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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

U.S. ARMY TACTICAL WHEELED VEHICLES
MODERNIZATION STRATEGY:
AN OPTIMIZATION MODEL

by

Roy Goh Choo Seng

December 2007

Thesis Advisor:	D. Nussbaum, Prof
Second Reader:	David Holm

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**U.S. ARMY TACTICAL WHEELED VEHICLES
MODERNIZATION STRATEGY:
AN OPTIMIZATION MODEL**

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This thesis addresses the issue of optimal budget allocation in the modernization of the U.S. Army's Light Tactical Wheeled Vehicles (LTWV). To achieve the objective for this research, a decision optimization tool was requested by the U.S. Tank-Automotive and Armaments Life Cycle Management Command (TACOM LCMC) and Program Executive Office, Combat Support / Combat Service Support (PEO CS/CSS) to provide an analytical tool to serve as the underpinning for modernization strategies for the LTWV over the next fifteen fiscal years.

The optimization tool was implemented in Excel, using Excel Premium Solver Platform as the solver engine. An initial analysis was done to demonstrate the validity of the model, using notional data and the weighted values from the Value Model. Sensitivity analyses were also performed on the model by varying the inputs, such as the budgetary and average age requirements, to look at the capabilities that can be provided during the modernization period.

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EXECUTIVE SUMMARY

This thesis looks into the various challenges and issues that arise when developing a modernization strategy for the U.S. Army's Light Tactical Wheeled Vehicles (LTWV). The scope for this thesis involves the development, implementation and analysis of a decision optimization tool that seeks to find a modernization strategy that satisfies constraints such as budget, operational and age requirements. The input parameters in the decision tool are designed to be configurable so that users can observe the outcome effects by varying the input parameters. The goal is to enable the decision tool users to gain insights into potential future modernization strategies for the LTWV fleet and to support policy makers in making decisions about the future of the LTWV fleet.

Light tactical mobility is currently provided by the High-Mobility Multi-purpose Wheeled Vehicle (HMMWV). The HMMWV has been the cornerstone of the light tactical mobility mission over the past 20 years and has performed admirably in various roles. Unfortunately, the HMMWV has become less survivable in the modern operational environment, and may not adequately meet operational requirements of future warfighting concepts. HMMWVs in the current Iraq conflict have undergone many modifications to make them more survivable in the non-contiguous warfare environment. Unfortunately, increases in armor protection have exacerbated capability gaps in other areas such as mobility, reliability and operational flexibility. Compounding the increased operational demands on the LTWV fleet is that the LTWV fleet is an already aged fleet. Currently, the average age of the fleet is greater than the designed lifespan of any given vehicle. As the vehicles reach the end of the useful life, more frequent breakdowns are seen which disable the vehicles from completing their missions and thus, increase Operations & Support (O&S) costs.

Asymmetric warfare practiced by insurgents and terrorists places an increased demand on the LTWV to serve as a robust combat vehicle. The LTWV fleet has been put in roles to support current operations that it was never designed for which has created increased operational requirements in the areas of force protection, mobility, reliability,

payload and maintainability. These increased requirements have stretched the design limitations of the current LTWV fleet. The current LTWV fleet simply lacks the performance capabilities to serve in this dynamic combat role. The Army sees the need to employ a new vehicle to meet the increased operational demands of the 21st Century. The Army is currently designing such a vehicle, the Joint Light Tactical Vehicle (JLTV).

The Army requires that the JLTV perform sufficiently in every area in which the High Mobility Multipurpose Wheeled Vehicle (HMMWV, or Humvee) falls short. Eventually, the JLTV will replace the HMMWV and become the new LTWV. The JLTV will assume every mission responsibility that the HMMWV currently holds, including the role of a robust combat vehicle capable of responding to insurgents' style of asymmetric warfare. The Army plans to begin integrating the JLTV as early as 2013, and will continue JLTV integration until every HMMWV is retired from service. Because the JLTV cannot immediately be implemented, there still exists the problem of the ever-aging HMMWV fleet. To solve this, the Army has implemented a policy called the Recapitalization Program (or "recapping"), which converts aged combat HMMWV variants into a new more robust variant.

Over time, as the JLTV is integrated, the LTWV fleet will be comprised of a mixture of HMMWVs and JLTVs. Each year a number of HMMWVs will undergo "recapping", be retired and a number of new HMMWVs will be procured to help fill the HMMWV requirements for Grow The Army until JLTV can begin production. Therefore, the composition of the LTWV fleet will change every year. TACOM LCMC and the PEO CS/CSS have requested a decision tool that models this process in hopes of gaining insight into potential modernization strategies.

The decision optimization tool will be a linear program in Excel that solves multi-objective optimization problems. This tool is based on the LTWV LP model that was formulated by Professor Dell Robert. The linear program also ensures that all solutions meet the various budgetary and operational constraints of the Armed Forces. This thesis contributes to the development of the linear program in Excel as well as a base analysis to provide a conceptual framework, inviting further analysis, updating and application.

The optimization tool is constructed using the concept of goal programming that make use of nonnegative deficiency variables to model the extent of goal violations that need not be rigidly enforced. The objective function will be to minimize all the weighted sums of the deficiency variables in order to satisfy all the goals as closely as possible.

This tool utilizes the weighted values from the value model that is part of Koerner and McDonald's (2007) thesis research topic. These weighted values represent the capabilities values that can be provided by each vehicle variant. The value model uses a hierarchical diagram, starting with overarching, qualitative attributes at the top that break down into specific quantitative measures at the bottom. The updated value hierarchical diagram can be seen in the below figure:
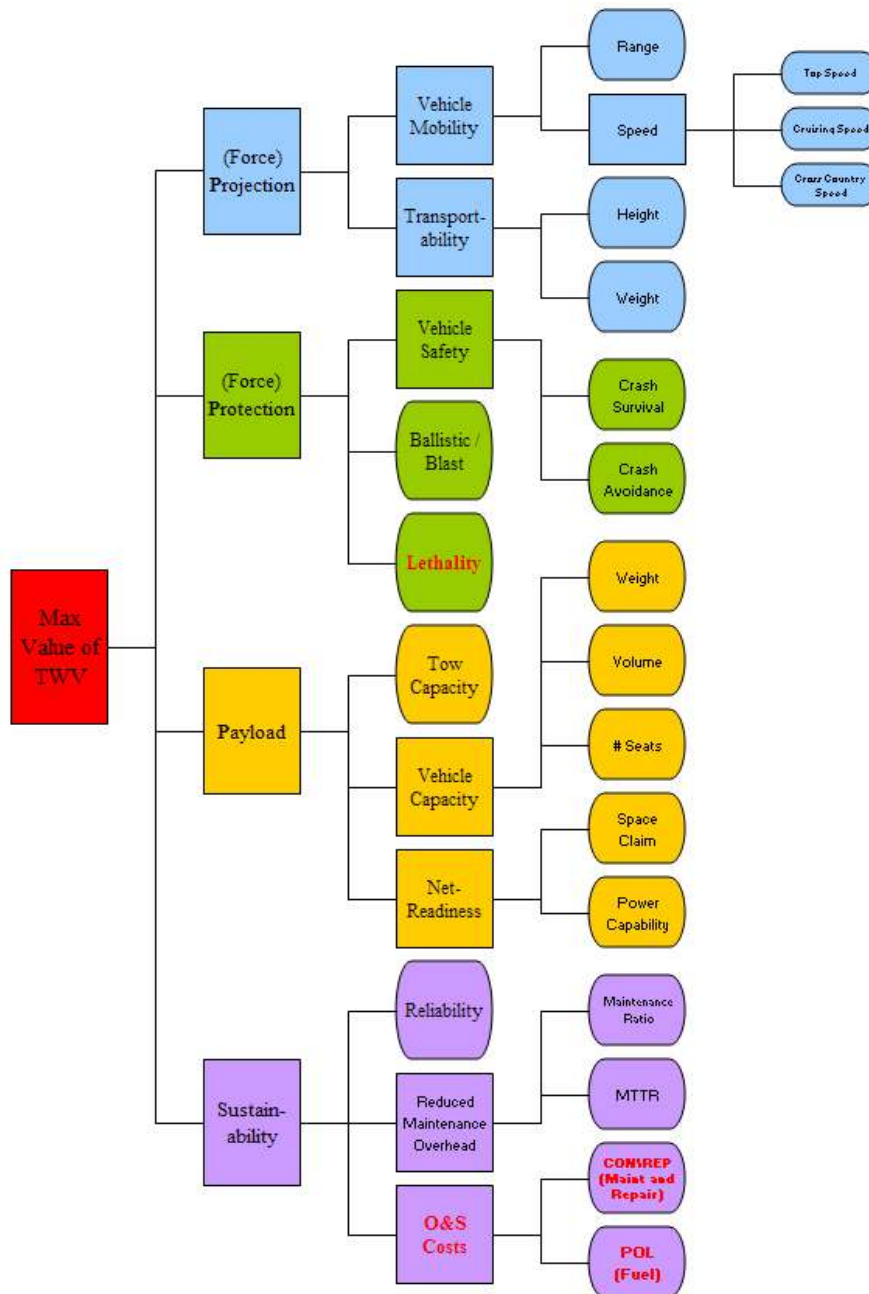
The Value Hierarchy

The Excel implementation for this decision optimization tool provides a GUI that allows TACOM users to configure the number of planning years and the number of vehicle variants that they are interested in. It also allows the users to plot their graphs easily from the optimization results. By adding these features to the tool, this research will provide non-trivial insights to the LTWV fleet modernization process.

ACKNOWLEDGMENTS

I like to thank my thesis advisor, Professor Daniel Nussbaum, for his time and guidance in assisting me to the completion of this research project. I also like to thank David Holm, my second reader, for spending time reading my thesis despite his busy schedule. Special thanks to LTC Lee Ewing and Professor Dell Robert for their help and advice to me on my project even though they are not my second readers. Also special thanks to Mr. Edward Lesnowicz for arranging and fixing my time slots with Professor Nussbaum every quarter.

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I.   INTRODUCTION

This thesis looks into the issue of optimal budget allocation in the modernization of the U.S. Army's Light Tactical Wheeled Vehicles (LTWV). The objective for this research is to create a decision optimization tool that the TACOM LCMC and Program Executive Office, Combat Support / Combat Service Support (PEO CS/CSS) can use to plan and support its modernization strategies for the next 15 fiscal years.

A.   PROBLEM STATEMENT

Tactical Wheeled Vehicles are non-tracked, wheeled vehicles, used for combat and support missions by the armed forces. For example, the High Mobility Multipurpose Wheeled Vehicle (HMMWV, or Humvee) is a Light TWV and comprises approximately 50% of the TWV fleet. Possible roles for a HMMWV include as a reconnaissance vehicle, an ambulance, a transportation vehicle or a combat vehicle.

This thesis focuses on the Light TWV portion of the greater TWV fleet. The LTWV fleet is aging at an accelerated rate and the current average age of the fleet is greater than the designed lifespan of any given vehicle. This aging of the LTWV fleet results in more frequent breakdowns, which prevent the vehicles from completing their missions and increase Operations & Support (O&S) costs. Additionally, the LTWV fleet struggles to meet the increased operational requirements in Iraq peacekeeping missions such as Operation Iraqi Freedom (OIF), thereby generating major shortcomings in the areas of force projection, force protection, payload and sustainability.

To meet the demanding mission requirements of the TWV, a newer, more robust Joint Light Tactical Vehicle (JLTV) is currently being developed and will eventually replace the current HMMWV as the Army's new LTWV. As part of a successful integration of the JLTV into the LTWV fleet, two challenges must be addressed and resolved. The first issue is that there is urgency for the transition to the JLTV. This urgency is driven by the fact that a majority of the LTWV fleet is already past its planned lifespan, and performance has been degraded for current missions. The second issue is

that the JLTV is in its design phase and therefore will not be available to replace the current fleet of HMMWVs any time soon.

While the JLTV is being developed, the Army is carrying out a series of maintenance works on some of the existing HMMWVs to increase their lifespan. The JLTVs will be gradually integrated into the LTWV fleet once they become available. The pace of implementing this plan must meet the operational readiness needs of the Army while staying within the allowed budget.

Below are the four options that the Army has adopted for fleet modernization:

- Buy New: Order a brand new HMMWV or JLTV to fill the demand for a particular vehicle type.

- Recapitalization (Recap): Upgrade an HMMWV to a more robust variant. The vehicle is unusable while being upgraded in the maintenance depot.

- Reset: Perform overhaul maintenance so that the vehicle is like new. While it is in the maintenance depot, the vehicle will be out of service for a portion of a year. Limitations must set to prevent too many vehicles from going out of service at any one time.

- Retire: Retire a HMMWV from service permanently. A new vehicle may replace a retiring vehicle. Currently, retirement rarely happens, as Army doctrine dictates that a vehicle should be repaired unless its repair costs exceed the cost to purchase a new vehicle. Only then will a vehicle be retired. As the JLTV is placed into service, a commensurate number of HMMWVs may be retired to reduce Operations & Support (O&S) costs.

Over the next several years, as the newer JLTVs are being phased in and the older HMMWVs are being phased out, the LTWV fleet is going to be made up of a mixture of the newer and older vehicles. Every year, funds will need to be allocated to either repair older existing vehicles or to purchase new vehicles.

This thesis investigates the optimal allocation of the LTWVs to meet budgetary, operational and age requirements.

It is the TACOM LCMC and PEO CS/CSS' responsibility to conduct the life cycle management activities to include planning the strategic future allocation of the LTWV fleet. TACOM LCMC and PEO CS/CSS have requested a decision tool that will aid in future planning and decision making processes. The decision tool has two components: a multiple objective decision analysis (MODA), which we refer to as the Value Model (VM), and a LTWV linear program (LP) that utilizes the results from the Value Model to find an optimal LTWV fleet modernization strategy. The results from using the decision tool will enable the TACOM users to gain insights into potential future modernization strategies for the LTWV fleet and to support policy makers in making decisions about the future of the LTWV fleet.

The Value Model has previously been addressed by two graduate students, Heather Koerner and Gordon McDonald, in their research thesis titled "A Conceptual Framework for the U.S. Army Tactical Wheeled Vehicle Optimization Model" (Koerner and McDonald, 2007). This current thesis builds upon their work and covers the design and development of this decision optimization tool as well as some conceptual analysis. The optimization model accepts budgetary and operational requirement constraint inputs for any given fiscal year, from which it develops and outputs the optimal configuration of the LTWV fleet. The input parameters in the decision tool are also designed to be configurable so that TACOM users can observe the outcome effects by varying the input parameters.

The decision optimization tool will be a linear program in Excel that minimizes the cost of procuring new vehicles and maintaining current vehicles while maximizing the overall value of the LTWV fleet. The linear program also ensures that all solutions meet the various budgetary and operational constraints of the Army and recommends how many and which type of vehicles to buy, recap, reset or retire.

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II. BACKGROUND

In 2004, U.S. Army leadership directed the development of an all-encompassing Tactical Wheeled Vehicle Strategy (Headquarters, Department of the Army, 2006). This development is a subset of the overall Army Modernization Strategy, defined in the 2006 Army Modernization Plan. The purpose of the strategy is to achieve the proper balance between the support of current operations and TWV fleets, Army Transformation, and the development of future fleet capabilities, while optimizing strategies for procurement, recapitalization and sustainment. This approach seeks to develop field combat-capable units through a) an approximate mix of significant organizational restructuring into modular units, b) insertion of new equipment (modernization), and c) ensuring readiness of current equipment (reset), including the rebuilding and upgrading of key existing equipment through recapitalization. The Light Tactical Vehicle Fleet Strategy is one of the Army's TWV modernization efforts to replace the aging HMMWV with a newer version of LTWV, the JLTV.

A. HIGH MOBILITY MULTI-PURPOSE WHEELED VEHICLE (HMMWV)

HMMWVs that underwent the upgrades or modifications in the transmissions and engines have their names postfix with "A1" or "A2", depending on the type of upgrades. The current HMMWV's mission statement is "to provide a light tactical wheeled vehicle for command and control, troop and light cargo transportation, special purpose shelter carrier, ambulance, towed weapons prime mover, and special weapons platform throughout all areas of the battlefield or mission area." (U.S. Army Training And Doctrine Command Tactical Wheeled Vehicle Modernization. Operational Requirements Document, ORD for the HMMWV, 2004)

The HMMWV vehicles have at least 11 variants. They consist of:

- M998 Cargo/Troop Carrier

- M1038 Cargo/Troop Carrier, with winch

- M1043 Armament Carrier

- M1044 Armament Carrier, with winch

- M1045 TOW Carrier

- M1046 TOW Carrier, with winch

- M997 Ambulance, basic armor 4-Litter

- M1035 Ambulance, 2-Litter

- M1037 Shelter Carrier

- M1042 Shelter Carrier, with winch

- M1097 Heavy HMMWV (payload of 4,400 pounds)

These variants basically fall into the following five categories: Cargo/Troop, Armament, TOW Missile, Ambulance and Shelter Carriers.
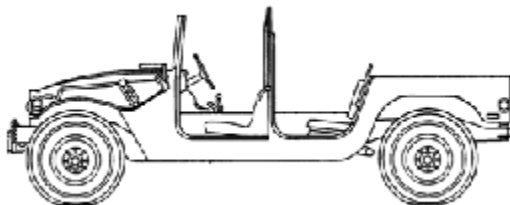
Figure 1.   Cargo/Troops Carrier Series [From 3]

The first version of the HMMWV is the M998. It is the baseline for the M998 series of 1 ¼ - ton trucks that are also known as the HMMWV vehicles. This light utility series consists of the M998, M998A1, M1038 and M1038A1 HMMWVs. The vehicles are equipped with basic armor and can be used for transportation of equipment and materials up to a payload of 2500 pounds or for the transportation of up to 10 personnel (two man crew and eight passengers).
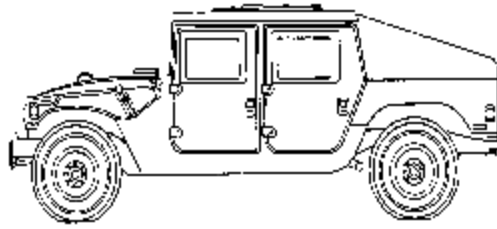
Figure 2.   Armament Carrier Series [From 3]

This series consists of armament carrier configurations of the HMMWV family: the M1043, M1043A1, M1044, and M1044A1 HMMWVs. These vehicles are equipped with supplemental armor. The weapon mount, located on the roof of the vehicle, is adaptable to mount either the M60, 7.62mm machine gun, the M2 .50 caliber machine gun, or the MK 19 Grenade Launcher.

M1045 AND M1045A1

Figure 3.   TOW Missile Carrier Series [From 3]

The M1045, M1045A1, M1046 and M1046A1 HMMWVs are TOW missile carrier configurations of the HMMWV family. This series is equipped with supplementary armor. A TOW launcher mounted on the roof of the vehicle is used in combat with other armored vehicles, and also provides added ballistic protection for TOW system components, crew and ammunition.
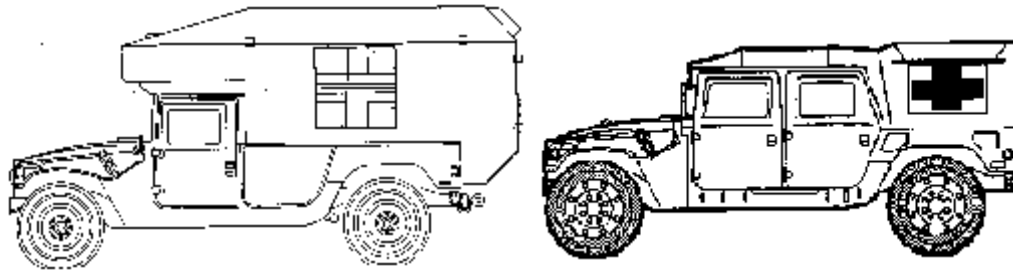
Figure 4.   Ambulance Series [From 3]

The M996, M996A1, M997, M997A1, M1035 and M1035A1 HMMWVs are the ambulance configuration of the HMMWV family. The vehicles are equipped with basic armor and are used to transport casualties from the battlefield to medical aid stations. The M997/M997A1 is designated as a Maxi-Ambulance and can transport more patients than the M996/M996A1 (Mini-Ambulance) and the M1035/M1035A1 (Soft-top Ambulance).
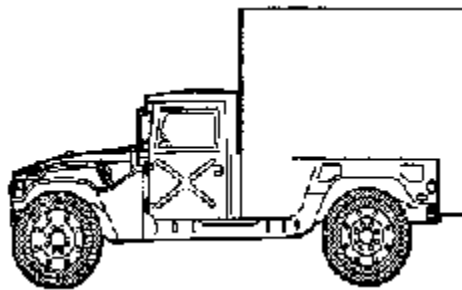
Figure 5.   Shelter Carrier Series [From 3]

The M1037 and M1042 HMMWVs belong to the shelter carrier configurations of the HMMWV family. The vehicles are equipped with basic armor and are used to secure and transport the electrical equipment shelter (S250) with a total payload (including crew) of 3,600 pounds.
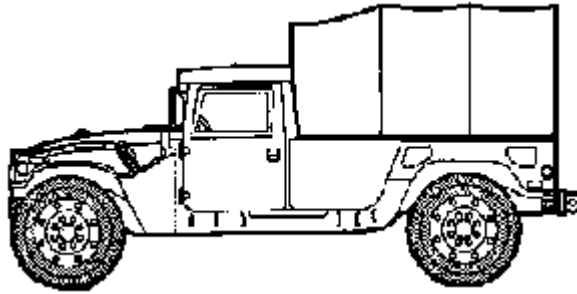
Figure 6.   Cargo/Troop Carrier (High Payload) Series [From 3]

This series consist of the M1097 and M1097A1 HMMWVs. They have the same functions as the Cargo/Troop Carrier series, except that they have a higher payload capacity of 4400 pounds. To accommodate the higher payload capacity, the vehicles are equipped with reinforced frames, cross members, lifting shackles, heavy duty rear springs, shock absorbers, reinforced control arms, heavy duty tires and rims, and a transfer case and differential with a modified gear ratio.
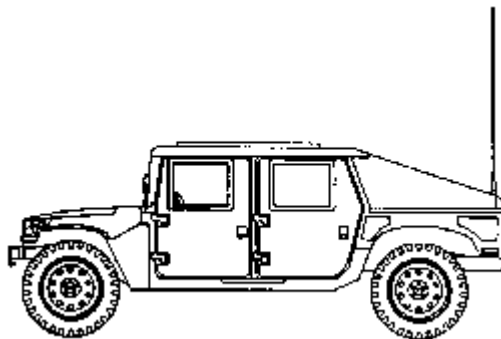
Figure 7.   Up-Armored Armament Carrier Series [From 3]

The M1109 and M1114 HMMWVs belong to the armament carrier configuration of the HMMWV family, but are equipped with additional armor both on the sides and underneath the vehicle to protect the crew from small arms ammunition and mines. Its primary function is to conduct reconnaissance and security operations. The weapon mount, located on the roof of the vehicle, is adaptable to mount either the M60, 7.62mm machine gun, the M2 .50 caliber machine gun, or the MK 19 Grenade Launcher.

