is a very restrictive limitation and may not provide the best equipping policy because money may be left on the table. Whole brigade lots cannot be built with the remaining funds without carrying inventory into the next year.

6. End effects are a potential issue. Maximizing the value of the fleet at the end does not guarantee anything about the condition of the fleet one year afterwards. For example, there could be too many required vehicle retirements one year after the end of the model horizon. Model excursions should extend the horizon to ensure enough years are included so that prescriptions in the initial years are not unnecessarily impacted. This is likely the case because vehicle options offered late in the time horizon are never chosen by CPAT.

## 5.2 CPAT IMPLEMENTATION REVIEW

The purpose of the implementation review is to ensure that the formulation is correctly implemented and that the assumptions as stated are explicitly modeled. A second important consideration of this section is to determine which model parameters have the greatest influence on CPAT solutions. To conduct a review of the CPAT model we use the data base, Unrestricted_4.0B_b30.cpat. This is the same data used for the evaluation of the value model. Due to time constraints for conducting the review, we use a reduced data set. Our analysis only includes excursions for the MBT, IFV, and the CAV vehicle variants. The MBT and IFV roles were selected because they contain the GCV and AMOD variants, which are important to any analysis. The CAV role is a lesser role, but still a driver in many solutions. Where a typical excursion using the unrestricted data set may take over an hour to get a solution within a 0.1% gap, using the reduced data set we are able to run numerous excursions to a zero gap, with each excursion taking only 10 to 15 seconds. Because we use a reduced data set for our analysis, conclusions concerning particular weapon systems should be avoided.

We make several sets of excursions in our analysis. The first we refer to as the baseline set. For these excursions, we ran six funding profiles: $1.0B, $1.25B, $1.5B, $1.75B, $2.0B, and $2.6B. Our intent for running these excursions is two-fold. First, to determine where reduced budget levels forced significant changes in alternative selection. The second is to establish a baseline for further excursions by changing other parameters at a given funding profile of interest. Appendix F contains the pivot tables showing the selected alternatives and both the modernization levels and fielding over the 28-year horizon for these six excursions. Figure 10 summarizes the six baseline excursions and we note several interesting patterns.

| Row Labels | 1 | 1.25 | 1.5 | 1.75 | 2 | 2.6 |
|---|---|---|---|---|---|---|
| **M2A3 OIF** | **1728** | **1728** | **1728** | **1728** | **1728** | **1728** |
| M2A3 ECP | 1728 | 1296 | 1368 | 1368 | 1080 | 1080 |
| GCV | | | | | 648 | 648 |
| BMOD IFV | | 432 | 360 | 360 | | |
| **M2A3 ECP** | | **1296** | **1368** | **1368** | **1080** | **1080** |
| GCV | | | | | 1080 | 1080 |
| BMOD IFV | | 1296 | 1368 | 1368 | | |
| **M1 ECP** | **700** | | | **700** | | **1120** |
| AMOD | 700 | | | 700 | | 1120 |
| **M3A3 CAV OIF** | **816** | **816** | **816** | **816** | **646** | **816** |
| BMOD CAV | | 238 | 204 | 204 | | 238 |
| M3A3 CAV ECP | 816 | 578 | 612 | 612 | 646 | 578 |
| **M3A3 CAV ECP** | | **68** | **612** | **612** | | **578** |
| BMOD CAV | | 68 | 612 | 612 | | 578 |
| **M1A2 SEP TUSK** | **1680** | **1680** | **1680** | **1680** | **1120** | **1680** |
| M1 ECP | 1120 | 1120 | 1120 | 1120 | 1120 | 1120 |
| AMOD | 560 | 560 | 560 | 560 | | 560 |
| **Grand Total** | **4924** | **5588** | **6204** | **6904** | **4574** | **7002** |

Figure 10. Baseline summary of six funding profiles shown in the columns ($Billions) for three roles: MBT, IFV, and CAV. The alternatives in bold are being modernized and nonbolded alternatives are being fielded.

The grand total of vehicles fielded increases to 6,904 as the budget increases until $2.0B; then there is a dramatic drop to 4,574 vehicles. This drop is due to two issues. First, is the purchase of the GCV. A second, and more subtle, reason is that the M1A2 modernization is squeezed out by the GCV purchase. We discuss the second issue later in this section. The most important take away from these baseline excursions is that there are interactions across roles. Unlike what we observed in the analysis of the value model, where alternatives only compete amongst each other within a role, in the optimization model the alternatives compete across roles. The optimization will ensure that each role is properly fielded, but the value-funding relationship may influence which alternatives are selected within a role.

The five excursions based on the $2.0B funding profile are used to determine how an increase in value for a given alternative in one role may affect the alternatives in another role. The first three excursions examine what would happen if the value for three alternatives is increased by 10%. The results of these excursions are shown in Appendix E. As expected from what we saw from the sensitivity analysis conducted by Sandia (Sandia National Laboratory, 2011) there is no change from the baseline results. For the fourth excursion, we increase all of the alternatives contained in the MBT role (role 7) by 10% and find that even increasing the value of all of the MBT alternatives is not enough to push AMOD back into the solution. The results for the fourth $2.0B funding profile excursion are shown in Figure 11.

| Row Labels | Baseline | NoRDTECosts |
|---|---|---|
| **⊟ M2A3 OIF** | **1728** | **1728** |
| M2A3 ECP | 1080 | 1008 |
| GCV | 648 | 720 |
| **⊟ M2A3 ECP** | **1080** | **1008** |
| GCV | 1080 | 1008 |
| **⊟ M1 ECP** | | **700** |
| AMOD | | 700 |
| **⊟ M3A3 CAV OIF** | **646** | **816** |
| BMOD CAV | | 306 |
| M3A3 CAV ECP | 646 | 510 |
| **⊟ M3A3 CAV ECP** | | **510** |
| BMOD CAV | | 510 |
| **⊟ M1A2 SEP TUSK** | **1120** | **1680** |
| M1 ECP | 1120 | 1120 |
| AMOD | | 560 |
| **Grand Total** | **4574** | **6442** |

Figure 11. Summary of $2.0B funding baseline profile with and without (far right column) RDTE costs being considered.

We note that when RDTE costs are not considered, AMOD is brought back into the portfolio. This suggests that the ~$1.0B allocated for RDTE costs in the first two years has a very influential impact on the solution. A similar analysis at the $1.5B funding profile shown in Figure 12 suggests that the GCV alternative is only funded if RDTE costs are not considered.

| Row Labels | Baseline | NoRDTECosts |
|---|---|---|
| **M2A3 OIF** | **1728** | **1728** |
| M2A3 ECP | 1368 | 1008 |
| GCV | | 720 |
| BMOD IFV | 360 | |
| **M2A3 ECP** | **1368** | **1008** |
| GCV | | 576 |
| BMOD IFV | 1368 | 432 |
| **M3A3 CAV OIF** | **816** | **816** |
| BMOD CAV | 204 | |
| M3A3 CAV ECP | 612 | 816 |
| **M3A3 CAV ECP** | **612** | **476** |
| BMOD CAV | 612 | 476 |
| **M1A2 SEP TUSK** | **1680** | **1680** |
| M1 ECP | 1120 | 1120 |
| AMOD | 560 | 560 |
| **Grand Total** | **6204** | **5708** |

Figure 12. Summary of $1.5B funding baseline profile with and without (far right column) RDTE costs being considered.

The results shown in Figures 11 and 12 suggest that RDTE costs do play a significant role in alternative selection when the overall budget is constrained. Therefore, additional sensitivity analysis should be considered on alternative RDTE funding profiles for different vehicle alternatives.

The next analysis again uses the $2.0B funding profile. This time, we examine how the changes to the upper-bound of the number of M2A3 ECP vehicles that may be purchased in one period affect the solution. CPAT currently assumes that there are 72 role-1 type vehicles in a heavy brigade and that the maximum number of M2A3 ECP vehicles allowed to be purchased for M2A3 Operation Iraqi Freedom (OIF) modernization is set to 216 in period 5 (FY2017) and 360 in periods 6 and 7 (FYs 2018 and 2019). In other words, the baseline models can upgrade up to three BCTs in the first period and up to five BCTs during the second and third periods with the ECP variant, but must limit purchases of M2A3ECP for the remaining 21 years to two BCTs per year. We are not sure how realistic this requirement is from a policy perspective, given that whatever is produced must be fielded two years later (no inventory is allowed). However, it is a necessary modeling limitation because of the 33% M2A3 OIF modernization requirement beginning in period 6. To examine the sensitivity of the purchase restriction we ran two excursions, with the first restricting the purchase limit to 144 ECPs per year and the second allowing up to 360 ECPs per year. To allow for this purchase restriction, we relax the modernization constraint to 10% for the first year and 20% for the remaining years.

