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A CONCEPTUAL FRAMEWORK FOR THE U.S. ARMY TACTICAL WHEELED VEHICLE OPTIMIZATION MODEL

by

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June 2007

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This thesis addresses the problem of optimizing the U.S. Army's Light Tactical Wheeled Vehicle (LTWV) fleet over the next 15 years. To achieve these ends we created a multiple objective decision analysis (MODA) model which assigns a value to each vehicle in the LTWV fleet, as well as a linear program (LP) which allows decision makers to find feasible modernization strategies for the LTWV fleet subject to multiple constraints such as budget and operational readiness.

The MODA assigns a value to every individual vehicle variant depending upon its measures of performance in several categories. Those values are used by the LTWV LP to prescribe solutions for decision makers. We implemented the LTWV LP using notional data and ran initial analyses to demonstrate the program's validity. Possible analyses include varying any of the LTWV LP inputs, such as operational, budgetary, and age requirements, as well as procurement availability bounds. The project serves as a conceptual framework for future refinement of the decision tool requested by the U.S. Tank-Automotive and Armaments Command (TACOM).

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LIST OF TERMS AND ABBREVIATIONS

AMP	Ampere
BA	Battlespace Awareness
BRAC	Base Realignment And Closure
C2	Command and Control
CA	Combat Arms
CASCOM	Combined Arms Support Command
CDD	Capability Development Document
CS	Combat Support
CSS	Combat Service Support
CTV	JLTV – Combat Tactical Vehicle
ECV	Expanded Capacity Vehicle
FoV	Family of Vehicles
FY	Fiscal Year
FY08$	Fiscal Year 2008 Dollars
GAMS	General Algebraic Modeling System
GMV	JLTV – Ground Maneuver Vehicle
GVW	Gross Vehicle Weight
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
ICD	Initial Capabilities Document
IED	Improvised Explosive Device
ILP	Integer Linear Program
JLTV	Joint Light Tactical Vehicle
JROC	Joint Requirements Oversight Council
KPP	Key Performance Parameter
LAV	Light Armored Vehicle
LEAD	Letterkenny Army Depot, Chambersburg, PA
LI	Light Infantry
LP	Linear Program or Linear Programming
LRR	Long Range Reconnaissance
LRS	JLTV – Long Range Surveillance Vehicle
LTC	Lieutenant Colonel (U.S. Army)
LTWV	Light Tactical Wheeled Vehicle
MMBOMF	Mean Miles Between Operational Mission Failure
MODA	Multi-Objective Decision Analysis
MOP	Measure of Performance
MPH	Miles Per Hour
MTTR	Mean Time to Repair
MUTT	Military Utility Tactical Truck
O&S	Operations and Support (O&S)
OIF	Operation Iraqi Freedom
ORD	Operational Requirements Document
OTM	On The Move

Recap	HMMWV Recapitalization Program
RDTE	Research, Development, Test & Evaluation
ROMO	Range of Military Operations
RPG	Rocket Propelled Grenades
RPM	Rotations Per Minute
RRAD	Red River Army Depot, Texarkana, TX
SDVF	Single-Dimensional Value Function
TACOM	Tank-Automotive and Armaments Command (US Army)
TOW	Tube-launched, Optically-tracked, Wire-guided
TRAC	TRADOC Analysis Center
TRADOC	Training and Doctrine Command
TWV	Tactical Wheeled Vehicle
USA	United States Army
UVH	JLTV – Utility Vehicle - Heavy
UVL	JLTV – Utility Vehicle - Light
VAM	Value Additive Model
VM	Value Model

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We would like to thank our thesis advisor, Professor Daniel Nussbaum, for guiding us to the successful completion of this project. Mr. Edward Lesnowicz also deserves our thanks for reading and re-reading our developing drafts. LTC Lee Ewing deserves special thanks for going above and beyond his duties as a second reader. Without his devotion, this project would never have been realized. Professor Robert Dell deserves recognition for formulating and implementing the optimization model, as well as helping us input data and run our analysis.

LTC Stuart Rogers and Mr. Raymond Kleinberg deserve thanks for aiding in our exhausting search for data and serving as subject matter experts in the field of Light Tactical Wheeled Vehicles.

We would like to dedicate this thesis to our families. Words alone cannot express the thanks we owe them. Their love and support has helped us throughout this year in ways unforeseen.