The LTWV fleet, consisting mainly of the HMMWV family, represents roughly half of the entire Army TWV fleet. The HMMWV program also provides vehicles that

satisfy Marine Corps and Air Force requirements. Since its inception in the 1980s, the HMMWV family has been a revolutionary and useful series of platforms that has been widely used to complete a wide range of missions. But major weaknesses in these platforms have appeared in recent years.

The HMMWVs are aging and are no longer meeting the expectations. In the Global War of Terrorism, HMMWVs have been pushed beyond their operational thresholds and been used to conduct levels of combat that exceed the vehicles' designs. The basic armor kit on the HMMWV is only able to provide minimal protection for the crew against improvised bombs, rifle fire, rocket-propelled grenades and military-grade land mines. Those HMMWVs with up-armored kits are able to provide better protection against fire attack from the side, but the armor plates on the underbelly of the vehicle do little to protect the crew from mine blasts. The additional armor kit also increases the weight of the vehicle, resulting in decreased maneuverability and payload capacity.

In 2005, the projected lifespan of an average HMMWV was approximately 13 years (HMMWV Recapitalization, http://www.globalsecurity.org) but has since dropped to less than two years after deployment to Iraq. In additional to the shorter lifespan, the projected average age of the HMMWV fleet is going to be almost 17 years old in FY10, well above the designed service life of 15 years. This projected age in FY10 assumes that current funding levels are used to continue to procure new vehicles without recapitalizing the older HMMWVs.

The diminishing projected lifespan and the increasing average fleet age has resulted in more breakdowns and malfunctions, thus causing Operations and Support (O&S) costs to rise. In 2000, a program was developed to rebuild and upgrade the fleet of over 100,000 vehicles to address rapidly rising O&S costs. This program was aborted in 2001 as it was not cost efficient. A more cost effective program, the Recapitalization Program, was then introduced. This program rebuilds the older HMMWV variants into ones with armor-capability. It also reduces overall operations and support costs and increases the service life of the HMMWV fleet. The result of this focused recapitalization effort is a vehicle with a ten year extended service life that is like new in appearance and performance.

The Army Recapitalization Program is necessary in order to continue operating the HMMWVs. This program, however, is only a temporary solution to the ever-increasing age of the LTWV fleet. The trade-off between performance and force protection means the HMMWVs still cannot meet the current operation requirements. The U.S. Army still needs to look for a new type of vehicle with capabilities and force protection that can meet increasing operational needs.

B.   JOINT LIGHT TACTICAL VEHICLE (JLTV)

In early 2006, the U.S. Army and the Marine Corps began the process of developing a new LTWV to replace the aging HMMWVs, taking into consideration the total cost of ownership. The Joint Services developed requirements for the new tactical wheeled vehicle platform that would provide increased force protection, survivability and improved capabilities compared to the current up-armored HMMWV. This new LTWV, called the Joint Light Tactical Vehicle, or JLTV, must also be able to operate with high mobility and meet transportability requirements. The JLTV is shown in Figure 8.

Figure 8.   Joint Light Tactical Vehicle

Below are the five fleet performance needs that must be addressed by the new LTWV fleet.

- A six passenger vehicle to move mounted combat forces,

- A two to four passenger vehicle to move mounted combat support forces and which has the ability to support multiple combat support mission tasks,

- A two to four passenger vehicle to move mounted combat service support forces and which has the ability to support multiple combat service support mission tasks,

- A two crew plus nine passenger or two crew with added shelter vehicle to move light (airborne/air assault) forces,

- A four passenger reconnaissance vehicle to move long-range reconnaissance forces.

The proposed JLTV fleet would include variants that can perform relatively well in fulfilling any of the needs listed above. Each variant must also satisfy the following desired attributes.

- Force Protection (Crew and Passengers Protection): this includes defeating or defending against some or all types of rocket propelled grenade warheads, and providing armor protection for personnel against known threats, including mines and RPG.

- Survivability (Vehicle Survivability): survivability includes mitigation of electronic IED defeat, shot detection/warning, self-recovery of vehicle, and instant fire suppression in engine and cabin compartments.

- Transportability: this includes vehicle transportability by a range of lift assets and air drop capability for fast deployment.

- Mobility: this includes maneuverability at maximum cruising speed and fuel efficiency across different types of terrain.

- Net-Readiness: the vehicle should be capable of Network Centric Warfare (NCW) with ready access to joint command, control, communications, computers, intelligence, surveillance and reconnaissance throughout the land battle space for improved Battle Awareness (BA).

- Sustainability: the vehicle must be self-sustainable and be able to operate independently for short periods of time without any support.

- Reliability: the vehicle should be highly reliable with self-recovery features, and able to provide two levels of maintenance (operator and unit levels) and onboard critical warning/diagnostics.

- Payload: the vehicle should have an increased ability to hold and move cargo, weapons, ammunition and troops with full armor attached to the vehicle.

Five generic JLTV types were proposed in the initial JLTV Capability Development Document (CDD) to address the current fleet performance gaps; the systems descriptions for each of the JLTV C4I Mission Role Variants (MRVs) are listed below:

- Combat Tactical Vehicle (CTV): This will be the base cargo/troop transportation vehicle. It will provide built-in armor protection capability for transporting a seven-man (two crew and five passengers) infantry fire team with weapons and ammunition over long distances. It comes with integral armor protection and is capable of mounting add-on armor for additional protection. The vehicle has a crew-served weapon mount and a joint communications system. The CTV can be re-configured to a number of variant vehicles.

- Command and Control/C4I Vehicle (C2): This vehicle has the same armor protection capability as the CTV; in addition, it provides C4I-hosting capability and is able to provide satellite communication (SATCOM) on the move. It will support multiple C4 mission configurations for the joint services. These C2 variants are also capable of towing standard towed mortars, radar sets, artillery pieces and smoke generators.

- Utility Vehicle (UV): The UV has armor protection and can be used for the transportation of combat support and combat service support materials.

It can also be used as common shelters such as ambulances and command posts.

- Long Range Surveillance Vehicle (LRSV): This vehicle also provides integral armor protection capability and can only be used to transport four passengers over long distances. It is generally lighter than the other JLTV variants in order to increase mobility. Its purpose is for long range command and control.

- Ground Maneuver Vehicle (GMV): This vehicle is operated by a two-man crew and can carry nine passengers with combat loads under armor protection over long distances. It is also capable of mounting a crew-served weapon and acting as a joint communications system.

Each generic type of JLTV will have different configurations. Within each configuration lie different sub-configurations that are defined by the vehicle's mission requirements. Each of these sub-configurations corresponds to a JLTV variant. There are altogether 18 possible vehicle variants that have been identified among the five types as shown in Table 1.

JLTV Variant	Configuration	Sub-configuration
Combat Tactical Vehicle	CTV1A	Reconnaissance
Combat Tactical Vehicle	CTV2A	Light Armament
Combat Tactical Vehicle	CTV3A	Light Armament
Combat Tactical Vehicle	CTV4A	Light Utility
Combat Tactical Vehicle	CTV5A	C2
Combat Tactical Vehicle	CTV6A	Light Ambulance
Combat Tactical Vehicle	CTV7A	Light Utility
Long Range Surveillance Vehicle	LRS1A	Reconnaissance
Long Range Surveillance Vehicle	LRS2A	C2
Utility Vehicle Light	UVL1	Light Ambulance
Utility Vehicle Light	UVL2	Light Utility
Utility Vehicle Light	UVL3	Light Shelter
Utility Vehicle Light	UVL4	Prime Mover
Utility Vehicle Heavy	UVH1	Heavy Armament
Utility Vehicle Heavy	UVH2	Heavy Ambulance
Utility Vehicle Heavy	UVH3	Heavy Utility
Utility Vehicle Heavy	UVH4	Heavy Shelter
Ground Maneuver Vehicle	GMV1	Heavy Utility

Table 1.   JLTV Variants

As stated in the JLTV Capability Development Document (CDD), the development of the JLTV will be incremental, and will occur in two stages. The first set of JLTVs is scheduled to begin production by 2013. The Army will initially procure 5,500 JLTVs. The second increment will be complete by 2016, when updated JLTV variants should be fleet ready. Between the two increments, JLTV manufacturers are expected to research and improve the design of the JLTV from the first increment. The areas of focus include force protection, fuel efficiency, power generation, and net readiness. Acquisition goals for the second increment indicate that a total of 33,137 JLTVs should be produced and operationally ready by 2016.

The Army's motivation for developing the JLTV is to replace the aging HMMWVs and produce a LTWV that is capable of meeting current and future mission requirements. The JLTV will meet these mission requirements based on its ability to excel in a decentralized battlefield.

III. DATA AND METHODOLOGY

This chapter describes the methodologies that will be used to create the decision optimization tool to be utilized in modeling the LTWV modernization.

A. APPROACH

This research uses the LTWV Value Model, the LP Model and the Excel Premium Solver Platform to develop a decision optimization tool that will allow TACOM users to conduct both baseline and sensitivity analyses on the results. This new decision optimization tool will replace the existing LTWV LP model that is currently implemented using General Algebraic Modeling System (GAMS).

Microsoft Excel is the platform for the LP model since it is a widely used application. Since TACOM LCMC and PEO CS/CSS users commonly use spreadsheets, they should be able to use this system with minimal training. Microsoft Excel comes with a default standard solver that can handle up to 200 variables and 200 constraints. This is not sufficient to handle the current LTWV LP model, due to the fact that the model requires a lot more variables and constraints, depending on the number of vehicle variants and capabilities and the number of planning years involved.

There are a number of solvers on the market that can solve larger problems than the default Excel solver. They were compared for their price, compatibility with Microsoft Excel, and for the problem size they can handle. Excel Premium Solver Platform was chosen over the other commercially available solvers. It is 100% upwardly compatible with the standard Excel Solver and can handle significantly more variables and constraints (up to 8000 variables and 8000 constraints) than the standard solver. The Premium Solver Platform is also able to handle multi-worksheet models with decision variables and constraints on different worksheets. Annex A compares the various Premium Solver products based on their ability to handle different sizes and types of problems.

The values and formulation for the LTWV LP model are taken from two existing models that are part of Koerner and McDonald's thesis research topic. The same approach, "Value Focused Thinking" (Keeney, 1992), is also being used for this research. This process flows from qualitative thinking to quantitative evaluation. The details for these two models (Additive Value Model and LP Model) can be found in Koerner and McDonald's research paper (2007).

B. DATASETS

1. LTWV Value Model

The LTWV Value Model is designed to quantify an LTWV for the purpose of making fleet inventory decisions. It is developed using the procedure and guidance specified in Keeney's Value Focused Thinking and Kirkwood's Strategic Decision Making (Cambridge: Harvard University Press, 1992). Information was gathered from the HMMWV Operational Requirements document and the JLTV Capability Development Document (CDD) to identify capabilities and attributes. A top-down approach was used, starting from the Key Performance Parameters (KPPS) of the JLTV CDD. The initial objective hierarchy from Koerner and McDonald's research paper defines three main capabilities: Mobility, Net-Readiness and Survivability. The most recent update from TACOM LCMC and PEO CS/CSS decision makers redefined the objective hierarchy, and it now consists of four main capabilities, namely, Force Projection, Force Protection, Payload and Sustainability.

The resulting objective hierarchy with attributes is shown below:

- Force Projection
    - Vehicle Mobility
        - Speed
            - **Cruising Speed (miles per hour)**
            - **Top Speed (miles per hour)**
            - **Cross Country Speed (miles per hour)**
        - **Max Range (miles)**
    - Transportability
        - **Weight (tons, gross vehicle weight)**
        - **Height (feet)**
- Force Protection
    - **Ballistic (%)**
    - **Lethality (%)**
    - Vehicle Safety
        - **Crash Survival**
        - **Crash Avoidance**
- Payload
    - Vehicle Capacity
        - **Max Weight (pounds)**
        - **Cargo Volume (cubic feet)**
        - **# Seats (count)**
    - **Tow Capacity**
    - Net-Readiness
        - **Space Claim**
        - **Power Capability (amps)**
- Sustainability
    - **Reliability**
    - Reduced Maintenance Overhead
        - **Maintenance Ratio**
        - **MTTR (hours)**

Legend
Capability
Attribute (units)

o O&S Costs

- **Maintenance and Repair (#)**
- **POL (Petroleum, Oil and Lubricants) (gallons)**

The current value functions are in the process of being validated by SME/engineers and that these currently represent only a best guess by analysts. Some of the newly added attributes for each of the four capabilities are as follows:

- Force Projection considers how far the vehicle can travel on a single tank of fuel and how easily the vehicle can be transported from one location to another.

  o Maximum Cruising Speed (Figure 9): Measured in MPH (miles per hour), this is the maximum speed a vehicle can travel on level paved surface roads at gross vehicle weight (GVW) on a single tank of fuel. Having a faster cruising speed means that the vehicle can reach a destination in a shorter time, thus making it time-efficient.
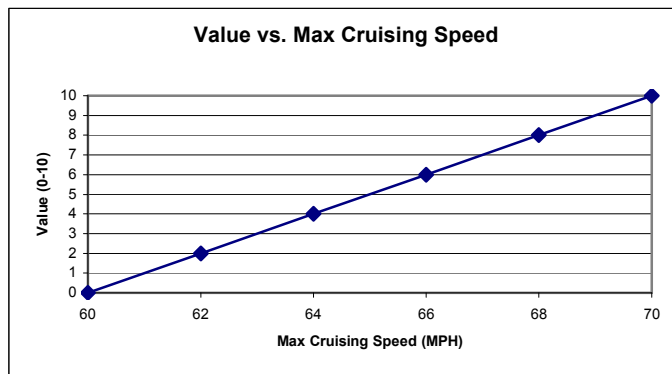

Figure 9.   Value vs. Max Cruising Speed

  o Cross Country Speed (Figure 10): This is similar to cruising speed except that the vehicle is traveling on unpaved roads or uneven terrain. It is measured as speed

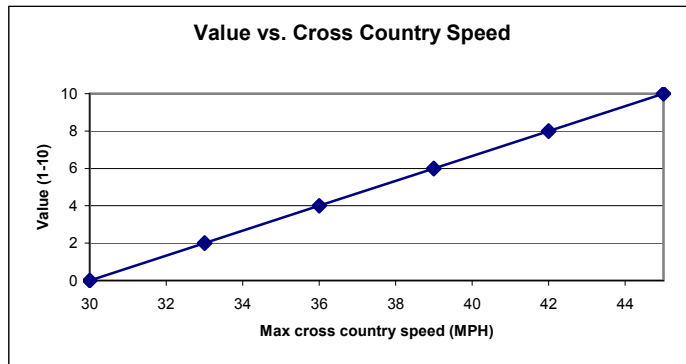on a 5% slope. A faster cross country speed yields a higher value for the vehicle.

Figure 10.   Value vs. Cross Country Speed

o   Gross Vehicle Weight (Figure 11): The weight of the vehicle is currently measured in pounds. It is used to determine how easily the vehicle may be towed or air-lifted. It shows constant returns to scale, emphasizing the criticality of each pound equally.
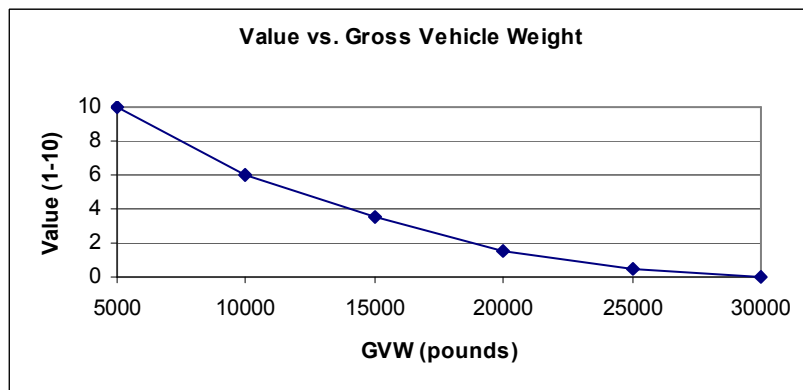

Figure 11.   Value vs. Gross Vehicle Weight

o   Height (Figure 12): This is the average height of the vehicle, measured in feet. It determines the space required to store or transports the vehicle by air or sea means.
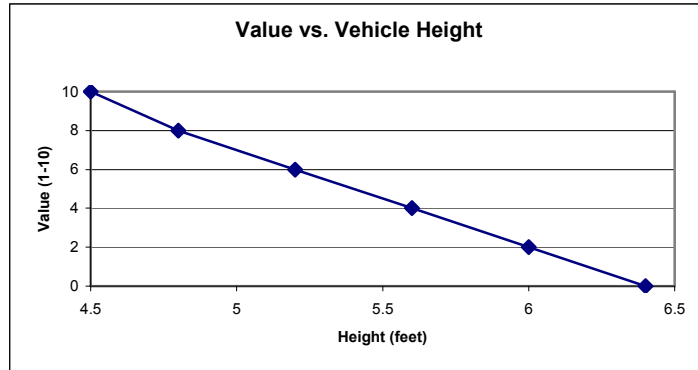
Figure 12.   Value vs. Vehicle Height

- Force Protection looks at measures taken to prevent or mitigate hostile actions against the vehicle and the crew in the vehicle.

  - Ballistic (Figure 13): This attribute looks at the type and the thickness of vehicle armor mounted on the vehicle in order to protect the crew from a mortar or mine blast. It is measured in percentage. A higher percentage means greater protection from these blasts.
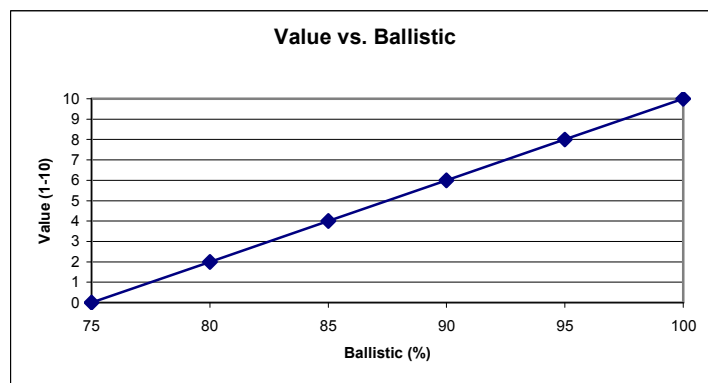

Figure 13.   Value vs. Ballistic

  - Lethality (Figure 14): This attribute, listed as a percentage, measures protection by evaluating the types of weapons and ammunition that are used in the vehicle to protect against any hostile attacks.
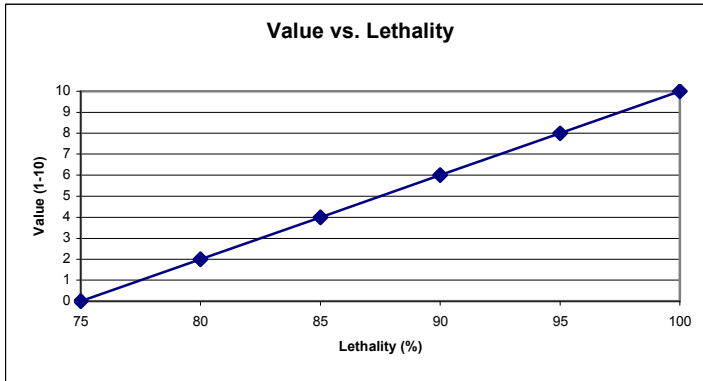
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Value vs. Lethality

(Graph: Value (1-10) on y-axis from 0 to 10, Lethality (%) on x-axis from 75 to 100. A line rises linearly from (75, 0) through points at (80, 2), (85, 4), (90, 6), (95, 8), to (100, 10).)

Figure 14.   Value vs. Lethality

o Crash Survival: This attribute looks at the design of the
vehicle and the measures taken (e.g. seat belts, crush
helmets or fire-proof vests) to prevent injuries or deaths
during a crash. It is measured in % GVW supported by
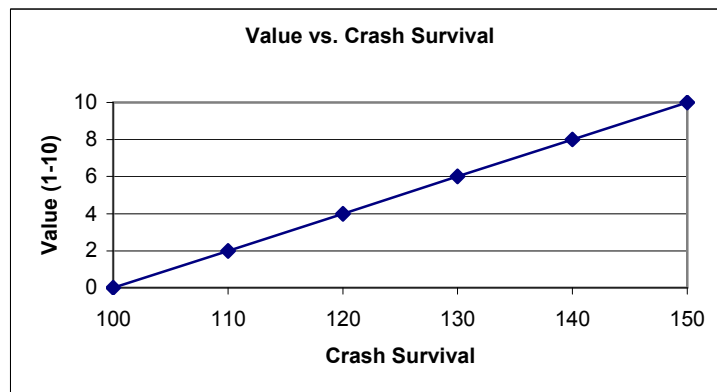vehicle in a rollover accident.

Value vs. Crash Survival

(Graph: Value (1-10) on y-axis from 0 to 10, Crash Survival on x-axis from 100 to 150. A line rises linearly from (100, 0) through points at (110, 2), (120, 4), (130, 6), (140, 8), to (150, 10).)