Figure 13 shows the result of this analysis. The top table shows the vehicle modernization schedule over 15 years, the middle table shows the purchase limited case with a vehicle modernization schedule over 18 years, and the bottom table shows the unlimited purchase case with a vehicle modernization schedule over 19 years.

| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **⊟ M2A3 OIF** | **216** | **360** | **144** | **216** | **216** | **216** | **144** | **144** | **72** | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 72 | 144 | 144 | 144 | | | | | | | | | | | 1080 |
| GCV | | | 72 | 72 | 72 | 72 | 144 | 144 | 72 | | | | | | | | 648 |
| **⊟ M2A3 ECP** | | | | | | | | | **72** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **1080** |
| GCV | | | | | | | | | 72 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 1080 |
| **⊟ M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **68** | **68** | | | | | | | | | | | **646** |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 68 | 68 | | | | | | | | | | | 646 |
| **⊟ M1A2 SEP TUSK** | | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | | | | | **1120** |
| M1 ECP | | 140 | 140 | 140 | 140 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | 1120 |

| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **⊟ M2A3 OIF** | **144** | **144** | **144** | **216** | **216** | **216** | **216** | **216** | **216** | | | | | | | | | | | **1728** |
| M2A3 ECP | 144 | 144 | 72 | 144 | 144 | 144 | 144 | 144 | 144 | | | | | | | | | | | 1224 |
| GCV | | | 72 | 72 | 72 | 72 | 72 | 72 | 72 | | | | | | | | | | | 504 |
| **⊟ M2A3 ECP** | | | | | | | | | | **72** | **72** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **72** | **1224** |
| GCV | | | | | | | | | | 72 | 72 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 72 | 1224 |
| **⊟ M3A3 CAV OIF** | **102** | **102** | **102** | **68** | **34** | **68** | **68** | **68** | **68** | **68** | **68** | | | | | | | | | **816** |
| M3A3 CAV ECP | 102 | 102 | 102 | 68 | 34 | 68 | 68 | 68 | 68 | 68 | 68 | | | | | | | | | 816 |
| **⊟ M1A2 SEP TUSK** | | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | | | | | | **1610** |
| M1 ECP | | 140 | 140 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | 1120 |
| AMOD | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | 490 |

| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **⊟ M2A3 OIF** | | **288** | **288** | **360** | **216** | **216** | **216** | **144** | | | | | | | | | | | **1728** |
| M2A3 ECP | | 288 | 216 | 288 | 144 | 144 | 144 | 72 | | | | | | | | | | | 1296 |
| GCV | | | 72 | 72 | 72 | 72 | 72 | 72 | | | | | | | | | | | 432 |
| **⊟ M2A3 ECP** | | | | | | | | | **72** | **72** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **1296** |
| GCV | | | | | | | | | 72 | 72 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 1296 |
| **⊟ M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **34** | **68** | **68** | **68** | **68** | | | | | | | | | | **816** |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 34 | 68 | 68 | 68 | 68 | | | | | | | | | | 816 |
| **⊟ M1A2 SEP TUSK** | **70** | **140** | **70** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | | | | | **1540** |
| M1 ECP | 70 | 140 | 70 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | 1120 |
| AMOD | | | | | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | 420 |

Figure 13. Vehicle fielding and modernization with a $2.0B funding profile. The tables show the equipping profiles over time. The top table is the baseline profile, the middle table shows the case where the M2A3 ECP fielding is limited to two BDEs for the first three periods, and the bottom table removes the BDE limit on M2A3 ECP fielding. The vehicles being modernized are shown in bold and the number of each vehicle being fielded are shown in the columns under their respective bold modernization entries for each period. For example, in the top table under the eighth period (FY2020) there are 144 M2A3 ECPs and 72 GCVs being fielded, which will replace 216 M2A3 OIF vehicles.

There are several interesting things to note about this analysis and it also demonstrates a fundamental tenant of optimization: when we apply a constraint to a problem, we cannot expect a better outcome. For example, even with the relaxed modernization constraint, the restricted purchases case finishes M2A3 OIF modernization the same year as the baseline case, resulting in a 0.3% increase in overall portfolio performance and an increase of vehicle modernization of 16% over the baseline case. Additionally, the same number of GCVs is purchased in the restricted case as in the baseline; however, AMOD is also purchased in the restricted case. For the unrestricted purchases case, modernization is accomplished a year sooner, resulting in an increase of 14% in overall modernization and AMOD is still purchased with an overall performance bump over the baseline case of 0.6%. Based on these findings, we suggest more studying of the maximum purchases allowed and relaxation of the modernization requirements using elastic constraints to allow exploration of more efficient modernization policies that are not based solely on a fixed schedule.

## 5.3 OTHER ISSUES

Overall, the GUI allows CPAT to be used by novice users unaccustomed to running optimization models. Except for the penalties on elastic variables, the user can access most of the input parameters of the optimization model. The developers put much of their effort into generation of output, which makes sense given that the ultimate user is the PM office. We did not have access to the underlying code of the output module and verification of the output was not our focus. However, through our analysis, we did find a couple of minor issues that should be addressed.

To illustrate our first issue with CPAT output, we use the "Mission Fielding Schedule" from the CPAT Results Explorer reproduced in Figure 14.

Mission Fielding Schedule by System Count

| $86.827B | | | FY13 | FY14 | FY15 | FY16 | FY17 | FY18 | FY19 | FY20 | FY21 | FY22 | FY23 | FY24 | FY25 | FY26 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $38.496B | IFV | M2A3 ECP | | | | | 216 | 360 | 72 | 144 | 144 | 144 | | | | |
| | | GCV | | | | | | | 72 | 72 | 72 | 72 | 144 | 144 | 144 | 144 |
| $44.447B | MBT | M1 ECP | | | | | | 140 | 140 | 140 | 140 | 140 | 70 | 70 | 70 | 70 |
| $3.884B | Cavalry | M3A3 CAV ECP | | | | | 102 | 170 | 170 | 68 | 68 | 68 | | | | |

| $86.827B | | | FY27 | FY28 | FY29 | FY30 | FY31 | FY32 | FY33 | FY34 | FY35 | FY36 | FY37 | FY38 | FY39 | FY40 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $38.496B | IFV | M2A3 ECP | | | | | | | | | | | | | | |
| | | GCV | 144 | 144 | 144 | 144 | 144 | 144 | | | | | | | | |
| $44.447B | MBT | M1 ECP | 70 | 70 | | | | | | | | | | | | |
| $3.884B | Cavalry | M3A3 CAV ECP | | | | | | | | | | | | | | |

Figure 14. Vehicle fielding for the $2.0B funding profile from the CPAT Results Explorer.

Correctness of this chart is not the issue and it can be verified to contain identical quantities, as shown the $2.0B baseline funding profile case in Figure 13. What is not apparent from this chart, but can be seen in Figure 12, is that GCV fielding begins for modernization of M2A3 ECP only three years after the purchase of the last of 1,080 ECP variants that were used to modernize the M2A3 OIF. This is not apparent in Figure 14 because fielding and modernization results are separated in the CPAT Results Explorer. This policy behavior is not likely something leadership would support and could be easily addressed with additional CPAT constraints.

The other issue concerns the correctness of the first several time periods of the Acquisition Expenditures from the "Total Expenditure vs. Budget" page from the Results Explorer. Figure 15 shows this table for the $1.25B funding level and the far right column shows our calculation. Note the inconsistencies for FY2015 and FY2016. Similar results are found in the other cases for the first few periods.