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EXECUTIVE SUMMARY

This thesis investigates the problem of modernizing the U.S. Army's Light Tactical Wheeled Vehicle (LTWV) fleet over the next 15 years. Specifically, we created a decision tool that seeks to find a modernization strategy that satisfies constraints such as budget, operational, and age requirements. The constraints in the decision tool are designed to be alterable so that the user can observe the outcome effects of varying constraints. Ultimately, the goal is to enable the user to gain insight into potential future modernization strategies for the LTWV fleet. The U.S. Tank-Automotive and Armaments Command (TACOM) requested this tool to support policy makers in making decisions about the future of the LTWV fleet.

The High Mobility Multipurpose Wheeled Vehicle (HMMWV) currently serves as the Armed Forces LTWV. The U.S. Army currently maintains an inventory of over 100,000 HMMWVs. The HMMWV fleet is large and versatile, fulfilling the role of reconnaissance, utility, combat, cargo/troop transport, and ambulance vehicles. However, the HMMWV is falling short of recent increased operational demands. Two major problems are causing the HMMWVs' recent shortcomings.

The first problem is the venerability of the HMMWV fleet. The current average age of the HMMWV fleet is greater than the designed lifespan of any given vehicle. This rise in age causes more frequent breakdowns, disabling the vehicles from completing their missions and increasing Operations & Support (O&S) costs.[1]

The second problem is the HMMWV fails to meet the increased operational requirements placed upon it by the Army.[2] Asymmetric warfare practiced by insurgents and terrorists places an increased responsibility on the HMMWV to serve as a robust combat vehicle. The HMMWV simply lacks the performance capabilities to serve in this

[1] Global Security. "HMMWV Recapitalization."; available from http://www.globalsecurity.org; INTERNET.

[2] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), ii.

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 is requiring that the JLTV perform sufficiently in every area that the HMMWV is falling 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 2012, 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" or be retired and a number of new JLTVs will be procured. Therefore, the composition of the LTWV fleet will change every year. TACOM has requested a decision tool that models this process in hopes of gaining insight into potential modernization strategies.

Our thesis work completes the initial formulation and implementation of this decision tool. Two main parts comprise the decision tool. The first part is a multiple objective decision analysis (MODA), which we refer as the Value Model (VM). The VM assigns a value to every HMMWV and JLTV variant based upon their performance over a series of competing objectives. The second part of the decision tool is a linear program (LP) which optimizes the value of the LTWV fleet for the next 15 years. The fleet value of any given year is determined using the current fleet inventory and the value results from the VM.

The goal of the VM is to assign a value to each LTWV variant. This value aims to capture a vehicle's overall operational ability. In this model, operational ability is represented as achievement over several competing objectives. We developed three main qualitative objectives that measure the operational ability of a vehicle. These broad objectives are mobility, net-readiness, and survivability. We drafted these objectives based upon vehicle capability documents and subject matter expert input. From these broad objectives, we used a top-down approach to further define sixteen quantitative sub-objectives. We measured a vehicle's achievement by quantitative performance in each sub-objective. A vehicle's value in each sub-objective is combined as a weighted sum to give its overall value.

The LTWV LP is the actual decision tool. Its constraints frame the modernization problem in terms of age, budgetary limitations, operational requirements, and bounds on the number of vehicles available for purchase. Operational requirements are measured in units of value, derived from the VM. The values from each vehicle are combined by objective to ensure the fleet maintains enough of each capability. The LTWV LP is written elastically, such that a constraint may be violated at the price of a corresponding penalty. In the LTWV LP, the penalties are set high enough that the program will only choose to violate a constraint if there is no feasible solution. The objective function of the LTWV LP seeks to find a feasible solution to this problem by minimizing the penalties incurred from violated constraints. The LTWV LP spans over 15 years, minimizing penalties each year. Each year the set of constraints evolves, and each subsequent year uses the fleet inventory numbers from the previous year. We collected data, implemented an LP developed by NPS faculty, and ran several initial analyses, illustrating the combined VM and LTWV LP proof of concept as a decision tool.

In the analysis we modeled several different scenarios by manipulating the constraint data that we possessed. We varied the maximum vehicle age, the yearly budget, and the minimum and maximum bounds on vehicles available for purchase. The most profound analysis we performed was simulating a delay in the implementation of the JLTV program. The result of this analytical excursion was that a delay of two years significantly lowered the fleet values every year. In eight of the 15 years simulated, the fleet could not maintain its starting value, dipping below its current state. Because delays in programs are not uncommon, preparing a contingency plan for such a delay is a recommendation that we would be willing to make to TACOM. This is just an example of many analyses that can be run with this decision tool.