Figure 15.   Value vs. Crash Survival

o Crash Avoidance: This attribute examines the preventive
measures that are designed into the vehicle to prevent a
crash. The more preventive measures a vehicle has, the
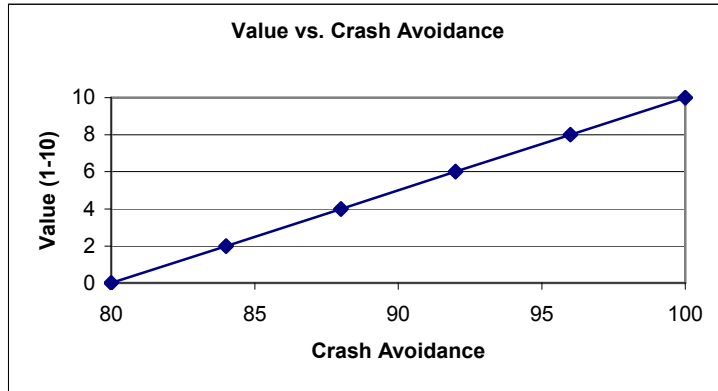more value it will be assigned. It is measured by NATO
lane change speed (mph).

Figure 16.   Value vs. Crash Avoidance

- Payload is the measure of a vehicle's ability and capacity to transport passengers, weapons and communication equipment onto the modern battlefield. It also measures the towing capability of a vehicle to retrieve another vehicle that is off-road.

  o Space Claim: This refers to the space that is available in the vehicle for the transportation of weapons, ammunition and equipment. The more space a vehicle has, the higher the value assigned to it.
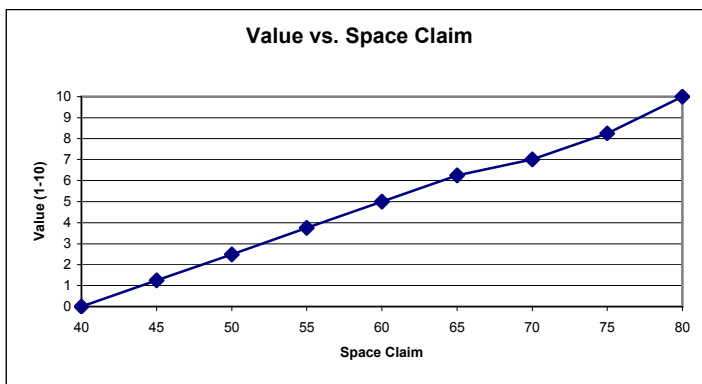

Figure 17.   Value vs. Space Claim

  o Power Capability: This is the maximum power (measured in amps) a vehicle can generate or provide for the

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operation of communication and other command and control equipment.

Value vs. Power Capability

Value (1-10)

10
9
8
7
6
5
4
3
2
1
0

50   100   150   200   250   300   350   400
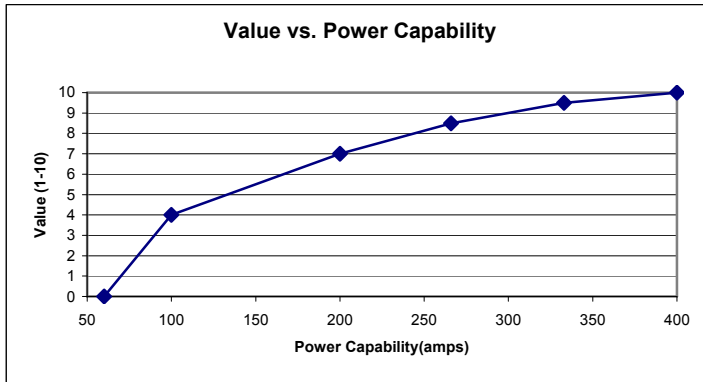
Power Capability(amps)

Figure 18.   Value vs Power Capability

- Sustainability ensures that a vehicle is reliable, affordable and has a low maintenance cost.

  o Maintenance Ratio: This is the ratio of maintenance man-hours required per hour of system operation. A lower ratio value will mean that this vehicle is more reliable and does not require a lot of maintenance work.
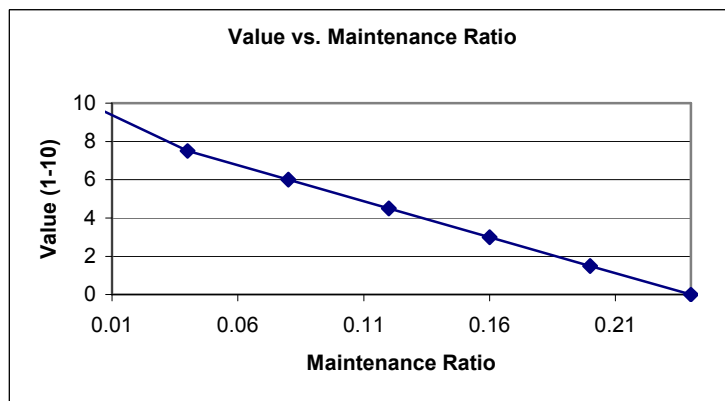
Value vs. Maintenance Ratio

Value (1-10)

10

8

6

4

2

0

0.01   0.06   0.11   0.16   0.21

Maintenance Ratio

Figure 19.   Value vs. Maintenance Ratio

o MTTR (Mean Time To Repair): This attribute is a measure of maintainability. It is the average time (in hours) required to perform corrective maintenance work on the vehicle.
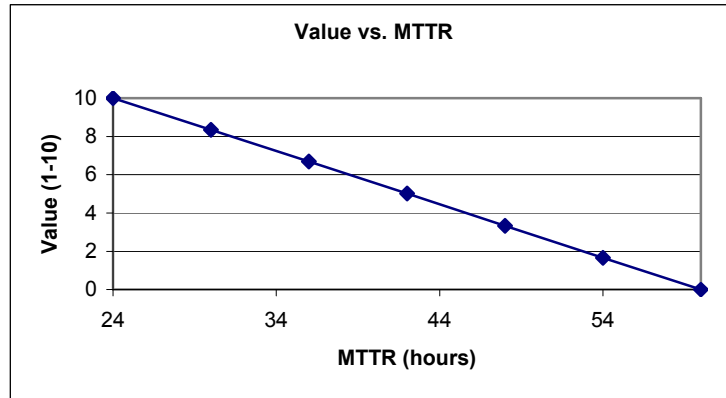
Value vs. MTTR

(Line chart: Value (1-10) on the y-axis ranging from 0 to 10, MTTR (hours) on the x-axis ranging from 24 to 54. A straight decreasing line from value 10 at MTTR 24 to value 0 at MTTR approximately 59.)

Figure 20. Value vs. MTTR

o Maintenance and Repair: This refers to the number of corrective maintenance works and repairs for a vehicle per year. More maintenance works and repairs will mean a lower value for this vehicle.
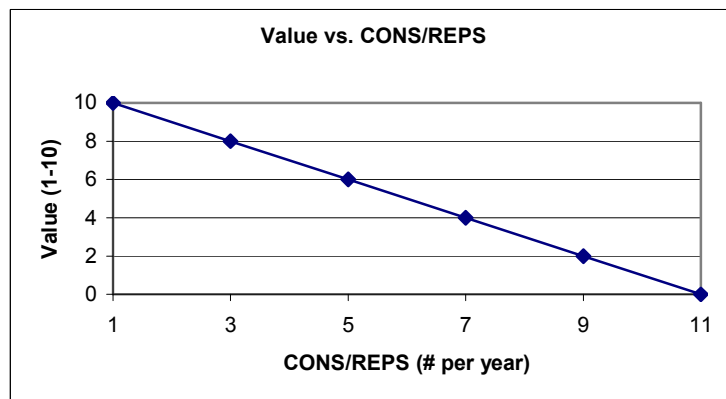
Value vs. CONS/REPS

(Line chart: Value (1-10) on the y-axis ranging from 0 to 10, CONS/REPS (# per year) on the x-axis ranging from 1 to 11. A straight decreasing line from value 10 at CONS/REPS 1 to value 0 at CONS/REPS 11.)

Figure 21. Value vs. CONS/REPS

- POL: This attribute is the maximum amount of Petroleum, Oil, and Lubricant that a vehicle can carry at any one time, measured in gallons.
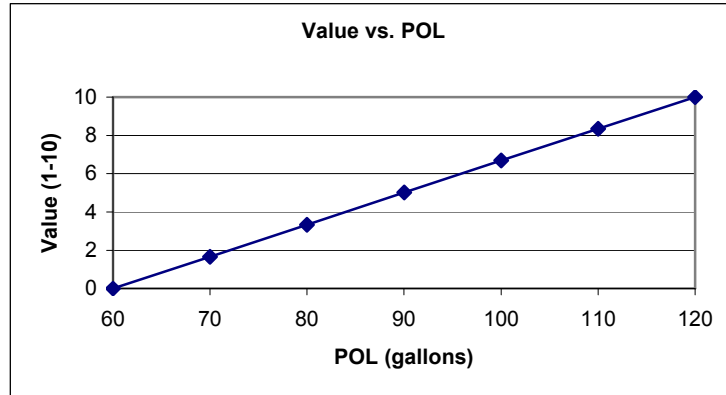

Figure 22.   Value vs. POL

2.   Results from the LTWV Value Model

The Value Model uses the information from the value function tables and the weight matrix (shown in Table 7) to assign values to the vehicles, on a scale of 1 to 10. As an example, the M1025 gets its Force Projection value of 1.311 from the product sum of its sub attributes and their respective weights, $(0.005\times5)+(0.046\times3.3)+(0.014\times3.3)$ $+(0.046\times5.7)+(0.092\times7.4)+(0.073\times2.0)=1.311$. The "ideal" vehicle would achieve a 10 in every attribute, and serves as a basis for comparison.

a. *Mission Variants*

The LTWV fleet is further categorized into different mission variants, namely, armament, reconnaissance and utility vehicles, thus giving the following results.
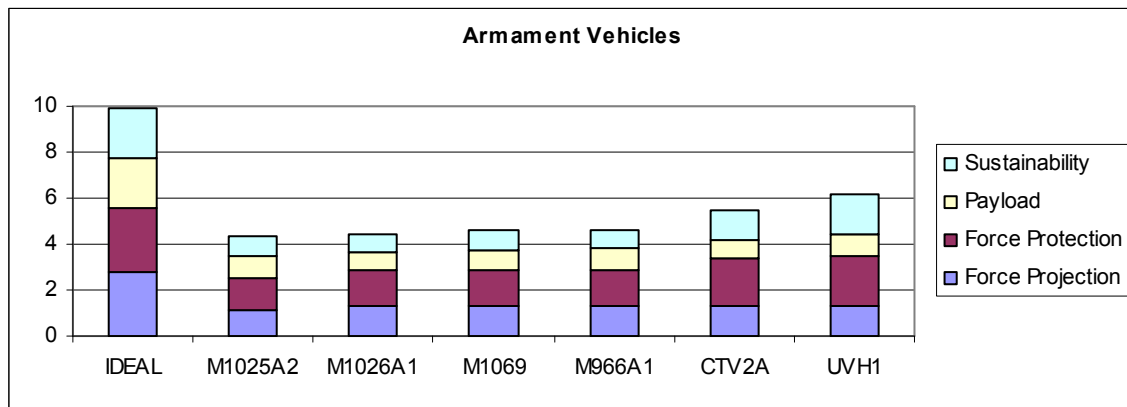
- Armament Vehicles

Figure 23. **Armament Vehicle Values, by Objective**

	Total	Force Projection	Force Protection	Payload	Sustainability
IDEAL	9.875	2.752	2.844	2.132	2.147
M1025	4.157	1.311	1.413	0.607	0.826
M1025A1	4.170	1.298	1.413	0.633	0.826
M1025A2	4.345	1.117	1.413	0.988	0.826
M1026	4.488	1.311	1.578	0.773	0.826
M1026A1	4.475	1.298	1.578	0.773	0.826
M1069	4.416	1.334	1.578	0.834	0.826
M966	4.303	1.311	1.578	1.143	0.826
M966A1	4.303	1.298	1.578	0.935	0.826
CTV2A	5.633	1.328	2.073	0.772	1.312
CTV3A	5.606	1.328	2.073	0.772	1.312
UVH1	6.514	1.308	2.133	0.974	1.776
Average	4.765	1.295	1.673	0.837	1.001
% Ideal	48.25%	47.04%	58.84%	39.25%	46.62%

Table 2. **Armament Vehicle Scores, by Objective**

- Reconnaissance Vehicles
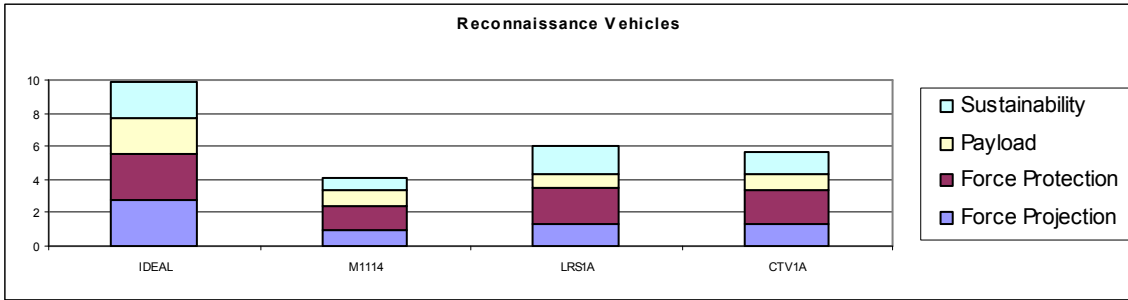
Figure 24. **Reconnaissance Vehicle Values, by Objective**

	Total	Force Projection	Force Protection	Payload	Sustainability
IDEAL	9.875	2.752	2.844	2.132	2.147
M1114	4.155	0.976	1.468	0.885	0.826
LRS1A	6.080	1.349	2.188	0.767	1.776
LRS2A	6.108	1.349	2.188	0.794	1.776
CTV1A	5.688	1.328	2.073	0.976	1.312
CTV5A	5.633	1.328	2.073	0.921	1.312
Average	5.533	1.266	1.998	0.869	1.400
% Ideal	56.03%	45.99%	70.26%	40.74%	65.23%

Table 3. **Reconnaissance Vehicle Scores, by Objective**

- Utility Vehicles
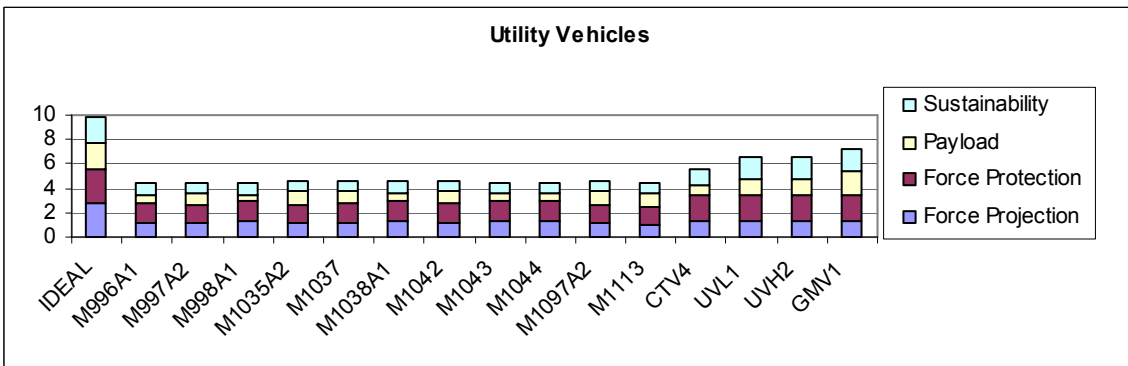
Figure 25. **Utility Vehicle Values, by Objective**

	Total	Force Projection	Force Protection	Payload	Sustainability
IDEAL	9.875	2.752	2.844	2.132	2.147
M996	4.364	1.229	1.578	0.730	0.826
M996A1	4.351	1.216	1.578	0.730	0.826
M997	4.389	1.197	1.578	0.787	0.826
M997A1	4.375	1.184	1.578	0.787	0.826
M997A2	4.437	1.117	1.578	0.916	0.826
M998	4.359	1.348	1.578	0.607	0.826
M998A1	4.345	1.334	1.578	0.607	0.826
M1035	4.586	1.348	1.578	0.834	0.826
M1035A2	4.664	1.117	1.578	1.143	0.826
M1037	4.569	1.229	1.578	0.935	0.826
M1038	4.524	1.348	1.578	0.772	0.826
M1038A1	4.511	1.334	1.578	0.772	0.826
M1042	4.608	1.229	1.578	0.974	0.826
M1043	4.447	1.296	1.578	0.747	0.826
M1044	4.420	1.296	1.578	0.720	0.826
M1097	4.591	1.131	1.528	1.106	0.826
M1097A1	4.591	1.131	1.528	1.106	0.826
M1097A2	4.578	1.117	1.528	1.106	0.826
M1113	4.445	1.003	1.472	1.143	0.826
CTV4	5.606	1.328	2.073	0.893	1.312
CTV6	5.551	1.328	2.073	0.838	1.312
CTV7	5.633	1.328	2.073	0.921	1.312
UVL1	6.484	1.308	2.133	1.268	1.776
UVL2	6.347	1.308	2.133	1.130	1.776
UVL3	6.347	1.308	2.133	1.130	1.776
UVL4	6.347	1.308	2.133	1.130	1.776
UVH2	6.486	1.308	2.133	1.269	1.776
UVH3	6.486	1.308	2.133	1.269	1.776
UVH4	6.486	1.308	2.133	1.269	1.776
GMV1	7.196	1.242	2.133	2.045	1.776
Average	5.138	1.253	1.767	0.990	1.128
% Ideal	52.03%	45.52%	62.13%	46.42%	52.55%

Table 4.   Utility Vehicle Scores, by Objective

b. Mission Variants Comparison

Table 5 shows that each of the three different mission variants receives the highest value in its main mission role, with armament vehicles performing best in force projection, reconnaissance vehicles best in force protection and sustainability, and utility vehicles best in payload.

	Total	Force Projection	Force Protection	Payload	Sustainability
Armament	50.10%	46.52%	60.67%	41.25%	49.63%
Reconnaissance	53.75%	44.24%	67.15%	41.09%	60.77%
Utility	50.73%	44.76%	60.18%	47.75%	48.85%

Table 5.   Average Percent Ideal

c. HMMWV and JLTV Comparison

The values shown in Table 6 demonstrate that the new JLTV shows significant improvement over the HMMWV in all objectives. This observation indicates that the LTWV fleet improving in its level of operational capabilities. By addressing capability gaps observed in the HMMWV, the JLTV has earned higher values.

	Total	Force Projection	Force Protection	Payload	Sustainability
IDEAL	9.875	2.752	2.844	2.844	2.147
HMMWV	4.427	1.231	1.547	1.547	0.826
% Ideal	44.84%	44.72%	54.40%	54.40%	38.49%
JLTV	6.124	1.316	2.116	2.116	1.595
% Ideal	62.01%	47.83%	74.40%	74.40%	74.32%

Table 6.   Comparison of HMMWV and JLTV scores, by objectives

C. METHODOLOGY

1. LTWV LP Model

The LTWV LP Model was developed by Professor Robert Dell of the Operations Research Department at the Naval Postgraduate School to prescribe recapitalizations, retirements, and new purchases for the U.S. Army LTWV fleet over the next 15 years. Elastic constraints - that is, constraints that can be violated at a penalty set by the decision

makers - are used to model operational, budget, capacity and age requirements. These requirements ensure that the fleet remains operationally ready at all times throughout the entire modernization process and still stays within the budget limit. This model was originally implemented in GAMS for the purpose of conceptualizing the model and analyzing the results. The end product for this model will eventually be implemented and used by TACOM decision makers. GAMS IDE (integrated development environment) is a general text editor and does not have a user interface for users' inputs or to display the results in graphical forms. Excel was chosen to replace GAMS IDE as the user interface because it is a widely used application and is able to generate graphs from date quickly. Premium Solver Platform is used as the underlying solver engine instead of the GAMS solver because it fully supports Excel and is an add-on to the Excel built-in solver.

2.   Excel LP Model

Excel LP Model uses the same formulation as the GAMS model with some enhancements and modifications to minimize the number of constraints in the model. The complete formulation of the Excel LP model is contained in Annex B.

Below are some of the enhancements that have been developed and implemented as part of this research project.

This model makes use of worksheets to partition the model into different functions. The worksheets are named according to their functions.

a.   Graphical User Interface

This is the worksheet (Figure 26) with which users can determine the size of the LP model, construct the model and run the model. It consists of five index counters and two actor counters to decrement or increment the number of indices and the discount factors in the model. The three buttons are used to initialize and construct the LP model after the size of the model has been determined, and to run the model after the data are entered.
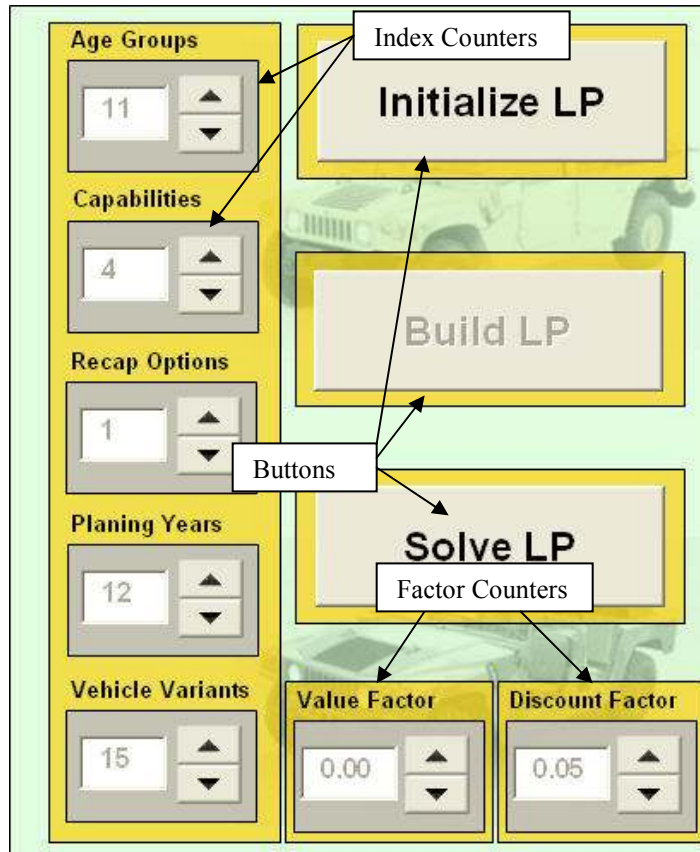
Figure 26.   User Interface Worksheet

b.   *Objective Function*

The objective function is to minimize the sum of all the penalties incurred by the elastic constraints, and the LPs solution will minimize this function. This forces the model to search for a feasible modernization strategy that produces the optimum vehicle value throughout the entire modernization period, satisfying the budgetary and capability requirements. The modernization strategies will be a combination of recaps, new purchases, and retirements for the LTWV variants, spread out over the entire modernization timeframe. This worksheet also displays two graphs. The first graph (Figure 27) shows the total capability value that can be provided by the LTWV fleet each year, and the second graph (Figure 28) shows the total expenditure and budget allocated by each planning year.