| Time Period | Acquisition Expenditures | M1A2 | AMOD | M1 ECP | M2A3 ECP | BMOD IFV | M2A3 OIF | BMOD IFV | M2A3 ECP | M3A3 CAV ECP | BMOD CAV | M3A3 CAV OIF | BMOD CAV | M3A3 CAV ECP | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FY13 | $0 | | | | | | | | | | | | | | |
| FY14 | $0 | | | | | | | | | | | | | | |
| FY15 | $774,578,000 | $478 | | $478 | | | $231 | | $231 | | | $109 | | $109 | $819 |
| FY16 | $784,630,000 | $249 | | $249 | | | $386 | | $386 | | | $182 | | $182 | $817 |
| FY17 | $924,518,000 | $434 | | $434 | | | $308 | | $308 | | | $182 | | $182 | $925 |
| FY18 | $661,062,000 | $434 | | $434 | | | $154 | | $154 | | | $73 | | $73 | $661 |
| FY19 | $1,110,430,000 | $434 | | $434 | | | $154 | | $154 | | | $522 | $486 | $36 | $1,110 |
| FY20 | $1,164,902,000 | $217 | | $217 | | | $669 | $514 | $154 | | | $279 | $243 | $36 | $1,165 |
| FY21 | $1,191,264,000 | $434 | | $434 | | | $514 | $514 | | | | $243 | $243 | | $1,191 |
| FY22 | $1,191,264,000 | $434 | | $434 | | | $514 | $514 | | | | $243 | $243 | | $1,191 |
| FY23 | $1,217,160,000 | $217 | | $217 | | | $514 | $514 | | | | $486 | $486 | | $1,217 |
| FY24 | $1,217,160,000 | $217 | | $217 | | | $514 | $514 | | $486 | $486 | | | | $1,217 |
| FY25 | $1,074,368,000 | $560 | $560 | | | | $514 | $514 | | | | | | | $1,074 |
| FY26 | $1,074,368,000 | $560 | $560 | | $514 | $514 | | | | | | | | | $1,074 |
| FY27 | $1,074,368,000 | $560 | $560 | | $514 | $514 | | | | | | | | | $1,074 |
| FY28 | $1,074,368,000 | $560 | $560 | | $514 | $514 | | | | | | | | | $1,074 |
| FY29 | $1,074,368,000 | $560 | $560 | | $514 | $514 | | | | | | | | | $1,074 |
| FY30 | $1,074,368,000 | $560 | $560 | | $514 | $514 | | | | | | | | | $1,074 |
| FY31 | $1,074,368,000 | $560 | $560 | | $514 | $514 | | | | | | | | | $1,074 |
| FY32 | $1,074,368,000 | $560 | $560 | | $514 | $514 | | | | | | | | | $1,074 |
| FY33 | $1,028,736,000 | | | | $1,029 | $1,029 | | | | | | | | | $1,029 |
| FY34 | $1,028,736,000 | | | | $1,029 | $1,029 | | | | | | | | | $1,029 |
| FY35 | $1,028,736,000 | | | | $1,029 | $1,029 | | | | | | | | | $1,029 |
| FY36 | $1,028,736,000 | | | | $1,029 | $1,029 | | | | | | | | | $1,029 |
| FY37 | $1,028,736,000 | | | | $1,029 | $1,029 | | | | | | | | | $1,029 |
| FY38 | $514,368,000 | | | | $514 | $514 | | | | | | | | | $514 |
| FY39 | $0 | | | | | | | | | | | | | | |
| FY40 | $0 | | | | | | | | | | | | | | |

Figure 15. Acquisition Expenditure deficiencies for $1.25B funding profile.

As mentioned earlier, CPAT fields vehicles as brigade sets. The assumption is that what is produced must be fielded at a set interval, in most cases two years after production. Partial sets are not allowed; in other words, inventory is not carried over from one period to another. One of the obvious drawbacks to this approach is that all of the allowable budget appropriation may not be used, as shown in Figure 16. The last column shows the budget surplus for the constant $2.0B funding profile.

| Time Period | Acquisition Budget | Acquisition Expenditures | RDTE Budget | Total Budget | Difference |
|---|---|---|---|---|---|
| FY13 | $2,000,000,000 | $0 | $1,431,400,000 | $1,431,400,000 | $568,600,000 |
| FY14 | $2,000,000,000 | $0 | $1,567,900,000 | $1,567,900,000 | $432,100,000 |
| FY15 | $2,000,000,000 | $340,578,000 | $1,576,100,000 | $1,916,678,000 | $83,322,000 |
| FY16 | $2,000,000,000 | $1,001,630,000 | $970,700,000 | $1,972,330,000 | $27,670,000 |
| FY17 | $2,000,000,000 | $1,580,942,000 | $407,600,000 | $1,988,542,000 | $11,458,000 |
| FY18 | $2,000,000,000 | $1,548,812,000 | $55,100,000 | $1,603,912,000 | $396,088,000 |
| FY19 | $2,000,000,000 | $1,548,812,000 | $76,000,000 | $1,624,812,000 | $375,188,000 |
| FY20 | $2,000,000,000 | $1,548,812,000 | $42,200,000 | $1,591,012,000 | $408,988,000 |
| FY21 | $2,000,000,000 | $1,992,520,000 | $2,500,000 | $1,995,020,000 | $4,980,000 |
| FY22 | $2,000,000,000 | $1,992,520,000 | $0 | $1,992,520,000 | $7,480,000 |
| FY23 | $2,000,000,000 | $1,992,520,000 | $0 | $1,992,520,000 | $7,480,000 |
| FY24 | $2,000,000,000 | $1,992,520,000 | $0 | $1,992,520,000 | $7,480,000 |
| FY25 | $2,000,000,000 | $1,992,520,000 | $0 | $1,992,520,000 | $7,480,000 |
| FY26 | $2,000,000,000 | $1,992,520,000 | $0 | $1,992,520,000 | $7,480,000 |
| FY27 | $2,000,000,000 | $1,775,520,000 | $0 | $1,775,520,000 | $224,480,000 |
| FY28 | $2,000,000,000 | $1,775,520,000 | $0 | $1,775,520,000 | $224,480,000 |
| FY29 | $2,000,000,000 | $1,775,520,000 | $0 | $1,775,520,000 | $224,480,000 |
| FY30 | $2,000,000,000 | $1,775,520,000 | $0 | $1,775,520,000 | $224,480,000 |
| FY31 | $2,000,000,000 | $0 | $0 | $0 | $2,000,000,000 |
| FY32 | $2,000,000,000 | $0 | $0 | $0 | $2,000,000,000 |
| FY33 | $2,000,000,000 | $0 | $0 | $0 | $2,000,000,000 |
| FY34 | $2,000,000,000 | $0 | $0 | $0 | $2,000,000,000 |
| FY35 | $2,000,000,000 | $0 | $0 | $0 | $2,000,000,000 |
| FY36 | $2,000,000,000 | $0 | $0 | $0 | $2,000,000,000 |
| FY37 | $2,000,000,000 | $0 | $0 | $0 | $2,000,000,000 |
| FY38 | $2,000,000,000 | $0 | $0 | $0 | $2,000,000,000 |
| FY39 | $2,000,000,000 | $0 | $0 | $0 | $2,000,000,000 |
| FY40 | $2,000,000,000 | $0 | $0 | $0 | $2,000,000,000 |

Figure 16. Total Budget versus the $2.0B funding profile budget.

Additionally, fielding decisions currently show high volatility from one period to the next. This behavior is undesirable because most manufacturers are not going to vary production by 50% or more from one year to the next without considerable expense to the government. The production volatility may be reduced by using inventory to smooth out the deviations from year to year.

# 6. CONCLUSIONS AND RECOMMENDATIONS

CPAT is a good application for optimization. At its core, CPAT is an optimization model; however, the CPAT objective function is derived using multiattribute decision analysis techniques. Therefore, we approached this evaluation by first focusing on the verification and validation of the performance model that produces the CPAT objective function coefficients. We then verified the CPAT optimization formulation and ensured that the OPL code was implemented as indicated by the formulation. The last step was to validate the overall CPAT model by observing changes to CPAT solutions when we varied in the most sensitive model parameters. We would like to highlight the following results of this analysis:

1. In general, the performance model provides robust results. This is primarily because only a small number of alternatives are considered for a given role. Changes in weights or the shape of the value function only affect a small number of alternatives in a given role.
2. The model contains many attributes that are not very relevant and essentially do not contribute to the differentiation among the alternatives.
3. It is possible to simplify the protection and lethality subobjectives by utilizing only the relevant categories that influence results.
4. All attributes should be weighted globally across all roles. The current weighting system results in 20 different models, one corresponding to each role. As a result of this current limitation, alternative values from one model should not be directly compared to values of another model.
5. Several parameters could be more general in the formulation. For example, $MaxBDE_m$ and $MissionReq_m$ could vary by year.
6. In Equation (1.10) from Andrade et al. (2011), the penalty should not be the same for all deviations (elastic variables); it should potentially vary by year.
7. Several constraints (Equations [1.11] and [1.14]; Andrade et al. [2011]) have issues as they are currently written. For example, the same penalty per unit exists for being over and under the mission requirement level.
8. In Andrade et al. (2011), Equation (1.27) is a potentially unnecessary complicating constraint that increases solution time. Consider a different formulation to determine brigade lot sizing or change the data so that the decisions are aggregated at the brigade-set level.
9. It is implied that what is produced must be fielded as a brigade set; in most cases, two years after production. Due to this constraint, all of the allowable budget appropriation may not be used.
10. End effects are a potential issue. Maximizing the value of the fleet at the end does not guarantee anything about the condition of the fleet one year afterwards. For example, there could be too many required vehicle retirements one year after the end of the model horizon. Model excursions should extend the horizon to ensure that enough years are included so that prescriptions in the initial years are not unnecessarily impacted. This is

likely the case because vehicle options offered late in the time horizon are never chosen by CPAT.