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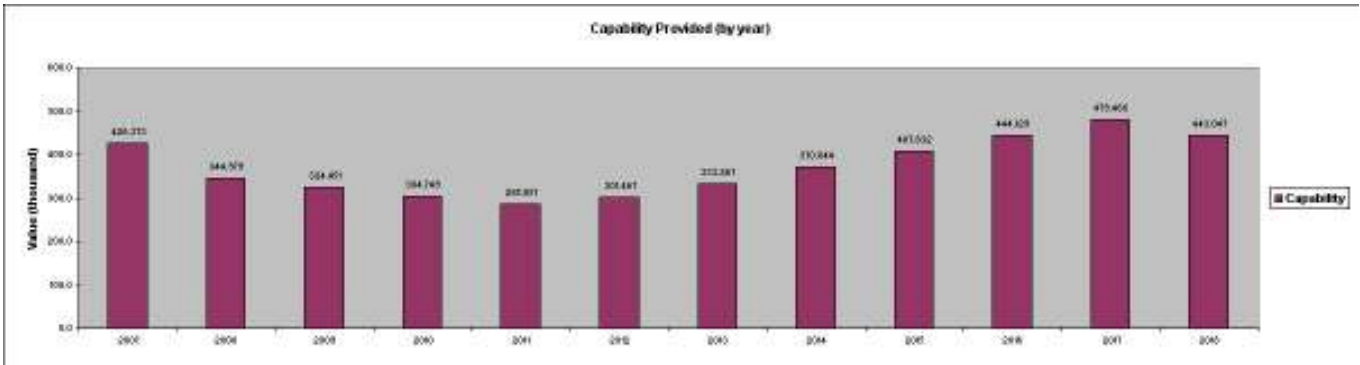
Figure 27.   Capability Value Provided Across Fiscal Year
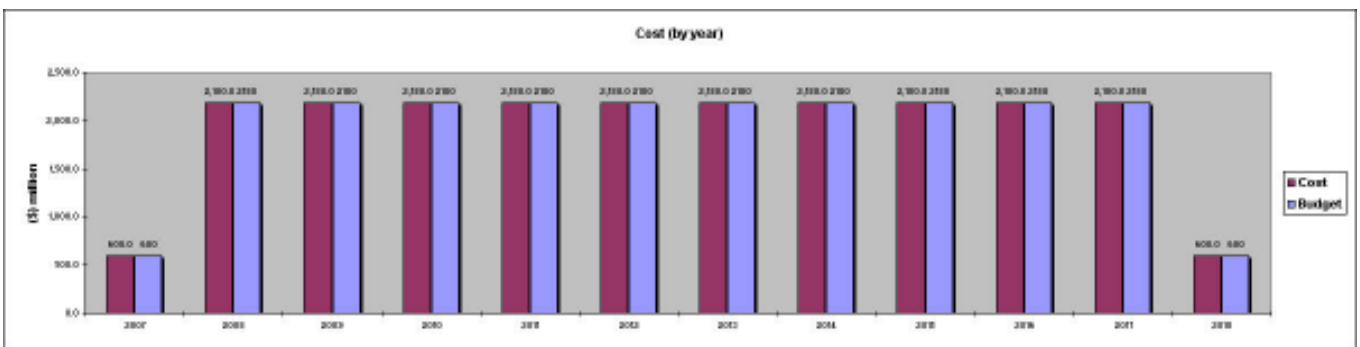
Figure 28.   Cost and Budget Across Fiscal Year

c.   *Indices*

The indices and their respective names that are incremented and entered from the user interface will be displayed in Figure 57. These indices will be used to define the parameters and decision variables in the LP model.

d.   *Parameters*

The parameters are defined after the "Initialize LP" and the "Construct LP" buttons in the user interface are pressed. The TACOM LCMC and PEO CS/CSS users will need to provide all the values in this worksheet for the LP model to continue. Operational capability is measured in units of value; the LTWV Value Model provides a basis for each vehicle and the annual demand required throughout the modernization period to be associated with these weighted values. These parameters in Figure 58, which

will be used in the constraints, determine the upper and lower bounds of the decision variables and the objective function values. Some examples are the maximum age for each of the vehicle variants and the yearly minimum/maximum purchase quantities allowed for each vehicle variants.

e.   Decision Variables

The decision variables are elements controlled by the constraints; their values determine the number of vehicles to recapitalize, retire and purchase for the entire modernization period. There are eight groups of decision variables in this LP model. The first four groups determine the number of vehicles to recapitalize, retire, and purchase, and the starting inventory for each year. The next four groups are elastic variables for demand, budget, and minimum and maximum age. These elastic variables have a penalty per unit violation in the constraints.

f.   Constraints

Various types of constraints are generated whenever the "Solve LP" button is pressed. After generation, the constraints, together with the objective function, parameters and decision variables are passed into the Premium Solver Platform engine to find a feasible optimal solution for the allocation of vehicles throughout the entire modernization period.

Operational requirement constraints ensure that the fleet has a diverse range of capabilities at all times. The minimum demand for each type of capability must be satisfied by the fleet each year in order to support ongoing operations.

Capacity constraints limit the number of vehicles that can be retired, recapped and purchased each year. The upper limit on the retiring vehicles determines the number of vehicles that can retire each year, in order to control the turnover rate of the fleet. The present retirement limit is set to a low number as there is a shortage of HMMWV vehicles to meet the Grow The Army requirements. This means that vehicles will continue to be fixed or recapped until they are no longer serviceable before they are retired. However, retirement of the HMMWVs will still occur, due to damage in Theater,

the higher demand for better capabilities and the introduction of the new JLTV that can fulfill these needs. The number of vehicles that can be recapped each year is limited by the number of vehicles that the maintenance workshops can handle. The number of new vehicles manufactured each year limits the number of new vehicles that can be purchased.

There are also budget constraints. Each year, the Army is allocated a finite amount for the LTWV modernization program. These constraints will limit the number of vehicles that can be retired or recapped or purchased new. Budgetary constraints will result in vehicles being retired or recapped in order to minimize operation and maintenance costs.

Non-negativity constraints are included to ensure that there are no negative values for all the decision and elastic variables.

g.   *Results*

This worksheet displays the decision variables and their values sorted in chronological order for the purpose of analysis.

IV.   DATA ANALYSIS

This chapter describes how the Excel LP Model makes use of the data from the LTWV Value Model for its optimization. This chapter also explains in detail how the results from the Excel LP Model are analyzed.

A.   QUANTIFICATION

The modernization of the LTWV fleet relies on the LTWV Value Model to quantify each vehicle variant in the fleet. All capabilities and attributes of the LTWV are identified and assigned numbers ranging from 0 to 10, with the best performing attribute being assigned a 10 and the worst performing attribute assigned a 0. A weight is also assigned to each capability and attribute to highlight the more influential of these, as shown in Table 7. The values for the capabilities and attributes of each of the vehicle variants are then cross-multiplied with their assigned weights and summed together to get the weighted values shown in Table 8. These weighted values are input into the Excel LP Model as the capability values each vehicle variant can provide each year.

Level 1 — Capability

Capability	Force Projection	Force Protection	Payload	Sustainability
Local weight	0.275	0.284	0.216	0.225
Global weight	0.275	0.284	0.216	0.225

Level 2 — Attribute/Sub-OBJ

Attribute/ Sub-OBJ	Vehicle Mobility	Transportability	Ballistic	Lethality	Vehicle Safety	Vehicle Capacity	Tow Capacity	Net-Readiness	Reliability	Reduced Maintenance Overhead	O & S Costs
Local weight	0.400	0.600	0.323	0.258	0.419	0.681	0.128	0.191	0.327	0.531	0.143
Global weight	0.110	0.165	0.092	0.073	0.119	0.147	0.028	0.041	0.073	0.119	0.032

Level 3 — Attribute/Sub-OBJ

Attribute/ Sub-OBJ	Speed	Max Range	Weight	Height	Crash Survival	Crash Avoidance	Max wt	Cargo Volume	# seats	Space Claim	Power Capability	Maint Ratio	MTTR	CONS/ REPS	POL
Local weight	0.583	0.417	0.556	0.444	0.231	0.769	0.313	0.500	0.188	0.333	0.667	0.615	0.385	0.857	0.143
Global weight	0.064	0.046	0.092	0.073	0.028	0.092	0.046	0.073	0.028	0.014	0.028	0.073	0.046	0.028	0.005

Level 4 — Attribute/Sub-OBJ

Attribute/ Sub-OBJ	Cruising Speed	Top MPH	Cross Country Speed
Local weight	0.071	0.714	0.214
Global weight	0.005	0.046	0.014

Table 7.   Weights for the Capabilities and Attributes of LTWVs

	Total	Force Projection	Force Protection	Payload	Sustainability
IDEAL	9.875	2.752	2.844	2.132	2.147
M1025	4.157	1.311	1.413	0.607	0.826
M1025A1	4.170	1.298	1.413	0.633	0.826
M1025A2	4.345	1.117	1.413	0.988	0.826
M1026	4.488	1.311	1.578	0.773	0.826
M1026A1	4.475	1.298	1.578	0.773	0.826
M1035	4.586	1.348	1.578	0.834	0.826
M1035A2	4.664	1.117	1.578	1.143	0.826
M1037	4.569	1.229	1.578	0.935	0.826
M1038	4.524	1.348	1.578	0.772	0.826
M1038A1	4.511	1.334	1.578	0.772	0.826
M1042	4.608	1.229	1.578	0.974	0.826
M1043	4.447	1.296	1.578	0.747	0.826
M1044	4.420	1.296	1.578	0.720	0.826
M1069	4.416	1.334	1.578	0.677	0.826
M1097	4.591	1.131	1.528	1.106	0.826
M1097A1	4.591	1.131	1.528	1.106	0.826
M1097A2	4.578	1.117	1.528	1.106	0.826
M1113	4.445	1.003	1.472	1.143	0.826
M1114	4.155	0.976	1.468	0.885	0.826
M966	4.303	1.311	1.578	0.588	0.826
M966A1	4.303	1.298	1.578	0.601	0.826
M996	4.364	1.229	1.578	0.730	0.826
M996A1	4.351	1.216	1.578	0.730	0.826
M997	4.389	1.197	1.578	0.787	0.826
M997A1	4.375	1.184	1.578	0.787	0.826
M997A2	4.437	1.117	1.578	0.916	0.826
M998	4.359	1.348	1.578	0.607	0.826
M998A1	4.345	1.334	1.578	0.607	0.826
CTV1A	5.688	1.328	2.073	0.976	1.312
CTV2A	5.633	1.328	2.073	0.921	1.312
CTV3A	5.606	1.328	2.073	0.893	1.312
CTV4A	5.606	1.328	2.073	0.893	1.312
CTV5A	5.633	1.328	2.073	0.921	1.312
CTV6A	5.551	1.328	2.073	0.838	1.312
CTV7A	5.633	1.328	2.073	0.921	1.312
LRS1A	6.080	1.349	2.188	0.767	1.776
LRS2A	6.108	1.349	2.188	0.794	1.776
UVL1	6.484	1.308	2.133	1.268	1.776
UVL2	6.347	1.308	2.133	1.130	1.776
UVL3	6.347	1.308	2.133	1.130	1.776
UVL4	6.347	1.308	2.133	1.130	1.776
UVH1	6.514	1.308	2.133	1.297	1.776
UVH2	6.486	1.308	2.133	1.269	1.776
UVH3	6.486	1.308	2.133	1.269	1.776
UVH4	6.486	1.308	2.133	1.269	1.776
GMV1	7.196	1.242	2.133	2.045	1.776

Table 8.   Weighted Values for each Vehicle Variant

B. MODEL IMPLEMENTATION

The LTWV LP model was formulated by Professor Dell Robert and is currently implemented in GAMS. This LP model is a multi-objective optimization problem. It attempts to maximize the LTWV value across the entire modernization period while also minimizing the cost of this modernization strategy. There are many methods that can be used to solve this type of problem, including preemptive optimization, alternative optima, and using weighted sums of objectives. This model uses goal programming (Rardin, 2000), by far the most popular approach to finding good solutions in multi-criteria problem settings.

Goal programming constructs a model in terms of target levels to be achieved, rather than quantities to be maximized or minimized. It makes use of nonnegative deficiency (elastic) variables to model the extent of goal violations or other soft (elastic) constraints that need not be rigidly enforced. Soft constraints or elastic constraints specify requirements that are desirable to satisfy but can still be violated in order to reach feasible solutions. The objective function in a goal programming model is to minimize the weighted sum of the deficiency (elastic) variables in order to satisfy all goals as closely as possible.

One goal of this project is to implement the LP model in Excel in order to provide a user interface that will allow the users to define the size of the model and generate meaningful and useful results.

1. Issues Encountered

Below are three issues encountered during the conversion from GAMS to Excel.

a. *Limitations of Excel Built-in Solver*

Microsoft Excel comes with an optional solver add-in that can handle small LP problem up to a maximum of 200 variables and 200 constraints. Because of this limitation, there is a need to look for another commercial solver that integrates well with Excel and can solve bigger LP problems. A solver from Frontline Systems, Inc., was

chosen because Frontline's solvers are all upwardly compatible extensions of the standard Microsoft Excel Solver, with much greater problem solving capacities, much faster speeds, and many new diagnostic and user interface aids.

b.   *Limitations of Excel 2003 Worksheet*

In addition to the default solver limitation, Microsoft Excel 2003 also has limitations on its worksheets. Every worksheet can only contain up to 65,536 rows and 255 columns of data. This means that the data and constraints must be contained in separate worksheets for the optimization; however, the default Excel solver can only optimize a model that has all the data and constraints contained in one worksheet. The Premium Solver Platform, a "flagship" worksheet optimization product from Frontline Systems, not only can solve more variables and constraints (up to 8000 variables and 8000 constraints), it can also handle data and constraints that are stored in different worksheets. Another alternative is to use Excel 2007, which can contain up to 1 million rows and 16,000 columns in each of its worksheets. This option was not chosen because Excel 2007 is relatively new and is not yet widely used in the TACOM LCMC and PEO CS/CSS organizations.

c.   *Limitations of Excel Premium Solver Platform*

Although the Premium Solver Platform can handle problems with up to 8000 variables and 8000 constraints, the LTWV LP model can easily expand to a scale at which the Premium Solver Platform can no longer handle it. The Premium Solver Platform currently can handle the LTWV LP model up to eleven age groups, four capabilities, one recap option, twelve planning years and fifteen vehicle variants. If there is a need to increase any of the indices (age group, capability, recap option, planning years and vehicle variants), then it will be necessary to purchase a higher version solver (Large-Scale LP Solver from Frontline Systems) that can handle up to 32,000 variables and 32,000 constraints. Frontline System also has an extended version of the Large-Scale LP Solver that can handle unlimited variables and constraints but which comes with a

higher price. For the purpose of this research, the Premium Solver Platform is sufficient to execute and analyze the results from the LTWV LP model.

2.   Assumptions

The first assumption is that a vehicle can only recap to a higher and better variant. This assumption is further enforced by putting a cross on those indices that contain the pairs of vehicle variants to recap from and recap. This option can be found under the "Indices" tab or worksheet of the Excel LP Model workbook, as shown in Figure 30.

Vehicles pairs where v can be converted into vehicle v1 (v,v1)		Enter a "x" to select those indices to be used in the model
M1025	M1025	
M1025	M1025A1	x
M1025	M1025A2	
M1025	M1097	
M1025	M1097A1	
M1025	M1097A2	
M1025	M996	
M1025	M996A1	
M1025	CTV1A	
M1025	CTV2A	
M1025	CTV3A	
M1025	LRS1A	
M1025	LRS2A	
M1025	UVL1	
M1025	UVH1	
M1025A1	M1025	
M1025A1	M1025A1	
M1025A1	M1025A2	x
M1025A1	M1097	
M1025A1	M1097A1	
M1025A1	M1097A2	
M1025A1	M996	
M1025A1	M996A1	
M1025A1	CTV1A	

Figure 29.   Vehicle Pairs for Recapitalization

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There are two counters (Value and Discount Factors, Figure 31) on the "User Interface" worksheet that represents the value provided for aging vehicles and the discount given for maintaining aging vehicles, respectively.

Vehicles pairs where v can be converted into vehicle v1 (v,v1)		Enter a "x" to select those indices to be used in the model
M1025	M1025	
M1025	M1025A1	x
M1025	M1025A2	
M1025	M1097	
M1025	M1097A1	
M1025	M1097A2	
M1025	M996	
M1025	M996A1	
M1025	CTV1A	
M1025	CTV2A	
M1025	CTV3A	
M1025	LRS1A	
M1025	LRS2A	
M1025	UVL1	
M1025	UVH1	
M1025A1	M1025	
M1025A1	M1025A1	
M1025A1	M1025A2	x
M1025A1	M1097	
M1025A1	M1097A1	
M1025A1	M1097A2	
M1025A1	M996	
M1025A1	M996A1	
M1025A1	CTV1A	

Figure 30.   **Vehicle Pairs for Recapitalization**

There are two counters (Value and Discount Factors, Figure 31) on the "User Interface" worksheet that represents the value provided for aging vehicles and the discount given for maintaining aging vehicles, respectively.

Figure 31. Value Factor and Discount Factor

The value factor is currently set to 0. This means that all the vehicles provide the same capability value throughout their entire lifespan.

The discount factor is currently set to 5%. This means that every year, there is a discount of 5% to account for annual expenses.

These values can be easily increased or decreased by model users.

The figure for the annual maximum purchase allowed for each vehicle variant is derived from the maximum number of vehicles that can be manufactured and delivered each year. The production of JLTVs is set to start in the year 2008 and is constant throughout the entire modernization period. It is also assumed that all production of the HMMWVs will stop after year 2012.

The demand for capability is purposely set higher than what can be provided by the LTWV fleet in order to look at the maximum capability that can be provided each year. It is also assumed to be consistent for the next twelve years, with a slight increase from 2012 onwards.

The maximum number of vehicle that can undergo recapitalization is set to a maximum of 2000 per year. This number is equivalent to the number of recaps the workshops can handle every year. The cost for each recap is also set at a constant 50,960 FY07$ (Koerner and McDonald, 2007) for each vehicle variant.

The annual operating costs for HMMWVs and JLTVs are set at 5,486.10 FY07$ and 5,386.10 FY07$, respectively. The actual operating costs were not available at the time that this research was conducted. They are assumed to be the same for all the HMMWV and JLTV variants.

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In the baseline case, the projected budget of 15.8 billion FY08$ (as stated in the JLTV CDD) is spread equally across ten years for the entire modernization period.

All the above figures and numbers can be easily updated by going to the "Params" worksheet to update once the actual numbers are available.

C.   OBSERVATIONS

The results for the Excel LP Model in which the budget has been evenly allocated across the ten year period are shown in Figures 31, 32, and 33. This model will also be used a baseline model for comparison in the sensitivity analysis portion. The ten year period can be adjusted to be shorter or longer , depending on the modernization period that TACOM users choose to utilize.
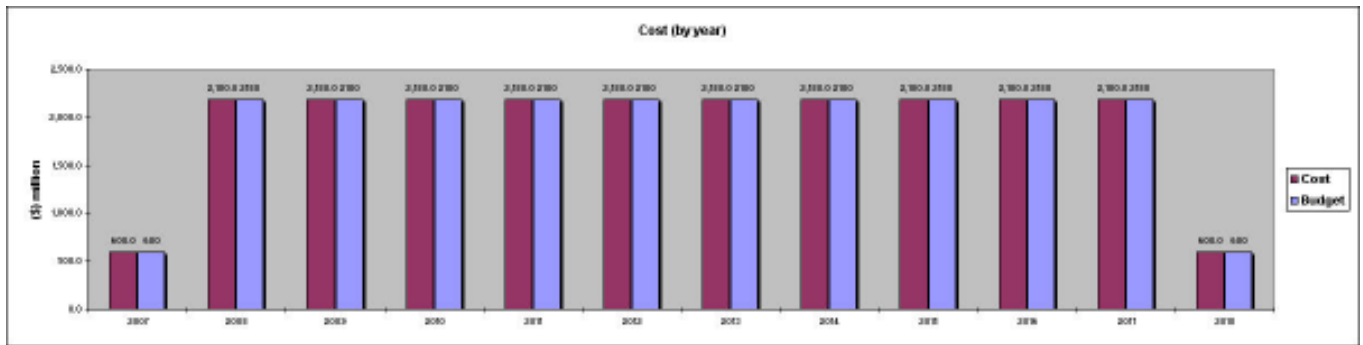
Figure 32.   Operation Cost for Evenly Distributed Budget
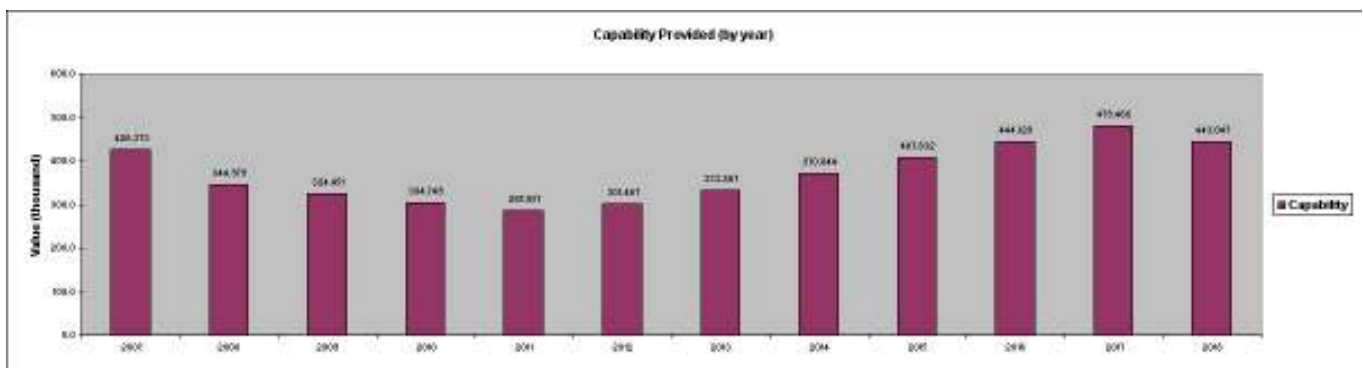
Figure 33.   Capability Provided by Evenly Distributed Budget

The budget of 15.8 billion FY08$ is used entirely during the ten year period as shown in Figure 32. There is a significant drop in the capability value, from 426,373 to

344,979, at the beginning of the modernization program in 2008. This drop in capability value results from the fact that the number of retiring HMMWVs is greater than the number of new JLTVs that are procured; the limited number of new JLTVs that are delivered will not be sufficient to sustain the existing high demand for capability. A steady increase in the capability value can be observed beginning in 2012, when there are fewer aging HMMWVs to be retired and the increasing numbers of delivered JLTVs are sufficient to sustain the demand. The maximum capability value that can be provided by the JLTVs is at the end of the modernization period in 2017 with a value of 479,466. The average capability value that is provided from 2007 to 2018 is 372,205. At the end of the modernization period, the capability value meets the requirements and exceeds the starting value of 426,373 at the beginning of the modernization period.
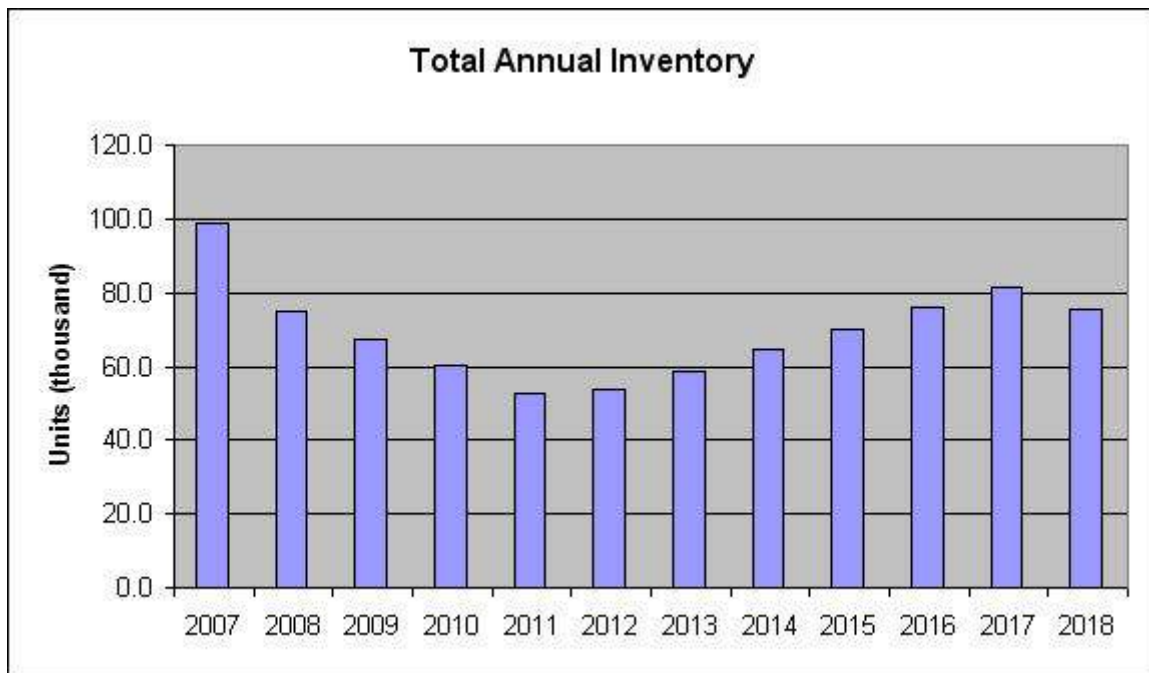
Figure 34.   Total Annual Inventory

Figure 34 demonstrates that, at the end of the modernization period, <u>fewer</u> vehicles are required to achieve <u>higher</u> capability values. This is due to the replacement to the higher capabilities of the JLTVs that have replaced the HMMWVs. The inventory details and the average age for each vehicle variant can be found in Annex A and Annex B.

D. SENSITIVITY ANALYSIS

Seven additional runs were executed using the Excel LP Model (Figures 34-54). These runs inputted different parameters in order to gauge their impacts on the total cost and capability provided during the modernization strategy period. These parameters include different allocations of the budget, the number of vehicles that can be delivered each year and the average age of the vehicles in the fleet.

1. Decreasing Budget Allocation
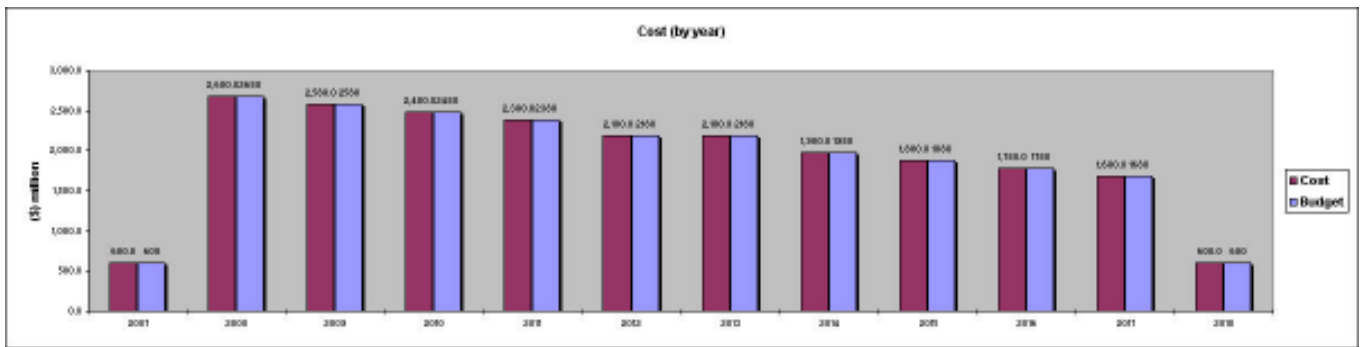
Figure 35.   Operation Cost for Decreasing Budget Allocation
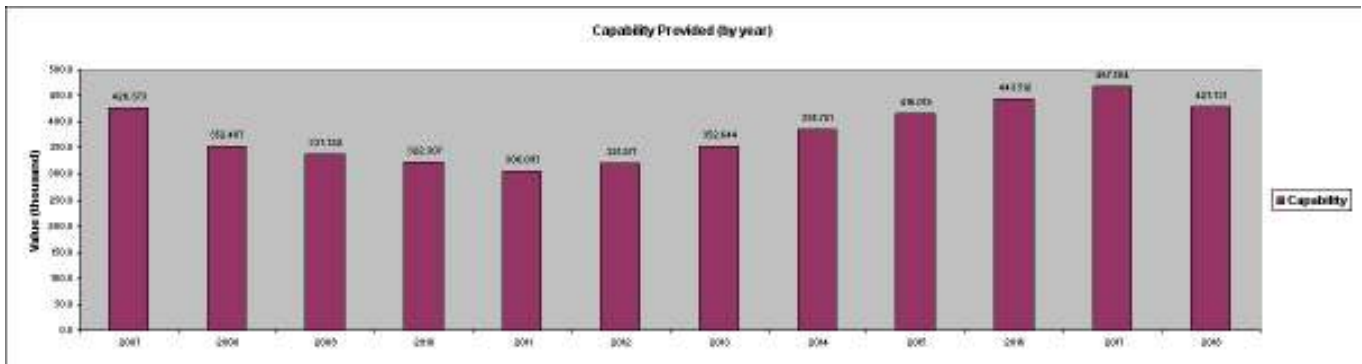
Figure 36.   Capability Provided by Decreasing Budget Allocation
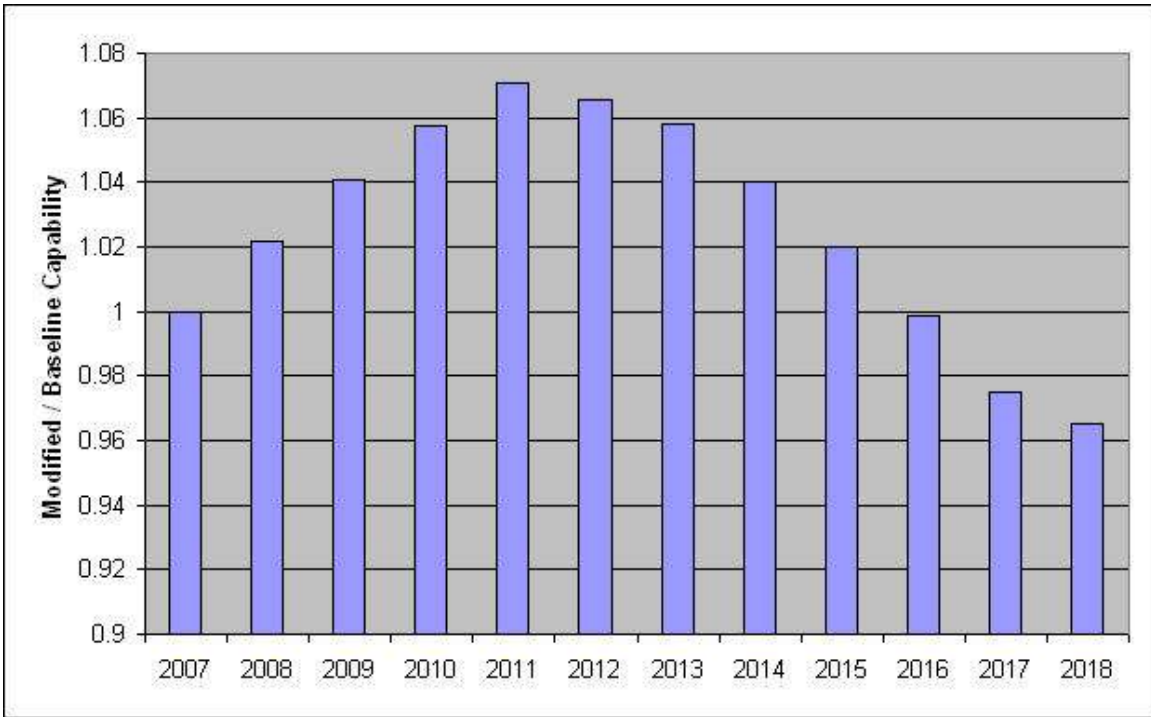
Figure 37.   Capability Comparison for Decreasing Budget Allocation

If a larger portion of the 15.8 billion FY08$ budget is allocated at the beginning of the modernization period and the annual figure then decreases during subsequent years, as shown in Figure 35, the lowest capability provided is in year 2011 at a value of 306,097, and the highest value that can be provided is 467,564 in year 2017. The average capability value that is provided from 2007 to 2018 is 379,947. The capability value that is provided at the end of the modernization exceeds the initial value of 426,373 at the beginning of the modernization period. These values are shown in Figure 36.

Figure 37 shows the ratio of the new capability provided by a decreasing budget allocation to the capability provided from the baseline model in Figure 33. This budget allocation generally provides higher capability values than the baseline model for eight consecutive years (2008 to 2015).

2. Increasing Budget Allocation
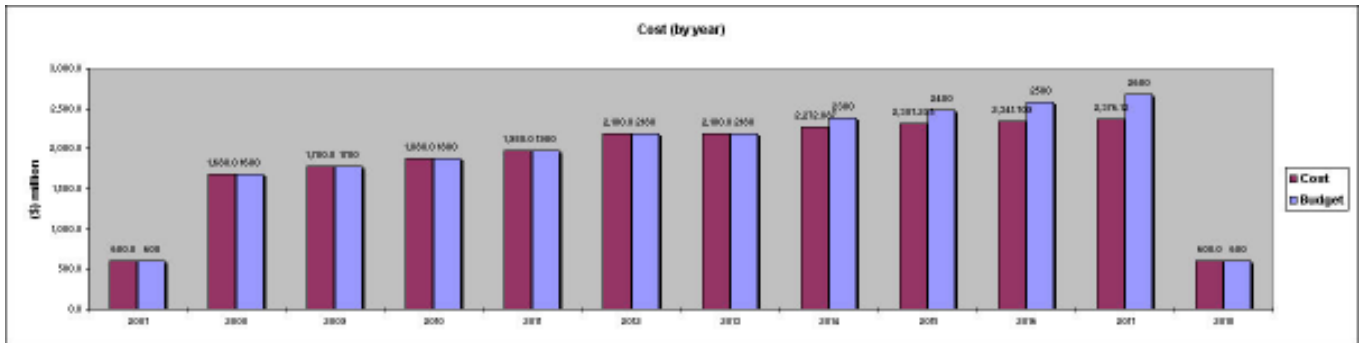
Figure 38.   **Operation Cost for Increasing Budget Allocation**
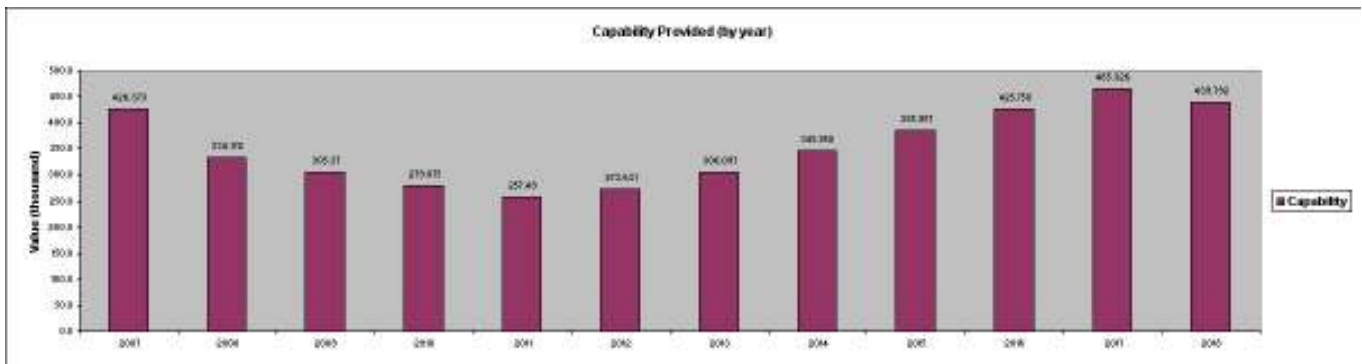
Figure 39.   **Capability Provided by Increasing Budget Allocation**
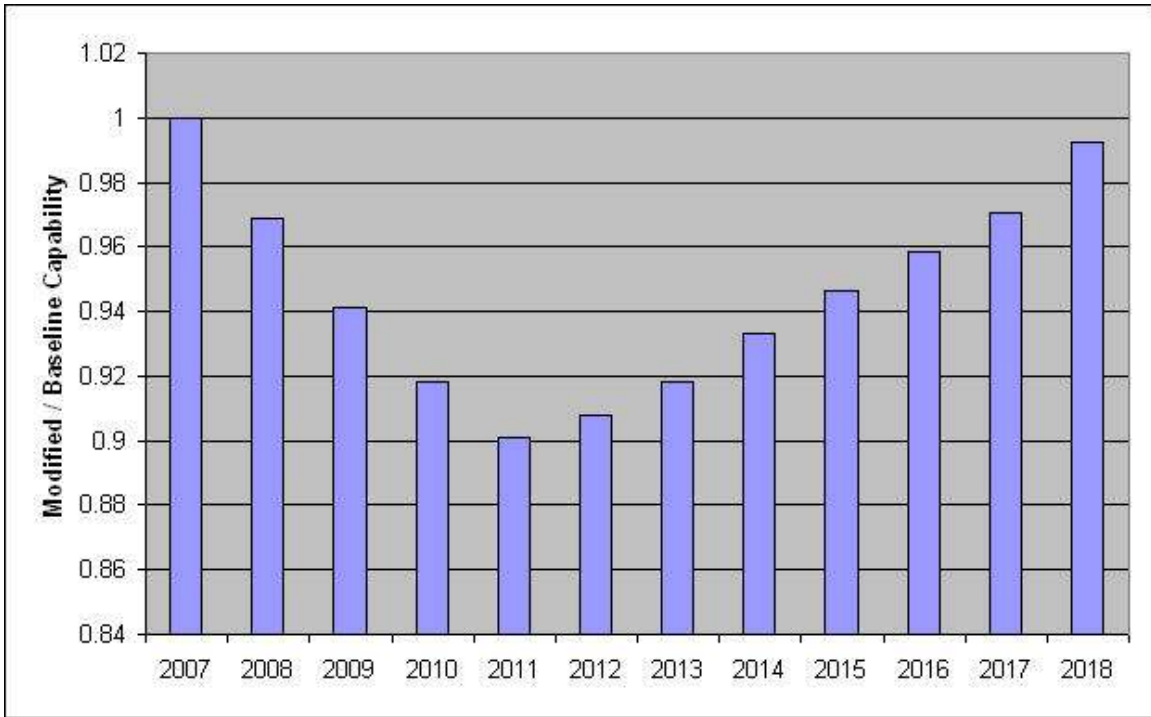
Figure 40.   **Capability Comparison for Increasing Budget Allocation**

If a smaller portion of the 15.8 billion FY08$ budget is allocated in the beginning of the modernization period and the annual figure then increases during subsequent years, as shown in Figure 38, the lowest capability provided is in year 2011 at a value of 257,490 and the highest value that can be provided is 465,326 in year 2017. The average capability value that is provided from 2007 to 2018 is 353,816. The capability value that is provided at the end of the modernization exceeds the initial value of 426,373 at the beginning of the modernization period. These values are shown in Figure 39.

Figure 40 shows the ratio of the new capability that can be provided to the capability provided from the baseline model in Figure 33. This budget allocation generally provides lesser capability values than the baseline model throughout the entire modernization period.

3.   Decrease in Budget Amount
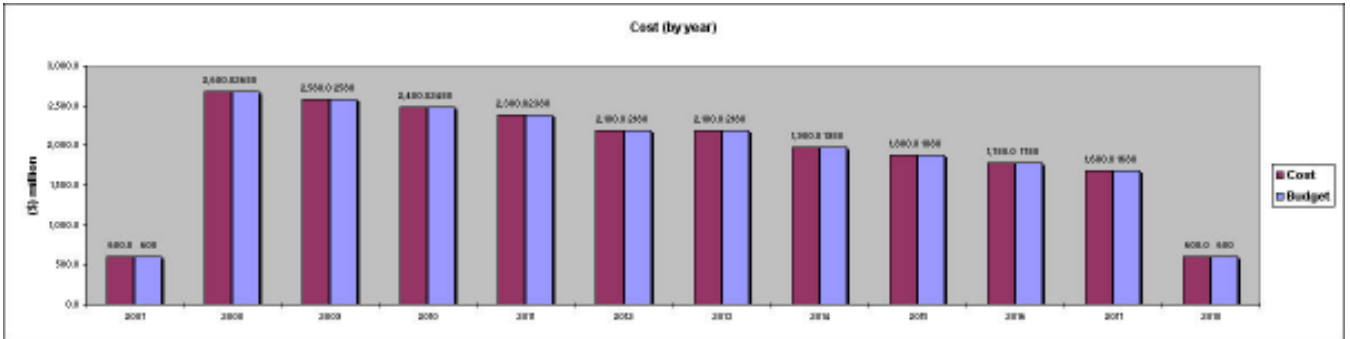
Figure 41.   Operation Cost for Decrease in Budget Amount
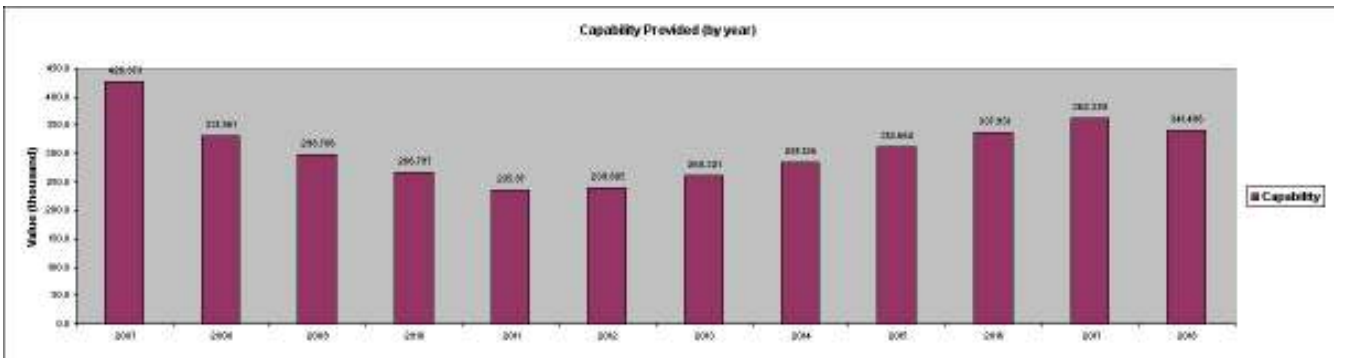
Figure 42.   Capability Provided by Decrease in Budget Amount
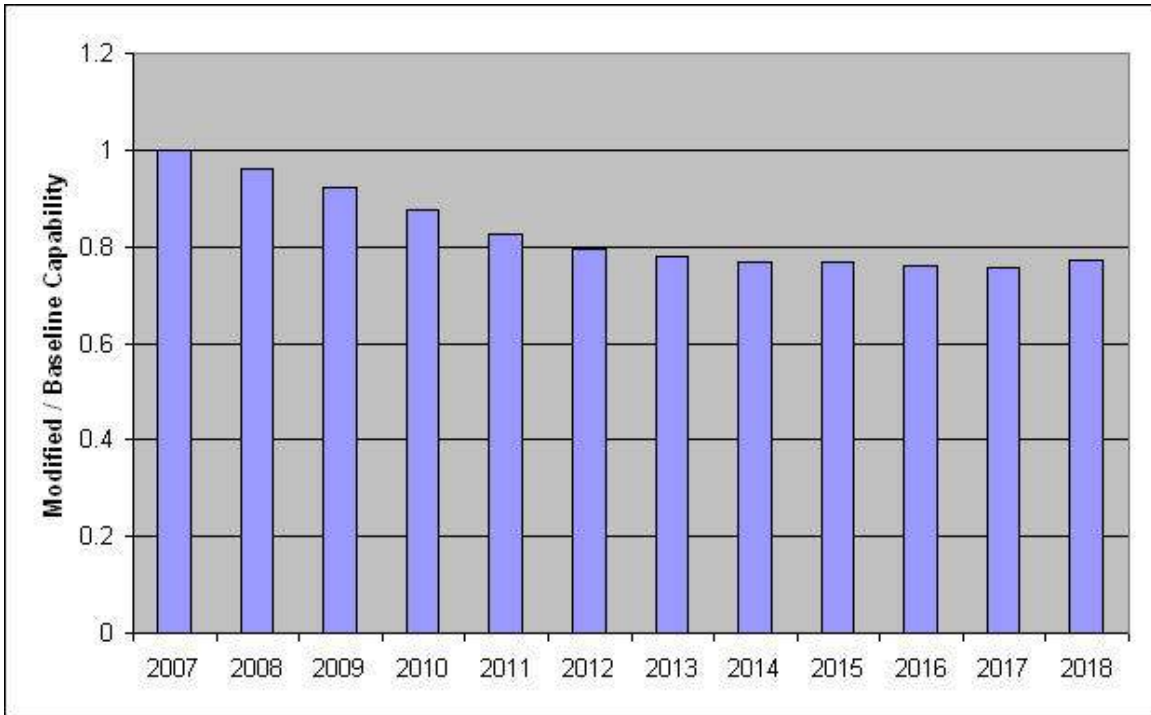
Figure 43.   Capability Comparison for Decrease in Budget Amount

If the budget of 15.8 billion FY08$ shrinks by 600 million FY08$ each year, as shown in Figure 41, the lowest capability provided is in year 2011 at a value of 235,970 and the highest value that can be provided is 362,399 in year 2017. The average capability value that is provided from 2007 to 2018 is 308,301. The capability value that is attained at the end of the modernization period fails to exceed the initial value of 426,373. These values are shown in Figure 42.