11. Unlike the value model, where alternatives only compete amongst each other within a role, in the optimization model alternatives compete across roles. Therefore, value trade-offs are critical in a reduced budget environment.
12. CPAT results are very sensitive to RDTE funding profiles for different vehicle alternatives.
13. CPAT results are sensitive to maximum purchases allowed parameters found on the fielding schedule. Elastic constraints should be considered to allow exploration of more efficient modernization policies that are not based solely on a fixed schedule.

Based on our technical review of the CPAT model, we have several near- and long-term recommendations. The near-term recommendations focus on issues that can be addressed with the current model and data. The long-term recommendations focus on larger structural changes and extensions of the current model.

## 6.1 Near-Term Recommendations

1. Study the effects of removing ineffective value measures. We suggest beginning with those measures that do not use a full range of the scale for a continuous measure (highlighted in Section 4.4) as well as the qualitative and binary measures that do not show much variation in scale (or value). See Appendix C for details on value measure range analysis.
2. Aggregate the level of detail at the brigade-set level. With the current version of the model, we see no need to run CPAT at the vehicle level of detail. Currently, all fielding and modernization decisions are being made at the brigade-set level, which implies that all production decisions must also be made at the brigade set level with a given delay. This aggregation will greatly simplify the model by allowing for the removal of the complicating constraint (1.27) and will allow for much faster solution times and a smaller optimal gap for most instances. If vehicle level of detail is desired, it can be computed very efficiently in a post processing environment.

## 6.2 Long-Term Recommendations

1. Determine a “single” objective value model by reducing the number of attributes and reweighting across all roles. This will allow users to make direct value comparisons between roles and strengthen the additive assumption implied by this mixed-integer linear program.
2. Fund a prototype CPAT Version 2 that will consider separate decisions for production and allow inventory to be carried from one period to the next. This next generation CPAT will then decouple the fielding of BDE sets from the vehicle production decisions and provide for cheaper long-run solutions with greater fleet performance.

# APPENDIX A. DESCRIPTIVE STATISTICS SUMMARY TABLE

This descriptive statistics summary table illustrates the model attributes considered for each vehicle role, the unit of measure for each attribute, and the scales used for each vehicle type. The model's 49 attributes and units of measure are listed in the rows and the 20 vehicle types are listed in the columns across the top of the table. The bottom of the table lists the number of attributes used by each vehicle role. The table highlights in color the scales used for each attribute across the 20 vehicle roles (red indicates 1 scale used for all roles, blue= scale 1, green= scale 2, purple= scale 3). Cells highlighted in gray are not used for the role and cells with a bisecting red line are classified. In many cases, only one scale is used (indicated in solid red) or there is one scale for HBCT (indicated in blue) and a second scale for SBCT roles (indicated in green).

**Legend**
- classified data
- measure not used for this role
- range same for all roles
- scale 1
- scale 2
- scale 3

**Descriptive Statistics Summary Table**

**Role-Attribute-Range Mapping**

| | | | HBCT | | | | | | | | | | SBCT | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subobjective | Measure | Unit | MBT | IFV | CAV | FIST | Eng | SPA | MtrCr | C2 (H) | Med | GP | ICV | ATGM | C2 (S) | RV | MCV | FSV | ESV | MEV | NBCRV | MGS |
| Survivability | Occupant Protection against Sm Arms & Md Cal | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Occupant Protection against RPG | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Occupant Protection against ATGM | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Occupant Protection against Tank KE | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Occupant Protection against Top Attack | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Occupant Protection against Undervehicle | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Occupant Protection against IED | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | CBRN Operation | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Survivability against Sm Arms & Med Cal | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Survivability against RPG | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Survivability against ATGM | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Survivability against Tank KE | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Survivability against Top Attack | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Survivability against Undervehicle | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Survivability against IED | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Silent Watch | Hours | | | | | | | | | | | | | | | | | | | | |
| Growth | Available Electrical Power | kW | | | | | | | | | | | | | | | | | | | | |
| | Exportable Electrical Power | kW | | | | | | | | | | | | | | | | | | | | |
| | Information System Growth | Qualitative | | | | | | | | | | | | | | | | | | | | |
| Lethality | Effective Range vs. Tanks | Meters | | | | | | | | | | | | | | | | | | | | |
| | Effective Range vs. IFVs | Meters | | | | | | | | | | | | | | | | | | | | |
| | Effective Range vs. Light Armor | Meters | | | | | | | | | | | | | | | | | | | | |
| | Effective Range vs. Personnel (point target) | Meters | | | | | | | | | | | | | | | | | | | | |
| | Effective Range vs. Personnel (area target) | Meters | | | | | | | | | | | | | | | | | | | | |
| | Efficiency vs. ADA site | Number of Rounds | | | | | | | | | | | | | | | | | | | | |
| | Efficiency vs. artillery platoon | Number of Rounds | | | | | | | | | | | | | | | | | | | | |
| | Efficiency vs. mech platoon | Number of Rounds | | | | | | | | | | | | | | | | | | | | |
| | Efficiency vs. MRL | Number of Rounds | | | | | | | | | | | | | | | | | | | | |
| | Efficiency vs. dismounted crew | Number of Rounds | | | | | | | | | | | | | | | | | | | | |
| | Missile Capability | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | ATGM Fire Control | Binary | | | | | | | | | | | | | | | | | | | | |
| | Mast Mounted Sensor | Binary | | | | | | | | | | | | | | | | | | | | |
| | Target Designation | Binary | | | | | | | | | | | | | | | | | | | | |
| | FTL Targeting | Binary | | | | | | | | | | | | | | | | | | | | |
| | Weapon Stabilization | Binary | | | | | | | | | | | | | | | | | | | | |
| | Transition from Firing to Moving | Seconds | | | | | | | | | | | | | | | | | | | | |
| Per Payload | Personnel Carry | # Personnel | | | | | | | | | | | | | | | | | | | | |
| | Litter Carry | # Patients | | | | | | | | | | | | | | | | | | | | |
| Mobility | Soft Soil Mobility | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Max Speed | MPH | | | | | | | | | | | | | | | | | | | | |
| | Turning Diameter | Feet | | | | | | | | | | | | | | | | | | | | |
| | Static Stability Factor | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Vehicle Width | Feet | | | | | | | | | | | | | | | | | | | | |
| | Dash Speed | Seconds | | | | | | | | | | | | | | | | | | | | |
| | Air Transportability | Qualitative | | | | | | | | | | | | | | | | | | | | |
| | Cruising Range | Miles | | | | | | | | | | | | | | | | | | | | |
| Sustainability | Operational Availability - Initial | Percentage | | | | | | | | | | | | | | | | | | | | |
| | Operational Availability - Worst Case | Percentage | | | | | | | | | | | | | | | | | | | | |
| | Sustainment Availability | Percentage | | | | | | | | | | | | | | | | | | | | |
| | **# Attributes Used By Role** | | 38 | 40 | 40 | 40 | 37 | 36 | 35 | 31 | 31 | 31 | 41 | 41 | 35 | 39 | 39 | 39 | 41 | 34 | 34 | 40 |

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# APPENDIX B. SUMMARY TABLE HEAVY BRIGADE COMBAT TEAM (HBCT)/STRYKER BRIGADE COMBAT TEAM (SBCT) ATTRIBUTE SCALES

The table illustrates when the possible range, defined as the minimum and maximum on the value function scale, is the same for a given attribute across all HBCT and SBCT roles. Cells highlighted in green indicate that all vehicles in the role use the same possible range. Cells highlighted in yellow indicate when the majority of the vehicles use the same range; for example, the value function for the Available Electrical Power attribute uses the same x-axis scale for all vehicles in the HBCT role, but two y-axis scales. For 27 of the 49 attributes in the model, the same scale is used across all 20 HBCT/SBCT roles.