Figure 43 shows the ratio of the new capability that can be provided to the capability provided from the baseline model in Figure 33. An annual decrease in the budget amount generally results in lesser capability values than the baseline model throughout the entire modernization period.

4. Increase in Budget Amount
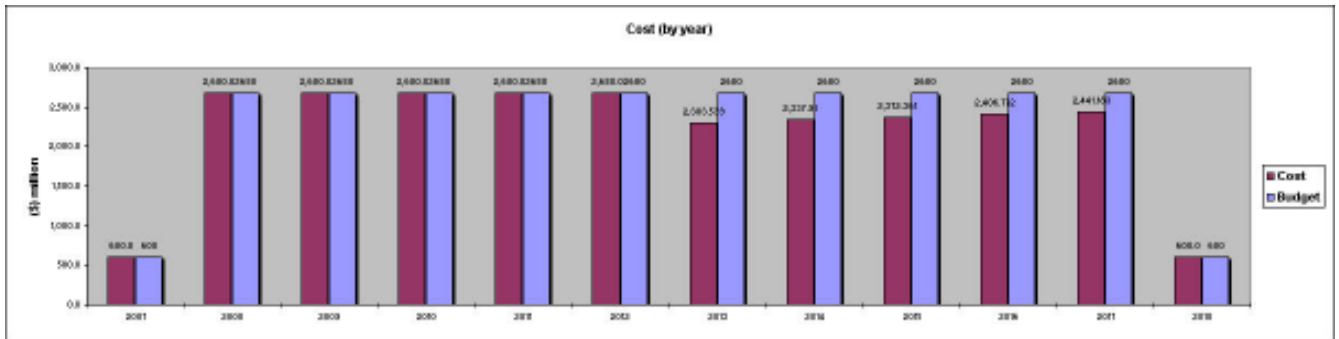
Figure 44. Operation Cost for Increase in Budget Amount
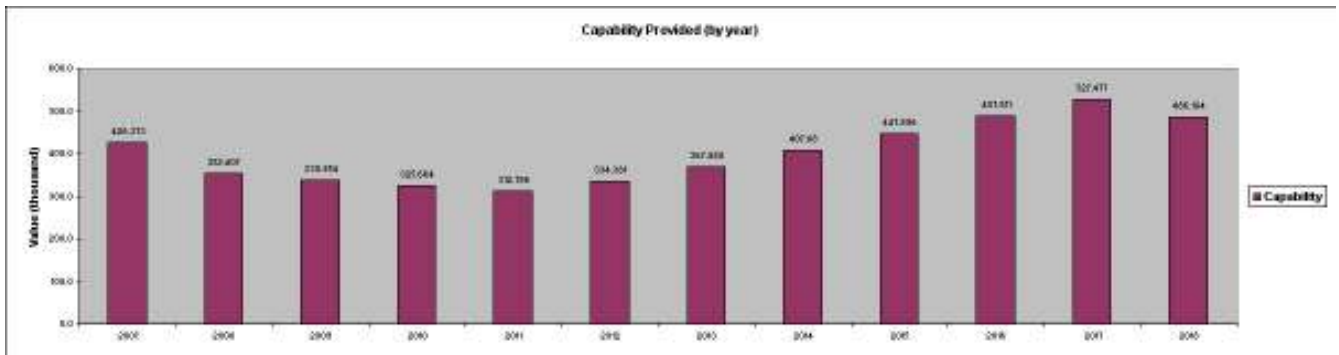
Figure 45. Capability Provided by Increase in Budget Amount
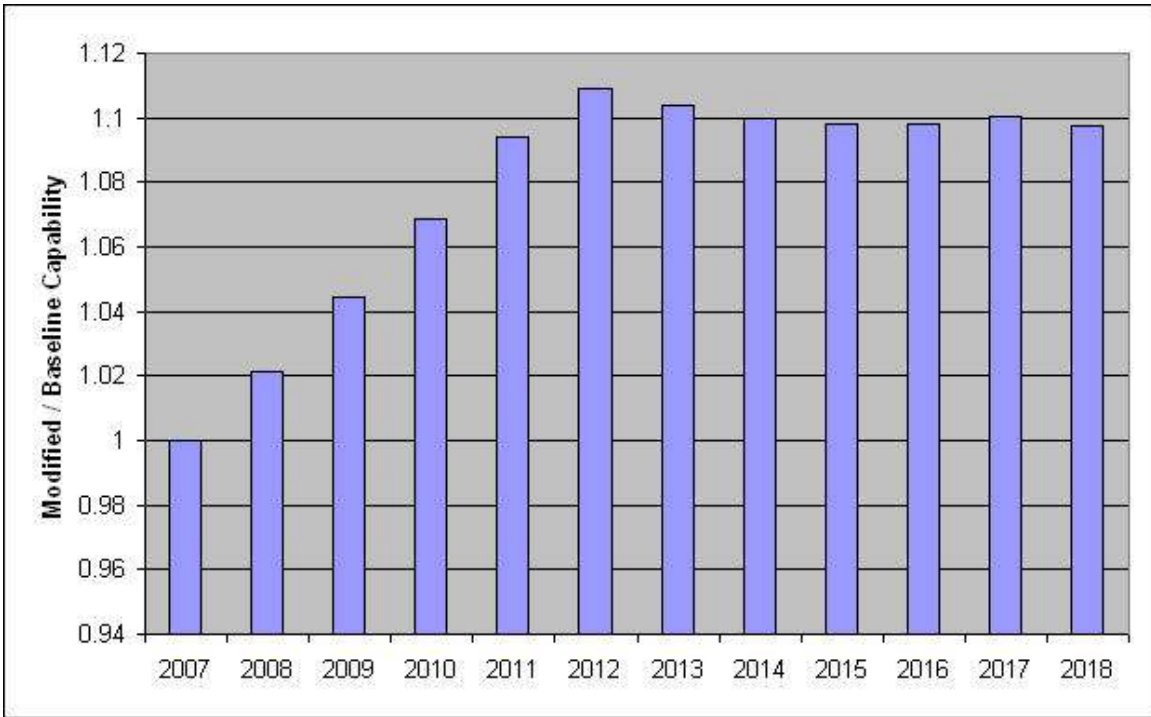
Figure 46.   Capability Comparison for Increase in Budget Amount

If the budget of 15.8 billion FY08$ increases by 500 million FY08$ each year, as shown in Figure 44, the lowest capability provided is in year 2011 at a value of 312,786 and the highest value that can be provided is 527,477 in year 2017. The average capability value that is provided from 2007 to 2018 is 401,303. The capability value that is attained at the end of the modernization exceeds the initial value of 426,373 at the beginning of the modernization period. These values are shown in Figure 45.

Figure 46 shows the ratio of the new capability that can be provided to the capability provided from the baseline model in Figure 33. An increase in budget amount generally provides better capability values than the baseline model throughout the entire modernization period, with the maximum increase in 2012.

5.   **Limited Production for all Vehicle Variants**
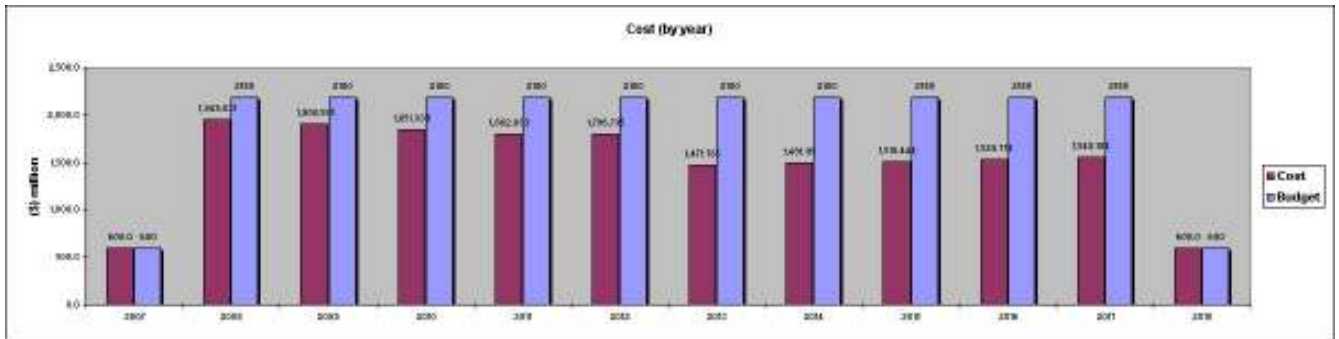
Figure 47.   Operation Cost for Limited Vehicle Production
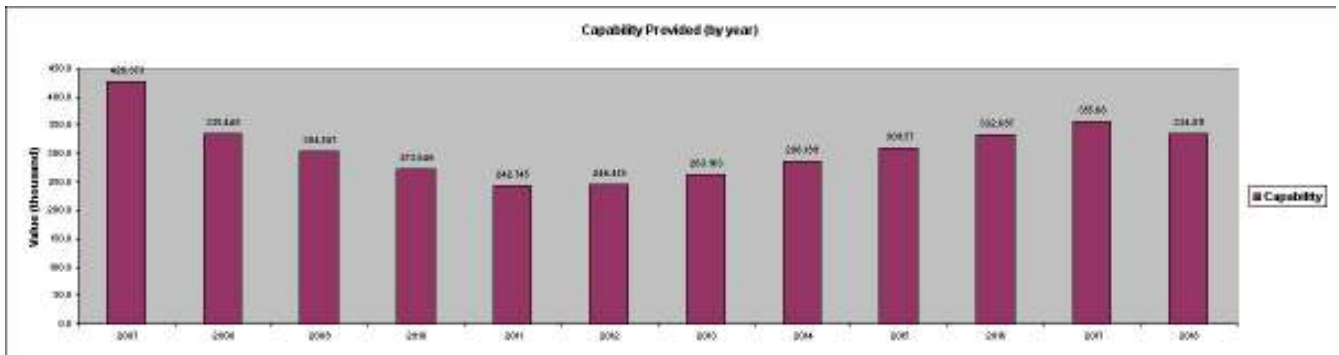
Figure 48.   Capability Provided by Limited Vehicle Production
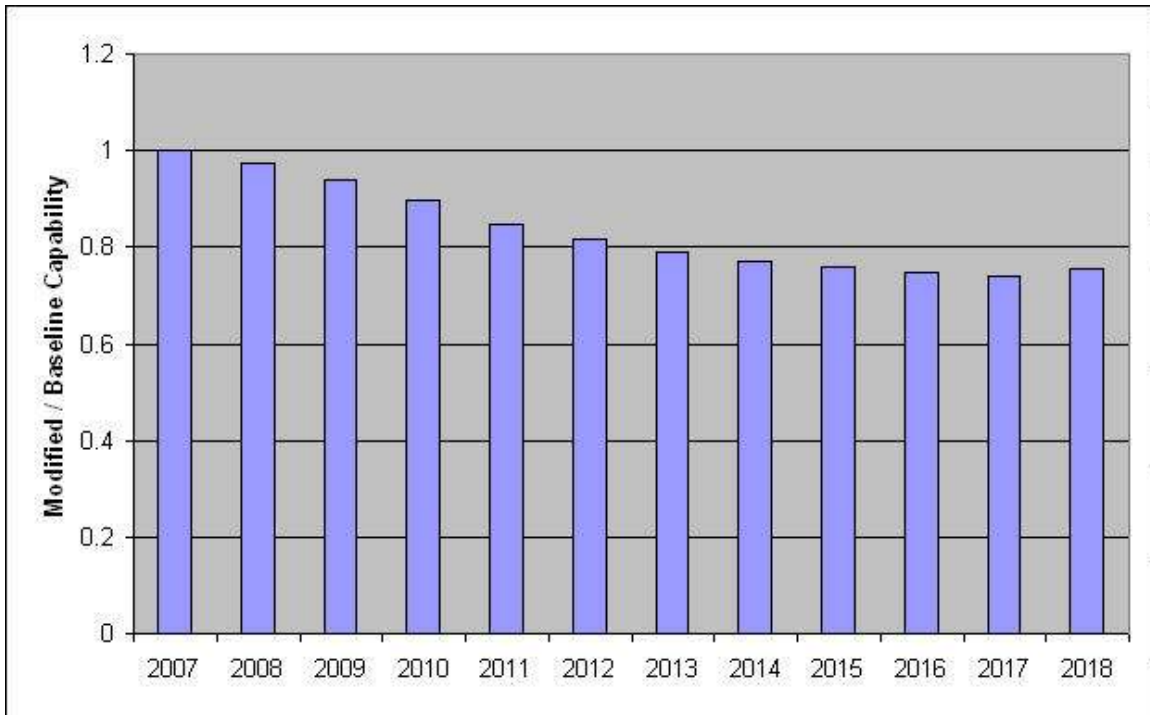
Figure 49.   Capability Comparison for Limited Vehicle Production

The maximum yearly purchase allowed for each vehicle variant can be determined by the budget available, by the inventory level and by the number of vehicles that can be produced by the manufacturers. If the maximum yearly purchase allowed for each vehicle variant must be decreased by 40% due to limited availability of new vehicles, as shown in Figure 47, the lowest capability provided is in year 2011 at a value of 242,745 and the highest value that can be provided is 355,680 in year 2017. The average capability value provided from 2007 to 2018 is 309,275. The capability value that is attained at the end of the modernization fails to exceed the initial value of 426,373 at the beginning of the modernization period. These values are shown in Figure 48.

Figure 49 shows the ratio of the new capability that can be provided over the capability provided from the baseline model in Figure 33. The decrease in vehicle production generally provides lesser capability values than the baseline model throughout the entire modernization period.

6. Limited Production for JLTV
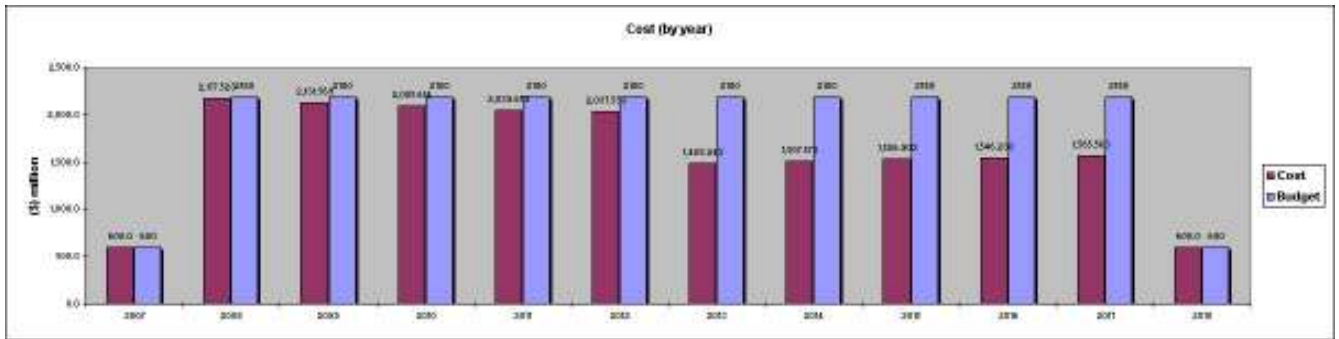
Figure 50.   Operation Cost for Limited JLTV Production
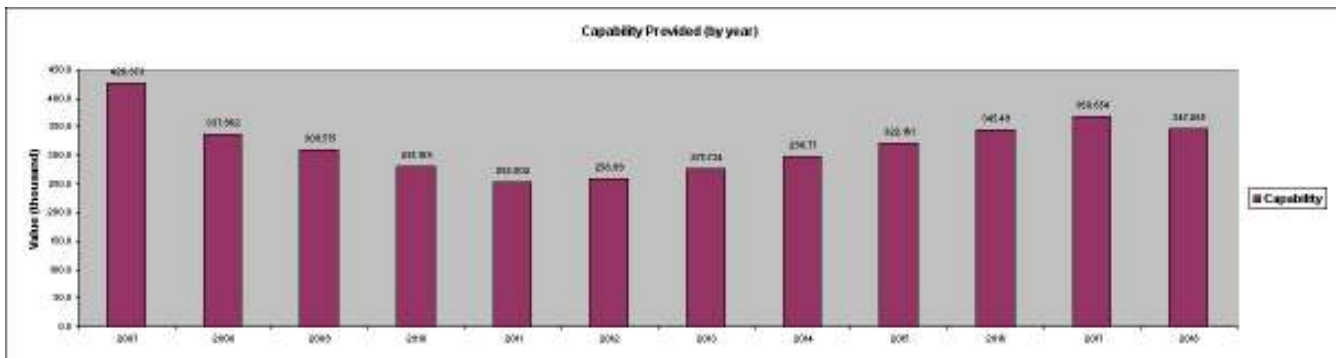
Figure 51.   Capability Provided by Limited JLTV Production
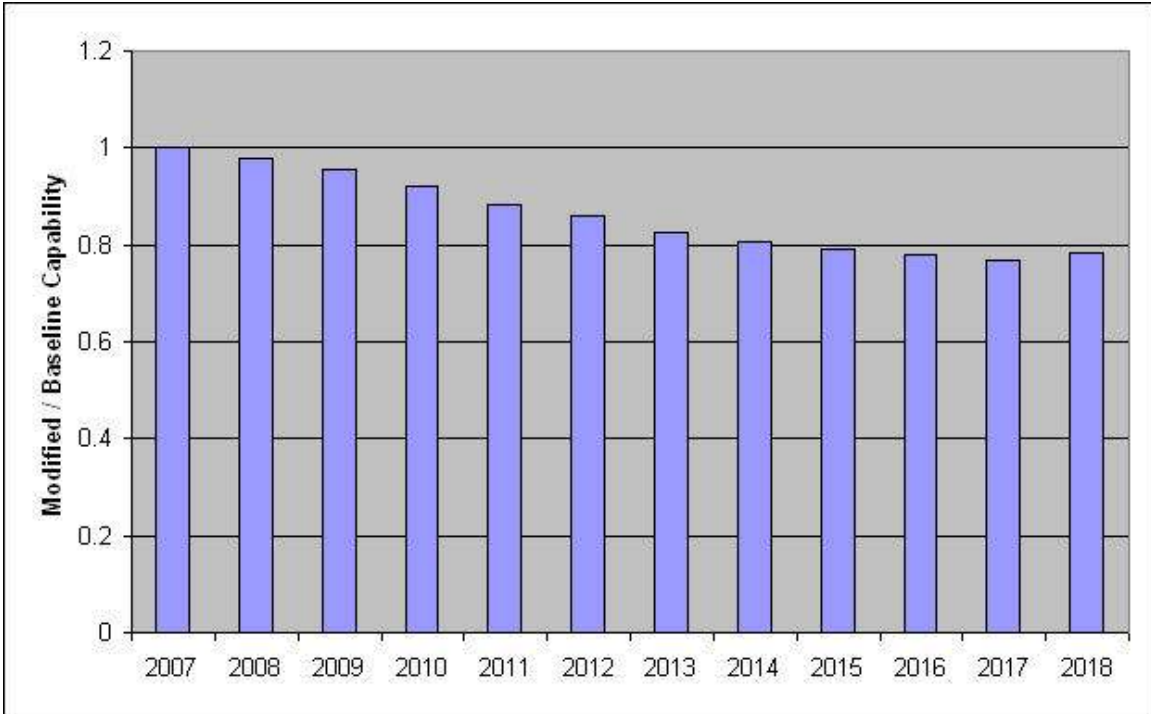
Figure 52.   Capability Comparison for Limited JTLV Production

If the maximum yearly purchase allowed for each JLTV variant is decreased by 40% due to limited production, as shown in Figure 50, the lowest capability provided is in year 2011 at a value of 252,802 and the highest value that can be provided is 368,654 in year 2017. The average capability value from 2007 to 2018 is 318,747. The capability value that is attained at the end of the modernization fails to exceed the initial value of 426,373. These values are shown in Figure 51.

Figure 52 shows the ratio of the new capability that can be provided to the capability provided from the baseline model in Figure 33. The decrease in JTLV production generally provides lesser capability values than the baseline model throughout the entire modernization period.

7.   Maintaining a Young Fleet
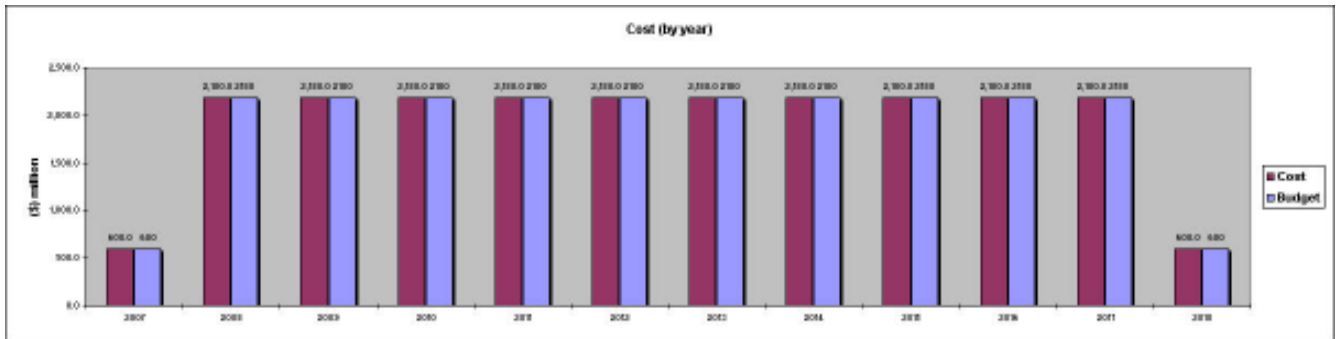
Figure 53.   Operation Cost for Maintaining a Young Fleet
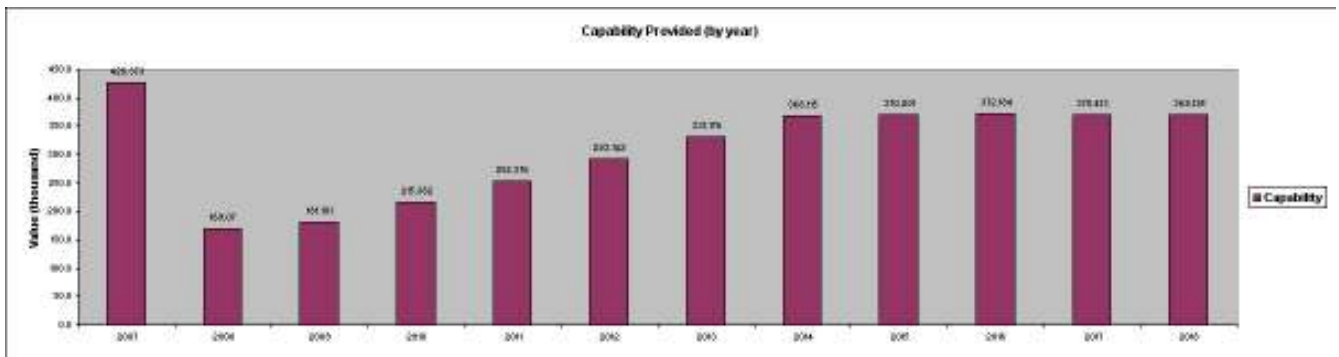
Figure 54.   Capability Provided by Maintaining a Young Fleet
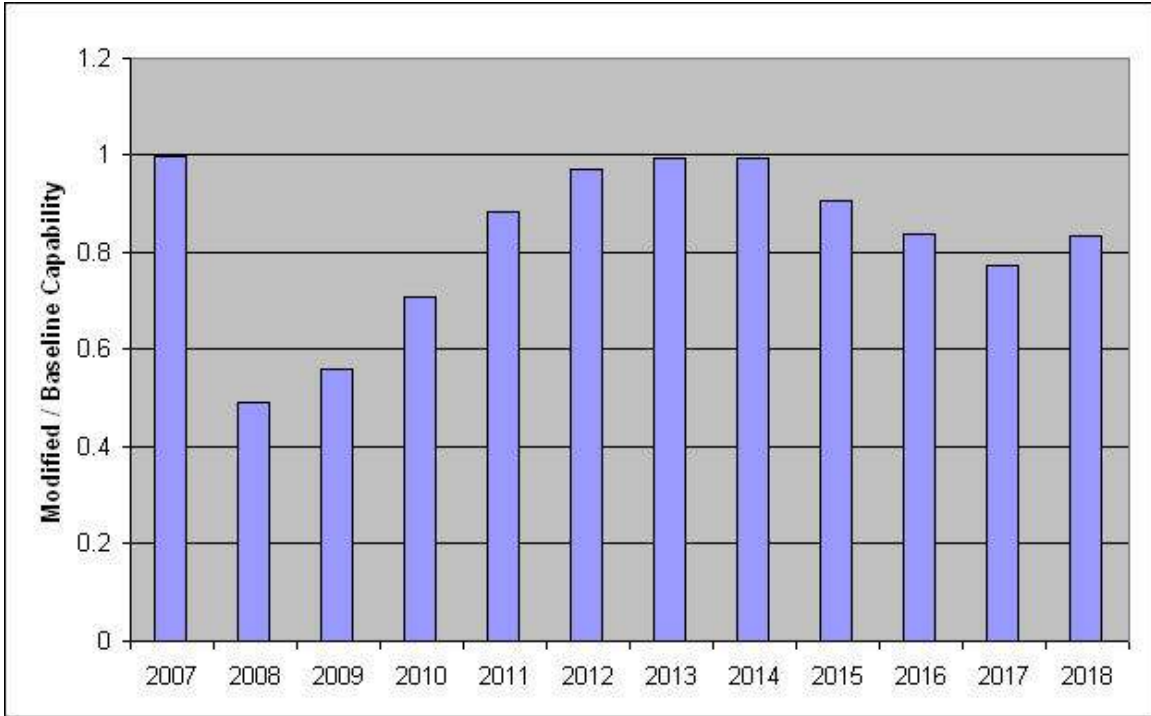
Figure 55.   Capability Comparison for Maintaining a Young Fleet

If the maximum average age for each vehicle variants is decreased to three years instead of the original ten years in order to maintain a younger fleet, and the budget is allocated as shown in Figure 53 that is the same as the baseline model, the lowest capability provided is in year 2008 at a value of 169,070 and the highest value that can be provided is 372,184 in year 2016. The average capability value from 2007 to 2018 is 309,894.   The capability value that is attained at the end of the modernization fails to exceed the initial value of 426,373 at the beginning of the modernization period. These values are shown in Figure 54.

Figure 55 shows the ratio of the new capability that can be provided over the capability provided from the baseline model in Figure 33. To maintain a younger fleet will generally means providing lesser capability values than the baseline model throughout the entire modernization period.

V. CONCLUSION AND RECOMMENDATION

A. CONCLUSION

It is necessary for the U.S. Army to replace the aging HMMWVs with the newer and more capable JLTVs in order to meet the increase in operational demands. The JLTVs are still in the design phase and will not be available for several years. Proper planning and allocation of the budget is necessary in order to facilitate a smooth transition for the Light Tactical Wheeled Vehicle fleet. This transition includes the extension of the lifespan of the HMMWV fleet until the JLTVs are ready to be integrated.

The U.S. Army has implemented many programs to extend the lifespan of the HMMWV fleet. One such program is the Recapitalization Program that upgrades HMMWVs to more robust variants while the JLTVs are being developed.

This thesis makes use of the Value Model and LP Model from Koerner and McDonald's research work (2007), implementing them a working tools that can be used by the U.S. Tank-Automotive and Armament Command (TACOM) and the Program Executive Office, Combat Support and Combat Service Support (PEO CS/CSS) to aid them in their planning and decision making.

This tool is developed in Excel and uses the Premium Solver Platform as the optimization engine. The information that is used by this tool comprises both real and notional data; this optimization tool is not designed to make specific recommendations for future planning, but rather to demonstrate the tool's versatility and evolutionary capabilities. The notional data gathered are logical, and require subject matter expert recommendations before they are used. The analytic results are generally, but not specifically, valid. Further analysis is recommended before any of these results are implemented as policy.

The results of this study indicate that increasing the budget does result in a higher capability to meet operational demand, but that the higher capability is limited by the number of new JLTVs that can be manufactured each year. One resolution to this

limitation is to spread the budget across a longer period so that more JLTVs would be available to provide the capabilities to meet operational demands. This raises an important point: Although the budget plays an important role in the contribution of better capabilities, the number of JLTVs that can be produced each year to sustain the demand is another important factor. The fewer JLTVs that can be delivered each year, the longer the modernization period required to meet the demand. The current results are base upon notional data but they are still able to give real insights into this modernization issue.

B.   RECOMMENDATIONS

The Excel LP model is compatible with all versions of Premium Solvers. It currently uses the Excel Premium Solver Platform that can solve for a limited number of variables and constraints. TACOM and LCMC and PEO CS/CSS users will be able to solve for more vehicle variants across more planning years with wider age groups if a higher version of Premium Solver, such as Large-Scale LP Solver, is used. The Excel LP model, by accommodating information for all the vehicle variants will be able to give more accurate results to TACOM LCMC and PEO CS/CSS decision makers.

APPENDIX A.   EXCEL PREMIUM SOLVER VERSIONS

Product Name	Software License	Linear Variables x Constraints	Non-Linear Variables x Constraints
Premium Solver	$745	2000 x 1000	400 x 200
Premium Solver Platform	$1,495	8000 x 8000	500 x 250
Risk Solver	$995	na	na
Risk Solver Engine	$695	na	na
Std. Large-Scale LP Solver Engine	$2,995	32000 x 32000	na
Ext. Large-Scale LP Solver Engine	$4,995	No fix limits	na
XPRESS Solver Engine - LP/MIP Only	$5,995	No fix limits	na
XPRESS Solver Engine - LP/QP/MIP	$7,695	No fix limits	No fix limits
Large-Scale GRG Solver Engine	$1,250	na	4000 x 4000
Ext. Large-Scale GRG Solver Engine	$2,500	na	12000 x 12000
Large-Scale SQP Solver Engine	$3,995	No fix limits	No fix limits
KNITRO Solver Engine	$3,995	na	No fix limits
MOSEK Solver Engine - SOCP	$3,995	No fix limits	na
MOSEK Solver Engine - SOCP/NLP	$4,995	No fix limits	No fix limits
OptQuest Solver Engine	$2,500	na	5000 x 1000

For more information on the solvers, please refer to www.solver.com

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APPENDIX B.   LINEAR PROGRAM FORMULATION

Indices and Sets [expected cardinality]

$a \in A$	set of age groups (years old) $\left[\,\lvert A \rvert \approx 25\right]$
$c \in C$	set of capabilities $\left[\,\lvert C \rvert \approx 6\right]$
$r \in R$	set of recap options $\left[\,\lvert R \rvert \approx 10\right]$
$t \in T$	set of planning years $\left[\,\lvert T \rvert \approx 15\right]$
$v \in V$	set of vehicle variants $\left[\,\lvert T \rvert \approx 20\right]$
$v' \in AT_{av}$	set of vehicles v' that can be obtained from vehicle v that is a years old
$v' \in AF_v$	set of vehicles v' that can be converted into vehicle v
$(v', v) \in AFT$	set of vehicles pairs where v' can be converted into vehicle v

Data

$\overline{age}_v$	maximum age for vehicle v
$aval_{artv'v}$	fraction of a year vehicle v is available in year t when it started out in year t as a vehicle v', a years old before having recap r
$\underline{buy}_{tv}, \overline{buy}_{tv}$	minimum and maximum purchases allowed for vehicle v in year t
ii_{av}	initial inventory of vehicle v and age a
$\underline{fage}_{tv}, \overline{fage}_{tv}$	minimum and maximum average age for vehicle v at the start of year t
$\overline{rcap}_{rt}$	maximum recaps r allowed in year t
map_{actv}	capability c offered by vehicle v and age a in year t
dem_{ct}	demand for capability c in year t
om_{atv}	year t operating cost for vehicle v that is age a
$cap_{artvv'}$	cost to recap vehicle v, a years old into v' using recap r in year t
new_{tv}	cost to take delivery of vehicle v in year t
old_{tv}	cost to retire vehicle v in year t
$budget_t$	budget available in year t
$\overline{retire}_{tv}$	maximum retires allowed for vehicle v in year t

Variables

$E_{artvv'}$ number of vehicle v, a years old to recap into v' using recap r at the start of year t

I_{atv} number of vehicle v, a years old at the start of year t

P_{tv} number of vehicle v to purchase at the start of year t

R_{atv} number of vehicle v, a years old to retire at the start of year t

$EAGElo_{t,v}$ elastic minimum average age of vehicle v at the start of year t

$EAGEhi_{t,v}$ elastic maximum average age of vehicle v at the start of year t

$EDEM_{ct}$ elastic demand capability c at the start of year t

$EBUD_{t}$ elastic budget at the start of year t

Formulation

Objective Function:

$$Min \sum_{t,v} EAGElo_{t,v} + \sum_{t,v} EAGEhi_{t,v} + \sum_{ct} EDEM_{ct} + \sum_{t} EBUD_{t}$$

Minimize all elastic variables

Subject to the following constraints:

$$I_{atv}\big|_{a\leq \overline{age}_v} + R_{atv} + \sum_{v'\in AT_v} E_{artvv'} = I_{a-1,t-1,v} \qquad \forall \ 2\leq a, t>2, v$$

Balance the inventory over time for vehicles that have retired or recapped into another vehicle variant

$$I_{atv}\big|_{a>\overline{age}_v} = 0$$

Inventory is set to zero for vehicles that exceeded their allowable maximum age

$$I_{atv} = \sum_{a',r,v'\in AF_v} E_{a'r,t,v'v} + P_{t,v} \qquad \forall \ a=1, t>2, v$$

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Balance the inventory over time for addition new vehicles and recapped vehicles

$$I_{atv} = ii_{av} \qquad\qquad \forall\, a, t = 1, v$$

The first year inventory for each vehicle type is set to the initial inventory level

$$\sum_{a,(v',v)\in AFT} E_{artv'v} \le \overline{rcap}_{rt} \qquad\qquad \forall\, r, t$$

The number of vehicles to recap is limited by the maximum recap capacity

$$\sum_{a} R_{atv} \le \overline{retire}_{tv} \qquad\qquad \forall\, t, v$$

The number of vehicles to retire is limited by the maximum retire capacity

$$\underline{buy}_{tv} \le P_{tv} \le \overline{buy}_{tv} \qquad\qquad \forall\, t, v$$

The number of new vehicles to purchase must be between the minimum and maximum capacity

$$\sum_{a} \underline{fage}_{tv} \left(\begin{array}{l} I_{atv} + \displaystyle\sum_{a,r,v'\in AF_v} aval_{artv'v} E_{artv'v} \\ + \displaystyle\sum_{a,r,v'\in AF_v} (1 - aval_{artvv'}) E_{artv'v} \end{array} \right) - EAGElo_{t,v} \,\dot{\le}\, \sum_{a} a\, I_{atv} \qquad \forall\, t, v$$

Overall fleet inventory age must be more than the allowable minimum average age (constraint can be violated by the elastic minimum average age variable)

$$\sum_{a} a\, I_{atv} \,\dot{\le}\, \sum_{a} \overline{fage}_{tv} \left(\begin{array}{l} I_{atv} + \displaystyle\sum_{a,r,v'\in AF_v} aval_{artv'v} E_{artv'v} \\ + \displaystyle\sum_{a,r,v'\in AF_v} (1 - aval_{artvv'}) E_{artv'v} \end{array} \right) + EAGEhi_{t,v} \qquad \forall\, t, v$$

Overall fleet inventory age must be less than the allowable maximum average age (constraint can be violated by the elastic maximum average age variable)

$$\sum_{a,v} w_c map_{actv} I_{atv} + \sum_{a,r,v,v' \in AF_v} w_c map_{0ctv} aval_{artv'v} E_{artv'v}$$
$$+ \sum_{a,r,v,v' \in AF_v} w_c map_{0ctv} \left(1 - aval_{artvv'}\right) E_{artv'v} \;\dot{\geq}\; dem_{ct} - EDEM_{ct} \qquad \forall\, ct$$

The value provided by each vehicle type must satisfy the demand for each capability (constraint can be violated by the elastic demand variable)

$$\sum_{a,v} om_{atv} I_{atv} + \sum_{a,r,(v',v) \in AFT} cap_{artvv'} E_{artvv'} + \sum_v new_{tv} P_{tv} + \sum_{a,v} old_{tv} R_{atv} \;\dot{\leq}\; budget_t + EBUD_t \quad \forall\, t$$

Operational, recap, purchase and retire costs are within budget (constraint can be violated by the elastic budget variable)

$$I_{atv} \geq 0 \;\; \forall atv; \;\; E_{artvv'} \geq 0 \;\; \forall artvv'; \;\; P_{tv} \geq 0 \;\; \forall tv; \;\; R_{atv} \geq 0 \;\; \forall atv;$$
$$EAGElo_{t,v} \geq 0 \;\; \forall tv; \;\; EAGEhi_{t,v} \geq 0 \;\; \forall tv; \;\; EDEM_t \geq 0 \;\; \forall ct; \;\; EBUD_t \geq 0 \;\; \forall t;$$

Ensures that all the variables satisfy non-negativity constraints

$$E_{artvv'} = 0 \qquad\qquad\qquad\qquad\qquad \forall\, a = 1, \forall\, r, \forall\, t = 1, \forall\, v, \forall\, v'$$

Initial recap capacity for the first age group and the first year is set to zero

$$R_{atv} = 0 \qquad\qquad\qquad\qquad\qquad \forall\, a, \forall\, t = 1, \forall\, v$$

Initial retire capacity for the first year is set to zero

Minimize penalties for violating elastic constraints.

$\dot{\leq}$ and $\dot{\geq}$ signify elastic constraints. These constraints can be violated but such violation has a penalty per unit violation.

APPENDIX C.   INVENTORY FOR EACH VEHICLE VARIANT

Inventory (M1025)

Inventory (M1025A1)

Inventory (M1025A2)

Inventory (M1097)

Inventory (M1097A1)

Inventory (M1097A2)

Inventory (M996)

Inventory (M996A1)

Inventory (CTV1A)

Inventory (CTV2A)

Inventory (CTV3A)

Inventory (LRS1A)

Inventory (LRS2A)

Inventory (UVL1)