| Subobjective | Attribute | HBCT | SBCT |
|---|---|---|---|
| Survivability | Occupant Protection against Small Arms & Medium Caliber | No-same x scale; 2 ys | Yes |
| | Occupant Protection against RPG | No-same x scale; 2 ys | Yes |
| | Occupant Protection against ATGM | No-same x scale; 2 ys | Yes |
| | Occupant Protection against Tank KE | No | Yes |
| | Occupant Protection against Top Attack | No-same x scale; 2 ys | Yes |
| | Occupant Protection against Undervehicle | No-same x scale; 2 ys | Yes |
| | Occupant Protection against IED | No-same x scale; 2 ys | Yes |
| | CBRN Operation | Yes | Yes |
| | Survivability against Small Arms & Medium Caliber | No-same x scale; 2 ys | Yes |
| | Survivability against RPG | No-same x scale; 2 ys | Yes |
| | Survivability against ATGM | No-same x scale; 2 ys | Yes |
| | Survivability against Tank KE | No | Yes |
| | Survivability against Top Attack | No-same x scale; 2 ys | Yes |
| | Survivability against Undervehicle | No | Yes |
| | Survivability against IED | No | Yes |
| | Silent Watch | Yes | Yes |
| Growth | Available Electrical Power | No-same x scale; 2 ys | Yes |
| | Exportable Electrical Power | No-SPA is different | Yes |
| | Information System Growth | No-same y scale; 2 possible orders for xs | No-same y scale, 2 possible orders for xs |
| Lethality | Effective Range vs. Tanks | Yes | No-2 possible combinations |
| | Effective Range vs. IFVs | Yes | Yes-only ATGM listed |
| | Effective Range vs. Light Armor | Yes | No-2 possible combinations |
| | Effective Range vs. Personnel (point target) | Yes | No-2 possible combinations |
| | Effective Range vs. Personnel (area target) | No-2 possible combinations | No-2 possible combinations |
| Lethality | Efficiency vs. ADA site | Yes | Yes |
| | Efficiency vs. Artillery platoon | Yes | Yes |
| | Efficiency vs. Mech platoon | Yes | Yes |
| | Efficiency vs. MRL | Yes | Yes |
| | Efficiency vs. Dismounted crew | Yes | Yes |
| | Missile Capability | Yes | Yes |
| | ATGM Fire Control | N/A | Yes |
| | Mast-Mounted Sensor | Yes | Yes |
| | Target Designation | Yes | Yes |
| | FTL Targeting | Yes | Yes |
| | Weapon Stabilization | Yes | Yes |
| | Transition from Firing to Moving | Yes-only SPA listed | Not Applicable |
| Personnel Payload | Personnel Carry | No-2 possible combinations | No-2 possible combinations |
| | Litter Carry | Yes-only Med listed | Yes-only MEV listed |
| Mobility | Soft Soil Mobility | Yes | Yes |
| | Max Speed | Yes | Yes |
| | Turning Diameter | Yes | Yes |
| | Static Stability Factor | Yes | Yes |
| | Vehicle Width | Yes | Yes |
| | Dash Speed | Yes | Yes |
| | Air Transportability | Yes | Yes |
| | Cruising Range | Yes | Yes |
| Sustainability | Operational Availability - Initial | Yes | Yes |
| | Operational Availability - Worst Case | Yes | Yes |
| | Sustainment Availability | Yes | Yes |
| *Sustainability-not used in analysis* | Part Commonality | Yes | Yes |
| | Embedded Diagnostics | Yes | Yes |
| | Mean Time Between Essential Function Failure | Yes | Yes |

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# APPENDIX C. QUANTITATIVE ATTRIBUTES – PERCENT RANGE USED WITHIN EACH VALUE FUNCTION

Our analysis shows that the actual range of the data often does not utilize the full possible range of the value functions. For this analysis, we define the *possible range* as the minimum and maximum on the value function scale, and the *actual range* as the minimum and maximum values of the data that is input into the model.

This table shows the percentage of the *actual range* used by the data in the model. Cells highlighted in yellow indicate that 0% of the range was used or no variability in the data; meaning all vehicle data within the role are the same. Red cells indicate that < 25% of the possible range is used, White 26%-49%, and green 50%-100%. Light-gray cells have data that extend beyond the value function's established range and dark gray cells were not assessed for the role.

| | Percent Range Used | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | HBCT | | | | | | | | | | SBCT | | | | | | | | | |
| **Attribute** | **MBT** | **IFV** | **CAV** | **FIST** | **Eng** | **SPA** | **MtrCr** | **C2 (H)** | **Med** | **GP** | **ICV** | **ATGM** | **C2 (S)** | **RV** | **MCV** | **FSV** | **ESV** | **MEV** | **NBCRV** | **MGS** |
| Silent Watch | 183.33% | 131.25% | 131.25% | 131.25% | 131.25% | 14.58% | 47.92% | 47.92% | 47.92% | 47.92% | 31.25% | 31.25% | 31.25% | 31.25% | 31.25% | 31.25% | 31.25% | 31.25% | 31.25% | 31.25% |
| Available Electrical Power | 60.60% | 45.11% | 45.11% | 56.87% | 51.14% | 51.47% | 39.71% | 73.53% | 73.53% | 39.71% | 20.59% | 20.59% | 20.59% | 20.59% | 22.06% | 20.59% | 20.59% | 20.59% | 20.59% | 20.59% |
| Exportable Electrical Power | 0.00% | 48.89% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 48.89% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Effective Range vs. Tanks | 2.40% | 11.25% | 11.25% | 100.00% | 105.00% | - | - | - | - | - | 100.00% | 0.00% | - | - | - | - | 100.00% | - | - | 0.00% |
| Effective Range vs. IFVs | 0.00% | 11.25% | 11.25% | 100.00% | 105.00% | - | - | - | - | - | 100.00% | 0.00% | - | - | - | - | 100.00% | - | - | 0.00% |
| Effective Range vs. Light Armor | 0.00% | 22.50% | 22.50% | 155.00% | 165.00% | - | - | - | - | - | 155.00% | 0.00% | - | 155.00% | - | 155.00% | 155.00% | - | - | 0.00% |
| Effective Range vs. Personnel (point target) | 100.00% | 25.71% | 0.00% | 14.29% | 14.29% | - | - | - | - | - | 0.00% | 0.00% | - | 0.00% | - | 0.00% | 0.00% | - | - | 0.00% |
| Effective Range vs. Personnel (area target) | 97.14% | 32.00% | 0.00% | 16.00% | 16.00% | - | - | - | - | - | 0.00% | 0.00% | - | 0.00% | - | 0.00% | 0.00% | - | - | 0.00% |
| Efficiency vs. ADA site | - | - | - | - | - | 0.00% | 0.00% | - | - | - | - | - | - | - | 0.00% | - | - | - | - | - |
| Efficiency vs. Artillery platoon | - | - | - | - | - | 0.00% | 0.00% | - | - | - | - | - | - | - | 0.00% | - | - | - | - | - |
| Efficiency vs. Mech platoon | - | - | - | - | - | 0.00% | 0.00% | - | - | - | - | - | - | - | 0.00% | - | - | - | - | - |
| Efficiency vs. MRL | - | - | - | - | - | 0.00% | 0.00% | - | - | - | - | - | - | - | 0.00% | - | - | - | - | - |
| Efficiency vs. Dismounted crew | - | - | - | - | - | 0.00% | 0.00% | - | - | - | - | - | - | - | 0.00% | - | - | - | - | - |
| Transition from Firing to Moving | - | - | - | - | - | 0.00% | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Personnel Carry | - | 33.33% | 0.00% | 42.86% | 50.00% | - | - | 42.86% | - | 114.29% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | - | 0.00% | 0.00% |
| Litter Carry | - | - | - | - | - | - | - | - | 0.00% | - | - | - | - | - | - | - | - | 0.00% | - | - |
| Max Speed | 0.00% | 2.00% | 2.00% | 54.00% | 54.00% | 2.00% | 54.00% | 58.00% | 58.00% | 54.00% | 8.00% | 8.00% | 8.00% | 8.00% | 8.00% | 8.00% | 8.00% | 8.00% | 8.00% | 8.00% |
| Turning Diameter | 0.00% | 35.00% | 35.00% | 200.00% | 200.00% | 50.00% | 215.00% | 245.00% | 230.00% | 215.00% | 13.33% | 13.33% | 13.33% | 13.33% | 13.33% | 13.33% | 13.33% | 13.33% | 13.33% | 13.33% |
| Vehicle Width | 0.00% | 19.44% | 19.44% | 58.33% | 19.44% | 11.11% | 33.33% | 54.33% | 33.33% | 40.78% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Dash Speed | 0.00% | 54.52% | 66.67% | 77.33% | 72.00% | 40.00% | 66.00% | 58.67% | 66.67% | 86.67% | 14.00% | 13.00% | 12.00% | 14.00% | 15.00% | 13.00% | 10.00% | 10.00% | 12.00% | 14.00% |
| Cruising Range | 0.40% | 22.84% | 57.87% | 91.51% | 77.33% | 17.29% | 48.62% | 103.33% | 92.13% | 70.80% | 101.89% | 101.00% | 106.44% | 116.73% | 102.59% | 102.68% | 100.96% | 99.08% | 110.60% | 100.22% |
| Operational Availability - Initial | 5.76% | 7.76% | 7.87% | 19.22% | 9.31% | 43.54% | 17.16% | 44.71% | 42.27% | 65.56% | 2.14% | 0.93% | 1.52% | 1.51% | 0.39% | 2.02% | 10.39% | 0.61% | 41.96% | 17.26% |
| Operational Availability - Worst Case | 10.44% | 12.33% | 12.91% | 28.89% | 14.60% | 57.58% | 24.86% | 59.38% | 55.82% | 86.89% | 3.59% | 0.79% | 5.40% | 1.05% | 1.26% | 4.50% | 15.08% | 1.85% | 47.10% | 22.42% |
| Sustainment Availability | 6.44% | 8.78% | 9.31% | 17.64% | 16.82% | 46.07% | 15.24% | 48.36% | 44.36% | 68.00% | 2.57% | 1.52% | 2.12% | 1.52% | 0.83% | 3.07% | 11.42% | 0.91% | 44.26% | 18.62% |
| | **KEY:** | (-) Not assessed for the role | | 0% (no variability) | | < 25% | | 26%-49% | | 50%-100% | | > 100% | | | | | | | | |