Inventory (UVH1)
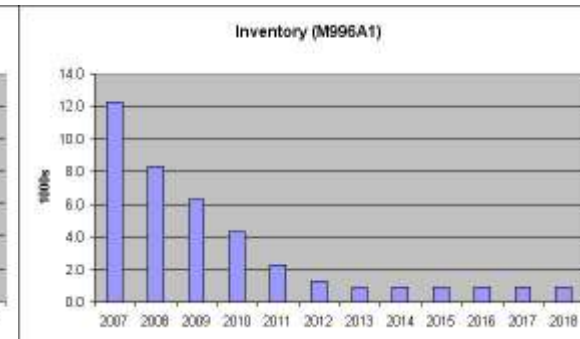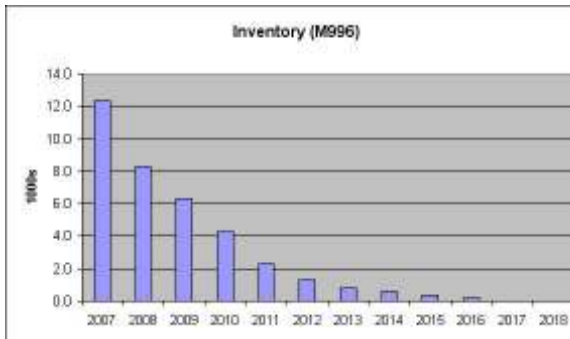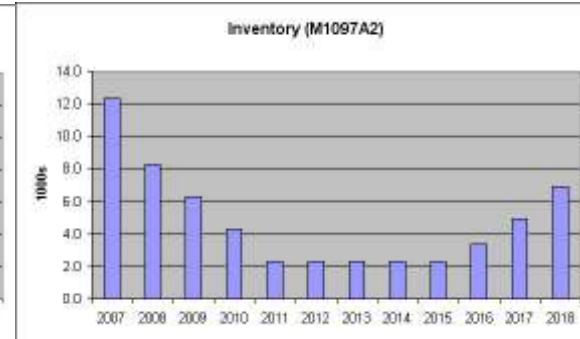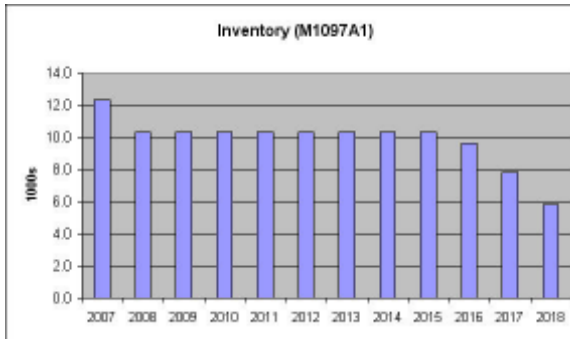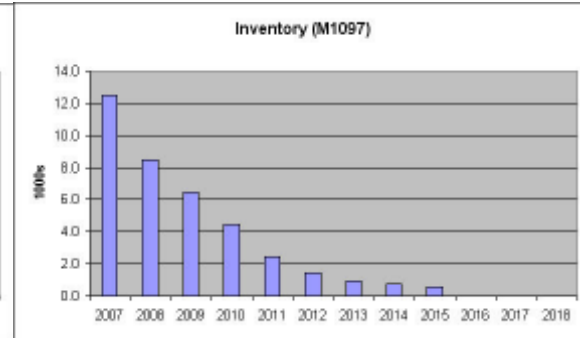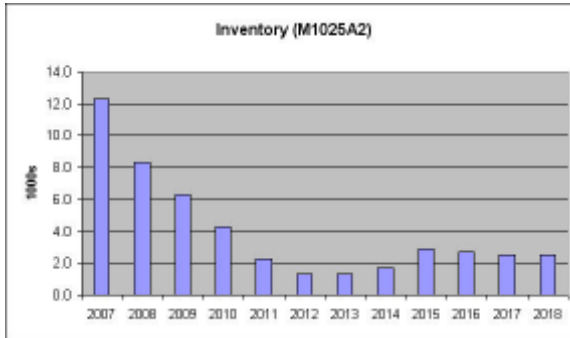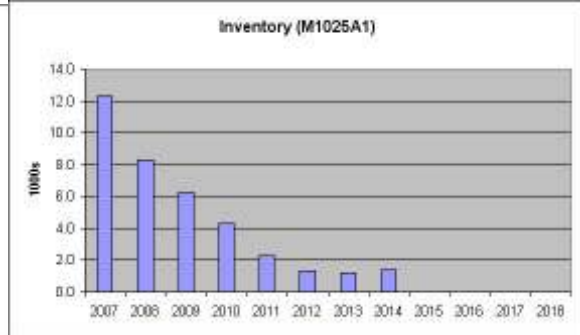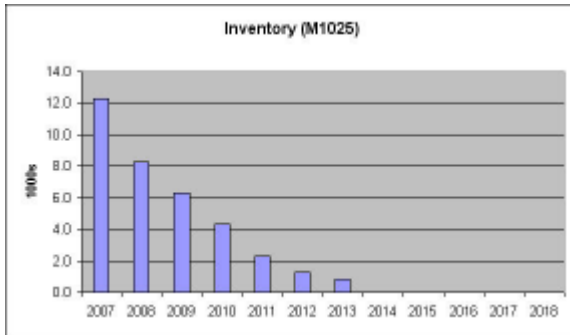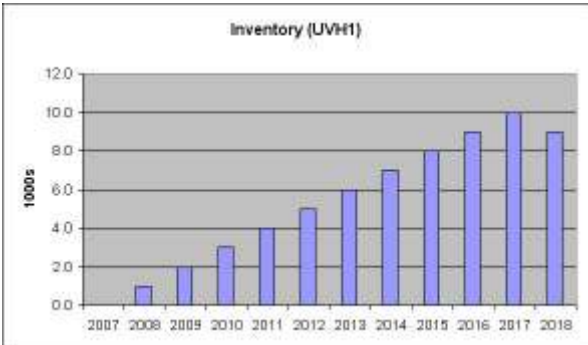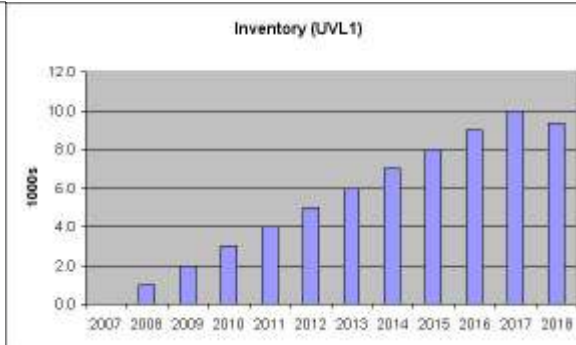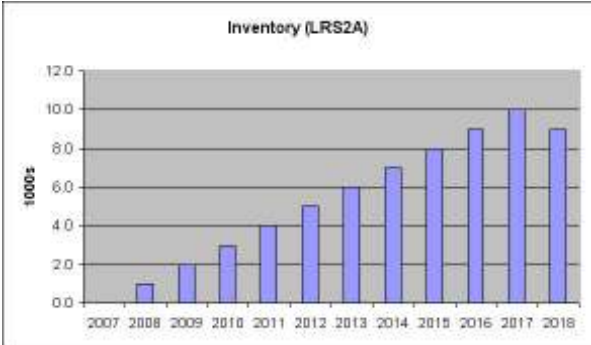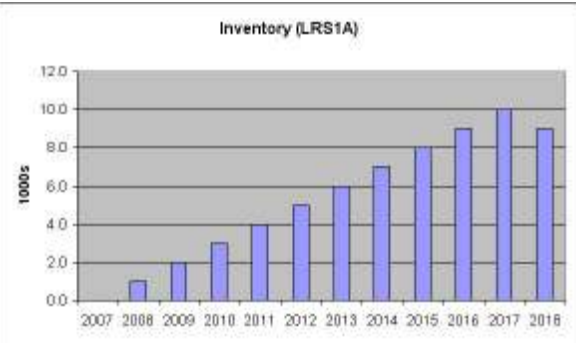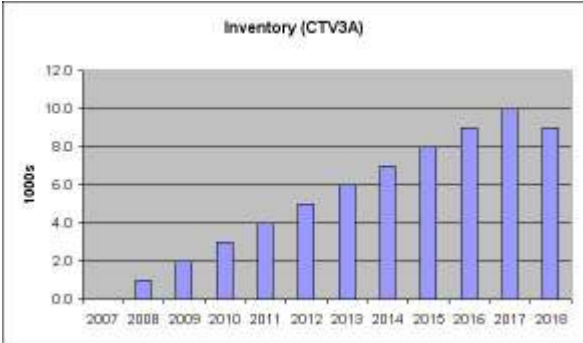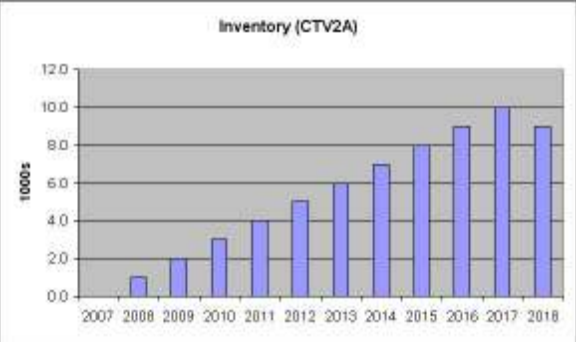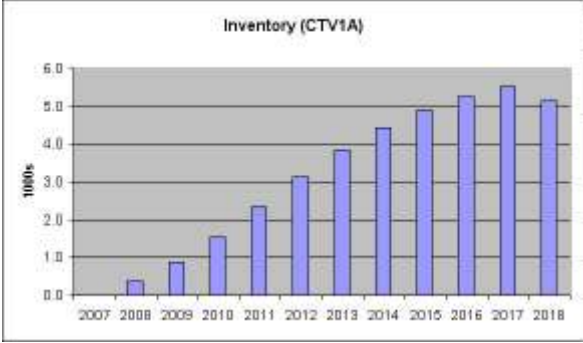
APPENDIX D.   AVERAGE AGE FOR EACH VEHICLE VARIANT

Average Age (M1025)

Average Age (M1025A1)

Average Age (M1025A2)

Average Age (M1097)

Average Age (M1097A1)

Average Age (M1097A2)

Average Age (M996)

Average Age (M996A1)

71

Average Age (CTV1A)

Average Age (CTV2A)

Average Age (CTV3A)

Average Age (LRS1A)

Average Age (LRS2A)

Average Age (UVL1)

Average Age (UVH1)
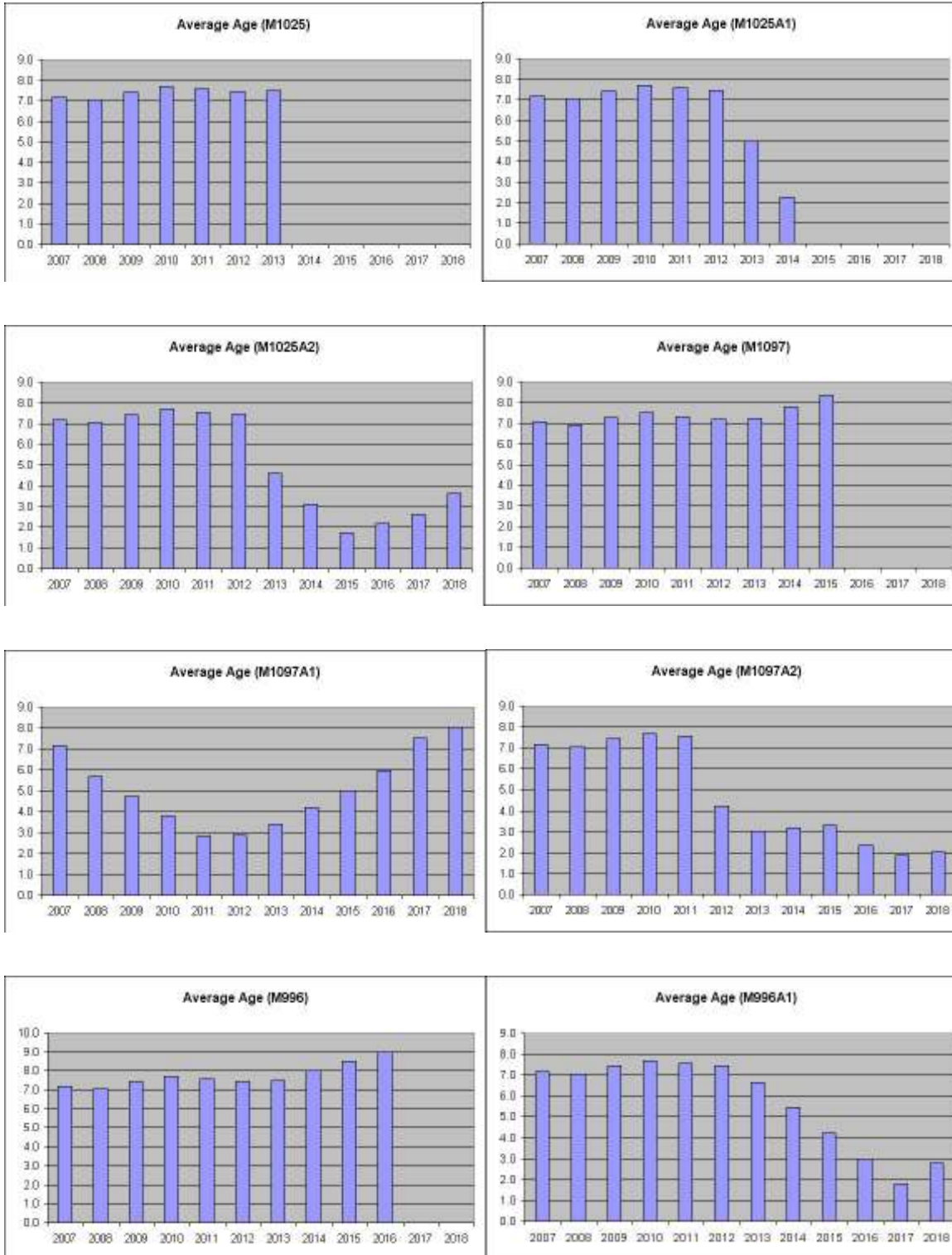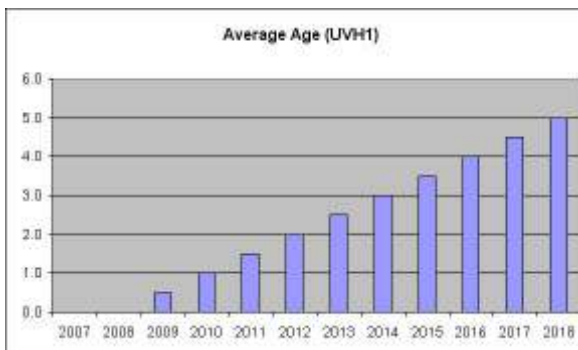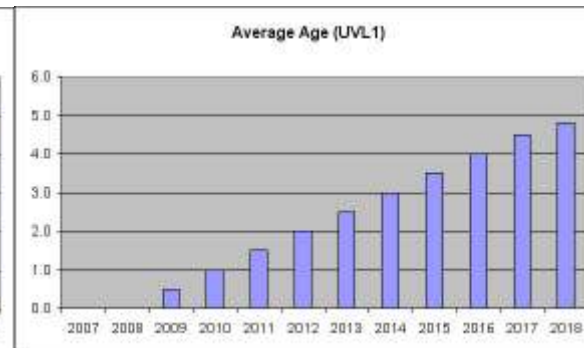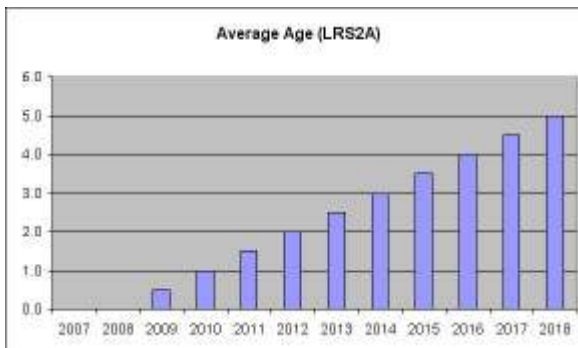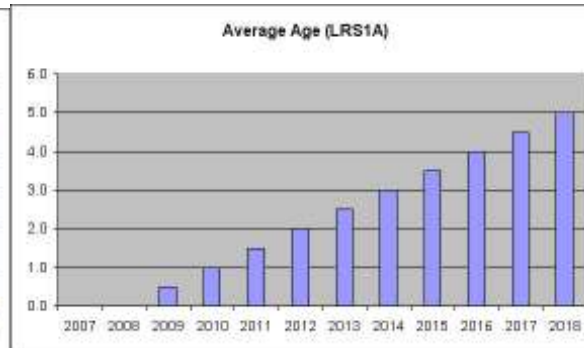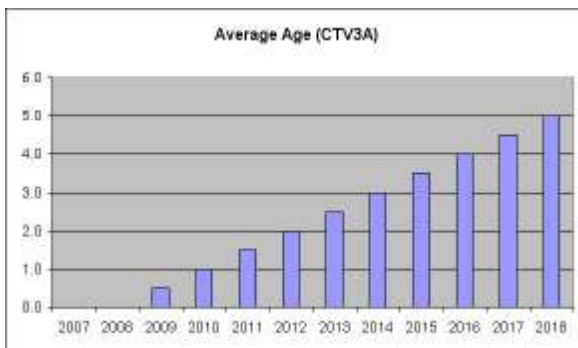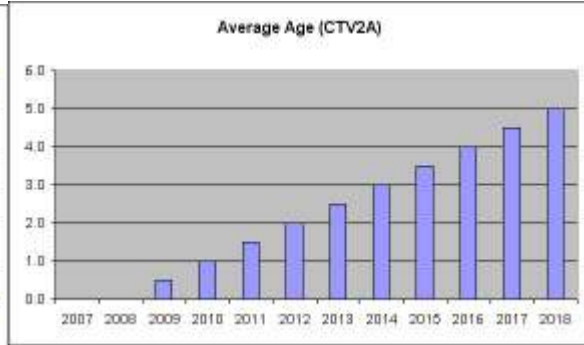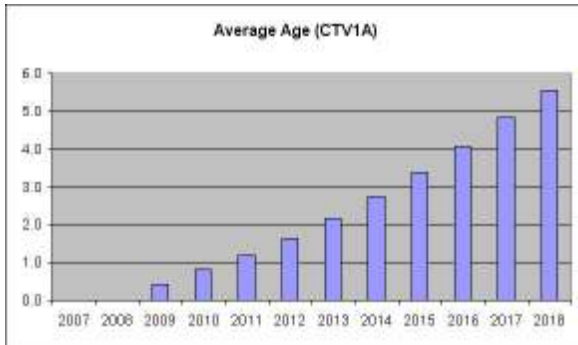
APPENDIX E. USER MANUAL

This manual provides a guide to aid users in operating the two options in the Excel LP model.

a. Build an LP Model

 i. Go to the "User Interface" tab[1] and set the indices according to the size of problem to be analyzed. A dialog box will prompt for the index value every time an index increases.

 ii. Press the "Initialize LP" button to define the indices as shown in Figure 56.
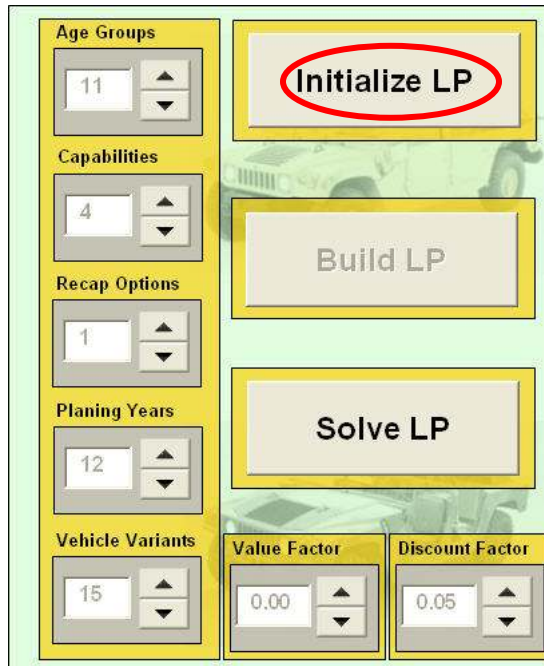
Figure 56.   Graphical User Interface

 iii. Go to the "Indices" tab and scroll right to display the two columns that are highlighted in yellow[2] shown in Figure 57.

---

[1] Tab refers to the individual worksheet in the Excel LP model.

[2] Any columns that are highlighted in yellow require inputs from the users.

Figure 57.   Indices

1. The first column is to indicate the vehicle pairs that can be recapped from and into. Put an "x" beside the valid pairs.

2. The second column is to enter a weighted value[3] for the various capabilities that the vehicles can provide.

iv. Return to the "User Interface" tab, and set the value and discount factors accordingly.

v. Press the "Build LP" button to construct the parameters, variables and constraints.

vi. Go to the "Params", "Vars" and "Constraints" tabs to ensure that they are defined accordingly.

b. Solve a LP Model

i. Go to the "Params" tab and enter the parameter values for all the columns that are highlighted in yellow, as shown in Figure 58. No inputs are needed for the "Vars" and the "Constraints" tabs.

---

[3] This weighted value can be obtained from the TWV Value Model.

Figure 58.   Parameters

ii. Return to the "User Interface" tab and press the "Solve LP" button to execute the Excel Premium Solver Platform.

iii. Once execution is completed, view the results in the "Results" tab (Figure 59) and the system-defined graphs in the "Objectives" tab (Figure 60).

Figure 59.   Results

Figure 60.   Objectives

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LIST OF REFERENCES

[1]   Defense Update. (2006) . "Joint Light Tactical Vehicle." Retrieved June 11, 2007 from http://www.defense-update.com

[2]   Ewing, P., Tarantino, W., & Parnell, G. (2006) "Use of decision analysis in the Army Base Realignment and Closure (BRAC) 2005 military value analysis." *Decision Analysis.* March 2006: 33-49.

[3]   Federation of American Scientists (FAS). (2000). "High Mobility Multipurpose Wheeled Vehicle (HMMWV) (M998 Truck)." Retrieved June 11, 2007 from http://www.fas.org

[4]   Global Security. (2007). "High Mobility Multipurpose Wheeled Vehicle (HMMWV)." Retrieved June 11, 2007 from http://www.globalsecurity.org

[5]   Global Security. "HMMWV recapitalization." Retrieved June 11, 2007 from http://www.globalsecurity.org

[6]   Global Security. "Joint Light Tactical Vehicle (JLTV)." Retrieved June 11, 2007 from http://www.globalsecurity.org

[7]   Global Security. "Up-armored HMMWV." Retrieved June 11, 2007 from http://www.globalsecurity.org

[8]   Headquarters, Department of the Army, (2006). Report to Congress: *Tactical Wheeled Vehicle Modernization Strategy*

[9]   Joint Requirements Oversight Council. (2007). *Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV)*. Washington, D.C.: Government Printing Office.

[10]   R. Keeney. (1992). *Value focused thinking*. Cambridge: Harvard University Press.

[11]   Keeney, R. L. & Raiffa, H. (1976). *Decision making with multiple objectives*. New York: Wisley.

[12]   Kirkwood, C. (1982). *Strategic decision making*. San Francisco: Duxbury Press.

[13]   H. Koerner & G. McDonald (2007). "A conceptual framework for the U.S. Army tactical wheeled vehicle optimization model."

[14]   J. Noyes & E. Weisstein (2005). "Linear Programming." Retrieved June 11, 2007 from http://www.mathwworld.com/LinearProgramming.html

[15] Rardin, R, L. (2000). *Optimization In operations research*, West Lafayette, IN: Purdue University Press. http://www.crk.umn.edu/library/links/apa5th.htm

[16] The General Algebraic Modeling System (GAMS). (1998). "The GAMS System." Retrieved June 11, 2007 from http://www.gams.com

[17] Trainor, T. G. , Parnell, B., Kwinn, J., Brence, E., Tollefson, R., Burk, P.,et al. (2004). "USMA Study of the Installation Management Agency CONUS Region Structure." West Point, NY.

[18] U.S. Army Modeling and Simulation Resource Repository (MSSR). (1998). "NATO Reference Mobility Model." Retrieved June 11, 2007 from http://www.msrr.army.mil/index.cfm?RID=MNS_A_1000379

[19] U.S. Army Tank and Automotive Command. "Joint Light Tactical Vehicle Request for Information (JLTV RFI)." Retrieve June 11, 2007 from http://contracting.tacom.army.mil

[20] U.S. Army Training And Doctrine Command Tactical Wheeled Vehicle Modernization. (2004). *Operational Requirements Document (ORD) for the High Mobility Multipurpose Wheeled Vehicle (HMMWV).* Fort Eustis, VA: Government Printing Office.

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