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# APPENDIX D. QUALITATIVE ATTRIBUTES–PERCENTAGE ALTERNATIVE SCORES BY BIN

The model has six qualitative attributes that are characterized by using a scale constructed with discrete scale increments in nonoverlapping bins. The tables below show the percent alternative scores by bin. For example, in the first table for the CBRN Operation attribute in the HBCT role, 86% of the alternatives score in bin 2 (Mask with threat-specific filter system) and 14% in bin 3 (Contains over pressure systems to protect against CBRN threats), no alternatives score in bin 1. For the SBCT role, 100% of the alternatives score in bin 2.

| **CBRN Operation** | **Percent** | |
|---|---|---|
| | **HBCT** | **SBCT** |
| None | - | - |
| Mask with threat-specific filter system | 86% | 100% |
| Contains over pressure systems to protect against CBRN threats | 14% | - |

| **Information Systems Growth** | **Percent** | |
|---|---|---|
| | **HBCT** | **SBCT** |
| None | - | - |
| HMS Suite | 57% | 55% |
| GMR Suite | 17% | 30% |
| WIN-T | - | - |
| Support Combination of Radio Suites | 26% | 15% |

| **Missile Capability** | **Percent** | |
|---|---|---|
| | **HBCT** | **SBCT** |
| None | 3% | 75% |
| TOW | 14% | 10% |
| TOW-RF | 59% | - |
| Fire and Forget | 24% | 15% |
| Multiple Fire and Forget | - | - |

| Soft Soil Mobility | Percent | |
|---|---|---|
| | HBCT | SBCT |
| Bin 1 | 4% | - |
| Bin 2 | 12% | 40% |
| Bin 3 | 13% | 60% |
| Bin 4 | - | - |
| Bin 5 | - | - |
| Bin 6 | 9% | - |
| Bin 7 | 7% | - |
| Bin 8 | 33% | - |
| Bin 9 | 7% | - |
| Bin 10 | 14% | - |

| Static Stability Factor | Percent | |
|---|---|---|
| | HBCT | SBCT |
| Bin 1 | 6% | - |
| Bin 2 | 81% | 100% |
| Bin 3 | 9% | - |
| Bin 4 | 4% | - |
| Bin 5 | - | - |

| Air Transportation | Percent | |
|---|---|---|
| | HBCT | SBCT |
| C-5 | 7% | - |
| C-17 | 68% | 50% |
| C-130 | 25% | 50% |

Legend: A dash (-) in the table indicates not applicable.

# APPENDIX E. PIVOT TABLES

The pivot tables below show the excursions we ran for each of the six funding profiles: $1.0B, $1.25B, $1.5B, $1.75B, $2.0B, and $2.6B. Our intent for running these excursions was: (1) to determine where reduced budget levels forced significant changes in alternative selection; and (2) to establish a baseline for further excursions by changing other parameters at a given funding profile of interest. Detailed discussions of these tables are referenced in the body of the report.

**Baseline excursion at $1.0B**

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 1 |
| Change | Baseline |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | Grand Total |
| **M2A3 OIF** | **216** | **360** | **288** | **144** | **72** | **72** | **72** | **72** | **144** | **144** | **144** | | | | | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 288 | 144 | 72 | 72 | 72 | 72 | 144 | 144 | 144 | | | | | | | | | | | | 1728 |
| **M1 ECP** | | | | | | | | | | | | | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **700** |
| AMOD | | | | | | | | | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 700 |
| **M3A3 CAV OIF** | **102** | **170** | **136** | **68** | **68** | **68** | **68** | **68** | **34** | **34** | | | | | | | | | | | | | **816** |
| M3A3 CAV ECP | 102 | 170 | 136 | 68 | 68 | 68 | 68 | 68 | 34 | 34 | | | | | | | | | | | | | 816 |
| **M1A2 SEP TUSK** | **140** | **70** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **70** | | | | | | | | | | **1680** |
| M1 ECP | 140 | 70 | 140 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | | 1120 |
| AMOD | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | | | 560 |

**Baseline excursion at $1.25B**

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 1.25 |
| Change | Baseline |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | Grand Total |
| **M2A3 OIF** | **216** | **360** | **288** | **144** | **144** | **216** | **72** | **72** | **72** | **72** | **72** | | | | | | | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 288 | 144 | 144 | 144 | | | | | | | | | | | | | | | | | | | 1296 |
| BMOD IFV | | | | | | 72 | 72 | 72 | 72 | 72 | 72 | | | | | | | | | | | | | | 432 |
| **M2A3 ECP** | | | | | | | | | | | | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **144** | **144** | **144** | **144** | **144** | **72** | **1296** |
| BMOD IFV | | | | | | | | | | | | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 144 | 144 | 144 | 144 | 144 | 72 | 1296 |
| **M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **102** | **68** | **34** | **34** | **68** | | | | | | | | | | | | | | | | **816** |
| BMOD CAV | | | | | 68 | 34 | 34 | 34 | 68 | | | | | | | | | | | | | | | | 238 |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 34 | 34 | | | | | | | | | | | | | | | | | | | 578 |
| **M3A3 CAV ECP** | | | | | | | | | | **68** | | | | | | | | | | | | | | | **68** |
| BMOD CAV | | | | | | | | | | 68 | | | | | | | | | | | | | | | 68 |
| **M1A2 SEP TUSK** | **140** | **70** | **140** | **140** | **140** | **70** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | | | | | | | **1680** |
| M1 ECP | 140 | 70 | 140 | 140 | 140 | 70 | 140 | 140 | 70 | 70 | | | | | | | | | | | | | | | 1120 |
| AMOD | | | | | | | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | 560 |

## Excursions at $1.5B

## Baseline excursion at $1.5B

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 1.5 |
| Change | Baseline |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Row Labels** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** | **25** | **26** | **27** | **28** | **Grand Total** |
| **M2A3 OIF** | **216** | **360** | **360** | **144** | **216** | **216** | **72** | **72** | **72** | | | | | | | | | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 360 | 144 | 144 | 144 | | | | | | | | | | | | | | | | | | | 1368 |
| BMOD IFV | | | | | 72 | 72 | 72 | 72 | 72 | | | | | | | | | | | | | | | | 360 |
| **M2A3 ECP** | | | | | | | | | | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **144** | **144** | **144** | **144** | **144** | **72** | **72** | | **1368** |
| BMOD IFV | | | | | | | | | | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 144 | 144 | 144 | 144 | 144 | 72 | 72 | | 1368 |
| **M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **68** | **102** | **68** | **68** | | | | | | | | | | | | | | | | | **816** |
| BMOD CAV | | | | | 34 | 34 | 68 | 68 | | | | | | | | | | | | | | | | | 204 |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 34 | 68 | | | | | | | | | | | | | | | | | | | 612 |
| **M3A3 CAV ECP** | | | | | | | | | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **68** | **68** | **34** | **612** |
| **M1A2 SEP TUSK** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | | | | | | | | | **1680** |
| M1 ECP | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | | | | | | | | | | | | | | | | | 1120 |
| AMOD | | | | | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | 560 |

## Excursion at $1.5B, without RDTE cost considered

## The GVC alternative is only funded if RDTE costs are not considered

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 1.5 |
| Change | NoRDTECosts |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Row Labels** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** | **25** | **26** | **27** | **28** | **Grand Total** |
| **M2A3 OIF** | **216** | **360** | **144** | **144** | **144** | **144** | **144** | **144** | **72** | **72** | **72** | **72** | | | | | | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 72 | 72 | 72 | 72 | 72 | 72 | | | | | | | | | | | | | | | | | 1008 |
| GCV | | | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | | | | | | | | | | | | | 720 |
| **M2A3 ECP** | | | | | | | | | | | | | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **144** | **144** | **72** | **72** | **1008** |
| GCV | | | | | | | | | | | | | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | | | | | 576 |
| BMOD IFV | | | | | | | | | | | | | | | | | | | | | 144 | 144 | 72 | 72 | 432 |
| **M3A3 CAV OIF** | **102** | **170** | **68** | **68** | **68** | **68** | **68** | **68** | **34** | **34** | **34** | **34** | | | | | | | | | | | | | **816** |
| M3A3 CAV ECP | 102 | 170 | 68 | 68 | 68 | 68 | 68 | 68 | 34 | 34 | 34 | 34 | | | | | | | | | | | | | 816 |
| **M3A3 CAV ECP** | | | | | | | | | | | | | | | | | **68** | **68** | **68** | **68** | **34** | **34** | **68** | **68** | **476** |
| **M1A2 SEP TUSK** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | | | | | | | | | **1680** |
| M1 ECP | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | | | | | | | | | | | | | | | | | 1120 |
| AMOD | | | | | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | 560 |

The two tables for Excursions at $1.5B below examine how changes in the upper-bound of the number of M2A3 ECP vehicles that may be purchased in one period affects the solution. The first table shows a case where the M2A3 ECP fielding is limited to two BDEs for the first three periods. The second table removes the BDE limit for M2A3 ECP fielding.

## Excursions at $1.5B, upper-bound for M2A3 ECP vehicles fielding 2BDE Limit

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 1.5 |
| Change | 2BDE Limit |

| Sum of FieldedCount / Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **M2A3 OIF** | **144** | **144** | **144** | **144** | **216** | **216** | **216** | **216** | **72** | **144** | **72** | | | | | | | | | | | | | **1728** |
| M2A3 ECP | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | | | | | | | | | | | | | | | | 1152 |
| BMOD IFV | | | | | 72 | 72 | 72 | 72 | 72 | 144 | 72 | | | | | | | | | | | | | 576 |
| **M2A3 ECP** | | | | | | | | | | | | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **144** | **144** | **144** | **144** | **72** | **1152** |
| BMOD IFV | | | | | | | | | | | | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 144 | 144 | 144 | 144 | 72 | 1152 |
| **M3A3 CAV OIF** | **102** | **102** | **102** | **68** | **68** | **102** | **136** | **136** | | | | | | | | | | | | | | | | **816** |
| BMOD CAV | | | | | 34 | 68 | 68 | 68 | | | | | | | | | | | | | | | | 238 |
| M3A3 CAV ECP | 102 | 102 | 102 | 68 | 34 | 34 | 68 | 68 | | | | | | | | | | | | | | | | 578 |
| **M3A3 CAV ECP** | | | | | | | | | **68** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **34** | **68** | **578** |
| **M1A2 SEP TUSK** | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | | | | | | **1680** |
| M1 ECP | 140 | 140 | 140 | 140 | 140 | 70 | 70 | 70 | 140 | 70 | | | | | | | | | | | | | | 1120 |
| AMOD | | | | | | | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | 560 |

## Excursions at $1.5B, upper-bound for M2A3 ECP vehicles fielding No Limit

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 1.5 |
| Change | No BDE Limit |

| Sum of FieldedCount / Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **M2A3 OIF** | **360** | **360** | **360** | **360** | **72** | **72** | **72** | **72** | | | | | | | | | | | | | | | | **1728** |
| M2A3 ECP | 360 | 360 | 360 | 360 | | | | | | | | | | | | | | | | | | | | 1440 |
| BMOD IFV | | | | | 72 | 72 | 72 | 72 | | | | | | | | | | | | | | | | 288 |
| **M2A3 ECP** | | | | | | | | | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **144** | **144** | **144** | **144** | **144** | **72** | **1440** |
| BMOD IFV | | | | | | | | | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 144 | 144 | 144 | 144 | 144 | 72 | 1440 |
| **M3A3 CAV OIF** | **170** | **170** | **170** | **170** | **68** | **68** | | | | | | | | | | | | | | | | | | **816** |
| M3A3 CAV ECP | 170 | 170 | 170 | 170 | 68 | 68 | | | | | | | | | | | | | | | | | | 816 |
| **M3A3 CAV ECP** | | | | | | | | | | | | | **136** | **136** | **136** | **136** | **136** | **34** | **34** | **34** | **34** | | | **816** |
| **M1A2 SEP TUSK** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | | | | | | | | | | | | **1680** |
| M1 ECP | 140 | 140 | 140 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | | | | 1120 |
| AMOD | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | | | | 560 |

## Baseline excursion at $1.75B

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 1.75 |
| Change | Baseline |

| Sum of FieldedCount / Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **M2A3 OIF** | **216** | **360** | **360** | **144** | **216** | **216** | **144** | **72** | | | | | | | | | | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 360 | 144 | 144 | 144 | | | | | | | | | | | | | | | | | | | 1368 |
| BMOD IFV | | | | | 72 | 72 | 144 | 72 | | | | | | | | | | | | | | | | | 360 |
| **M2A3 ECP** | | | | | | | | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **72** | **144** | **144** | **144** | **144** | **72** | | | **1368** |
| BMOD IFV | | | | | | | | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 144 | 144 | 144 | 144 | 72 | | | 1368 |
| **M1 ECP** | | | | | | | | | | | | | | | | | **70** | **70** | **70** | **70** | **70** | **140** | **140** | **70** | **700** |
| AMOD | | | | | | | | | | | | | | | | | 70 | 70 | 70 | 70 | 70 | 140 | 140 | 70 | 700 |
| **M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **102** | **136** | **34** | **34** | | | | | | | | | | | | | | | | | **816** |
| BMOD CAV | | | | | 68 | 68 | 34 | 34 | | | | | | | | | | | | | | | | | 204 |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 34 | 68 | | | | | | | | | | | | | | | | | | | 612 |
| **M3A3 CAV ECP** | | | | | | | | | **68** | **68** | **68** | **68** | **68** | **68** | **68** | **68** | **68** | | | | | | | | **612** |
| **M1A2 SEP TUSK** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | | | | | | | | | **1680** |
| M1 ECP | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | | | | | | | | | | | | | | | | | 1120 |
| AMOD | | | | | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | 560 |

## Excursions at $2.0B
## Baseline excursion for the $2.0B funding profile

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 2 |
| Change | Baseline |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Row Labels** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **Grand Total** |
| **M2A3 OIF** | **216** | **360** | **144** | **216** | **216** | **216** | **144** | **144** | **72** | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 72 | 144 | 144 | 144 | | | | | | | | | | | 1080 |
| GCV | | | 72 | 72 | 72 | 72 | 144 | 144 | 72 | | | | | | | | 648 |
| **M2A3 ECP** | | | | | | | | | **72** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **1080** |
| GCV | | | | | | | | | 72 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 1080 |
| **M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **68** | **68** | | | | | | | | | | | **646** |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 68 | 68 | | | | | | | | | | | 646 |
| **M1A2 SEP TUSK** | | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | | | | | **1120** |
| M1 ECP | | 140 | 140 | 140 | 140 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | 1120 |

**Excursions at $2.0B, increase 10% for given alternative**

The three tables below illustrate how a 10% increase in value for a given alternative in one role may affect the alternative in another role. In the first table, AMOD is increased by 10%, followed by M1ECP in the second table and M2AECP in the third table.

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 2 |
| Change | +10%AMOD |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Grand Total |
| **M2A3 OIF** | **216** | **360** | **144** | **216** | **216** | **216** | **144** | **144** | **72** | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 72 | 144 | 144 | 144 | | | | | | | | | | | 1080 |
| GCV | | | 72 | 72 | 72 | 72 | 144 | 144 | 72 | | | | | | | | 648 |
| **M2A3 ECP** | | | | | | | | | **72** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **1080** |
| GCV | | | | | | | | | 72 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 1080 |
| **M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **68** | **68** | | | | | | | | | | | **646** |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 68 | 68 | | | | | | | | | | | 646 |
| **M1A2 SEP TUSK** | | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | | | | | **1120** |
| M1 ECP | | 140 | 140 | 140 | 140 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | 1120 |

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 2 |
| Change | +10%M1ECP |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Grand Total |
| **M2A3 OIF** | **216** | **360** | **144** | **216** | **216** | **216** | **144** | **144** | **72** | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 72 | 144 | 144 | 144 | | | | | | | | | | | 1080 |
| GCV | | | 72 | 72 | 72 | 72 | 144 | 144 | 72 | | | | | | | | 648 |
| **M2A3 ECP** | | | | | | | | | **72** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **1080** |
| GCV | | | | | | | | | 72 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 1080 |
| **M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **68** | **68** | | | | | | | | | | | **646** |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 68 | 68 | | | | | | | | | | | 646 |
| **M1A2 SEP TUSK** | | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | | | | | **1120** |
| M1 ECP | | 140 | 140 | 140 | 140 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | 1120 |

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 2 |
| Change | +10%M2A2ECP |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Grand Total |
| **M2A3 OIF** | **216** | **360** | **288** | **216** | **216** | **216** | **144** | **72** | | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 216 | 144 | 144 | 144 | | | | | | | | | | | 1224 |
| GCV | | | 72 | 72 | 72 | 72 | 144 | 72 | | | | | | | | | 504 |
| **M2A3 ECP** | | | | | | | | **72** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **1224** |
| GCV | | | | | | | | 72 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 1224 |
| **M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **68** | **68** | | | | | | | | | | | **646** |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 68 | 68 | | | | | | | | | | | 646 |
| **M1A2 SEP TUSK** | | **140** | **70** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | **70** | | | | **1120** |
| M1 ECP | | 140 | 70 | 140 | 140 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | 1120 |

**Excursions at $2.0B, increase 10% for all alternatives in MBT role**

In this excursion, we increase all alternatives contained within the MBT role by 10%.

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 2 |
| Change | +10%Mission7 |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Grand Total |
| **M2A3 OIF** | **216** | **360** | **144** | **216** | **216** | **216** | **144** | **144** | **72** | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 72 | 144 | 144 | 144 | | | | | | | | | | | 1080 |
| GCV | | | 72 | 72 | 72 | 72 | 144 | 144 | 72 | | | | | | | | 648 |
| **M2A3 ECP** | | | | | | | | | **72** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **1080** |
| GCV | | | | | | | | | 72 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 1080 |
| **M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **68** | **68** | | | | | | | | | | | **646** |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 68 | 68 | | | | | | | | | | | 646 |
| **M1A2 SEP TUSK** | | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **70** | | | | | **1120** |
| M1 ECP | | 140 | 140 | 140 | 140 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | 1120 |

**Excursions at $2.0B, changes in upper-bound of M2A3 ECP vehicles**

The two tables for Excursions at $2.0B below examine how changes in the upper-bound of the number of M2A3 ECP vehicles that may be purchased in one period affects the solution. The first table shows a case where the M2A3 ECP fielding is limited to two BDEs for the first three periods. The second table removes the BDE limit for M2A3 ECP fielding.

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 2 |
| Change | 2BDE Limit |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | Grand Total |
| **M2A3 OIF** | **144** | **144** | **144** | **216** | **216** | **216** | **216** | **216** | **216** | | | | | | | | | | | **1728** |
| M2A3 ECP | 144 | 144 | 72 | 144 | 144 | 144 | 144 | 144 | 144 | | | | | | | | | | | 1224 |
| GCV | | | 72 | 72 | 72 | 72 | 72 | 72 | 72 | | | | | | | | | | | 504 |
| **M2A3 ECP** | | | | | | | | | | **72** | **72** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **72** | **1224** |
| GCV | | | | | | | | | | 72 | 72 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 72 | 1224 |
| **M3A3 CAV OIF** | **102** | **102** | **102** | **68** | **34** | **68** | **68** | **68** | **68** | **68** | **68** | | | | | | | | | **816** |
| M3A3 CAV ECP | 102 | 102 | 102 | 68 | 34 | 68 | 68 | 68 | 68 | 68 | 68 | | | | | | | | | 816 |
| **M1A2 SEP TUSK** | | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | | | | | | **1610** |
| M1 ECP | | 140 | 140 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | 1120 |
| AMOD | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | 490 |

| | |
|---|---|
| MissionID | (All) |
| FundingProfile | 2 |
| Change | No BDE Limit |

| Sum of FieldedCount | Column Labels | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row Labels | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | Grand Total |
| **M2A3 OIF** | | **288** | **288** | **360** | **216** | **216** | **216** | **144** | | | | | | | | | | | **1728** |
| M2A3 ECP | | 288 | 216 | 288 | 144 | 144 | 144 | 72 | | | | | | | | | | | 1296 |
| GCV | | | 72 | 72 | 72 | 72 | 72 | 72 | | | | | | | | | | | 432 |
| **M2A3 ECP** | | | | | | | | | **72** | **72** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **144** | **1296** |
| GCV | | | | | | | | | 72 | 72 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 1296 |
| **M3A3 CAV OIF** | **102** | **170** | **170** | **68** | **34** | **68** | **68** | **68** | **68** | | | | | | | | | | **816** |
| M3A3 CAV ECP | 102 | 170 | 170 | 68 | 34 | 68 | 68 | 68 | 68 | | | | | | | | | | 816 |
| **M1A2 SEP TUSK** | **70** | **140** | **70** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | | | | | **1540** |
| M1 ECP | 70 | 140 | 70 | 140 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | | | | | 1120 |
| AMOD | | | | | 70 | 70 | 70 | 70 | 70 | 70 | | | | | | | | | 420 |

## Baseline excursions at $2.6B

| | |
|---|---|
| MissionID | (All) |
| undingProfil | 2.6 |
| Change | Baseline |

| f FieldedCou | Column Lab | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row Labe | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | Grand Total |
| **M2A3 OIF** | **216** | **360** | **360** | **216** | **216** | **144** | **144** | **72** | | | | | | | | | | | | | | | | **1728** |
| M2A3 ECP | 216 | 360 | 288 | 144 | 72 | | | | | | | | | | | | | | | | | | | 1080 |
| GCV | | | 72 | 72 | 144 | 144 | 144 | 72 | | | | | | | | | | | | | | | | 648 |
| **M2A3 ECP** | | | | | | | | **72** | **144** | **144** | **144** | **144** | **144** | **72** | **72** | **72** | **72** | | | | | | | **1080** |
| GCV | | | | | | | | 72 | 144 | 144 | 144 | 144 | 144 | 72 | 72 | 72 | 72 | | | | | | | 1080 |
| **M1 ECP** | | | | | | | | | | | | | | | | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **1120** |
| AMOD | | | | | | | | | | | | | | | | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 1120 |
| **M3A3 CAV** | **102** | **170** | **170** | **68** | **68** | **34** | **34** | **34** | **68** | **34** | **34** | | | | | | | | | | | | | **816** |
| BMOD CAV | | | | | | 34 | 34 | 34 | 68 | 34 | 34 | | | | | | | | | | | | | 238 |
| M3A3 CAV | 102 | 170 | 170 | 68 | 68 | | | | | | | | | | | | | | | | | | | 578 |
| **M3A3 CAV ECP** | | | | | | | | | | | | **34** | **34** | **68** | **68** | **68** | **68** | **68** | **68** | **68** | **34** | | | **578** |
| **M1A2 SEP** | **70** | **140** | **140** | **140** | **140** | **140** | **140** | **140** | **70** | **70** | **70** | **70** | **70** | **140** | **140** | | | | | | | | | **1680** |
| M1 ECP | 70 | 140 | 140 | 140 | 140 | 140 | 140 | 140 | 70 | | | | | | | | | | | | | | | 1120 |
| AMOD | | | | | | | | | | 70 | 70 | 70 | 70 | 140 | 140 | | | | | | | | | 560 |

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# APPENDIX F. PROGRAM EXECUTIVE OFFICE (PEO) ANALYSIS TEAM RESPONSE TO FINAL DRAFT

Below are the relevant comments received from the sponsor in support of CPAT.

1. As part of our CPAT FY12 data refresh, the PEO analysis team is re-evaluating the measures to address the concern presented on page 2 regarding ineffective value measures.
2. CPAT limitations taken from previous PEO documents stated that the team should have conducted two additional panels. The later response from the PEO analysis team was that one panel was enough as long as it was the right group.
3. The PEO analysis team initially interpreted “trade-offs” mentioned in the document to mean the force structure input by TRADOC. Further discussion clarified that trade-offs in this document refer to the swing weights, specifically how the 20 performance models are weighted against each other by the optimization model.
4. The PEO analysis team is making adjustments to the value hierarchy that will result in a revaluation and reweighting of attributes.
5. The PEO analysis team identified an error in our initial value function sensitivity analysis. The corrected analysis has been incorporated in this document.
6. The PEO is working with AMSAA as part of the FY12 data refresh to refine specific value functions.
7. Value function scale much larger than existing data because the PEO wants flexibility to measure future systems with the same model. We propose that it is better to have “tighter” scale when possible. If the scale needs to be expanded in the future, then do so. Then to compare with past results, just run old alternatives in the new model.
8. NPS and the PEO analysis team discussed the optimization formulation in a meeting subsequent to the review of the final draft of this document. Most issues or confusion over how the formulation is implemented were resolved during this meeting. However, several are left unresolved. For example, we disagree with how the elastic constraints are used but this should not impact the execution of the model in practice as they are not used by the PEO analysis team.
9. Many of the most significant findings of this V&V are discussed in the implementation review. Most of the recommendations are accepted by the PEO analysis team and they plan to implement these recommendations in later versions of CPAT.

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