The decision tool we created is so adaptable for encompassing future scenarios that it is primed for further research. Further related projects include running an in-depth analysis of modernization strategies, further developing the data collected, or reproducing the tool with a more user-friendly interface. This thesis covers the conceptual framework necessary to formulate and implement TACOM's decision tool. With this framework, we were able to produce non-trivial insights to the LTWV fleet modernization.

I. INTRODUCTION

This thesis researches the problem of the modernization of the U.S. Army's Light Tactical Wheeled Vehicle (LTWV) fleet. The objective of this research is to create a decision tool that the U.S. Tank-Automotive and Armaments Command (TACOM) can use to plan its TWV modernization strategies for the next two decades.

A. PROBLEM STATEMENT

Tactical Wheeled Vehicles are wheeled vehicles used for combat, combat support, and combat service support missions by every branch of the armed forces. Perhaps the most recognizable TWV today is the High Mobility Multipurpose Wheeled Vehicle (HMMWV). HMMWVs fill a wide range of roles to include reconnaissance, utility, combat, cargo/troop transport, and ambulance. The HMMWV is a Light Tactical Wheeled Vehicle (LTWV) and comprises approximately 50% of the TWV fleet. The Army currently operates over 100,000 HMMWVs. This thesis focuses on the LTWV portion of the greater TWV fleet.

Currently, the LTWV fleet is aging. The average vehicle age is 17 years. The fleet is also deteriorating at an accelerated rate. This is due to its constant employment in combat zones and adverse environments, such as deserts. Consequently, vehicles need constant service, which causes significant maintenance costs and a decrease in vehicle operational availability. The vehicles no longer sufficiently fulfill their mission requirements. Their constant use in operations, such as Operation Iraqi Freedom (OIF) and the many associated Iraq pacification operations reveals major shortcomings in the fleet's *mobility, net-readiness and survivability*.

To meet the more demanding mission requirements of the LTWV, the Army is developing a newer, more robust vehicle. The Joint Light Tactical Vehicle (JLTV) will eventually replace the HMMWV as the Army's new LTWV. However, two problems exist with the fielding of the JLTV. First, a majority of the HMMWV fleet is past its life expectancy and current operations are accelerating its deterioration. Second, the JLTV cannot be integrated instantly, as the vehicle is still in its design phase. The production rate of the vehicle will require several years to achieve full fielding. Consequently, the LTWV fleet requires immediate attention to improve its performance to satisfy increased operational requirements.

The Army is solving this problem by performing maintenance on some of the existing HMMWVs to increase their lifecycle, and by gradually integrating the JLTVs, when available. The solution must meet the operational needs of the Army and remain within the allowed budget. For instance, not all of the HMMWVs can be simultaneously pulled from the field to be serviced at the same time, nor can the Army spend their entire budget on fixing HMMWVs, as they would lack sufficient funds to procure new JLTVs.

The Army has three options for fleet modernization:

- *Recapitalization (Recap):* Upgrade a HMMWV to a new, more robust variant. This makes the vehicle unusable while in the maintenance depot.
- *Buy New:* Order a brand new HMMWV or JTLV to fill the demand for a particular vehicle type.
- *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 JLTVs are being phased in and HMMWVs are being retired, the LTWV fleet will be comprised of a mixture of new and old vehicles. Every year, budgets will need to be allocated to either fix older existing HMMWVs or to purchase new HMMWVs or JLTVs. Our thesis examines modernization strategies in the context of meeting budgetary and operational requirements.

It is TACOM's responsibility to plan the future composition of the TWV fleet strategically, such that it meets its budgetary and operational requirements. TACOM requested that a decision tool be created to offer insight into future planning. This research serves as the conceptual framework for this decision tool. The decision tool is comprised of 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 of the VM to find feasible LTWV fleet modernization strategies. The results will help TACOM with making optimal decisions during the LTWV modernization process.

Chapter II of this thesis explores the history of the LTWV fleet. Chapter III discusses the analytical techniques required to create a multiple objective decision analysis (MODA) for the VM and an LP. Chapter IV covers the methodology of both the VM and the LTWV LP. Chapter V is an analysis of the decision tool, illustrating its power and potential. Lastly, Chapter VI summarizes our work and explores further research possibilities.

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II. BACKGROUND INFORMATION

A. HIGH MOBILITY MULTIPURPOSE WHEELED VEHICLE (HMMWV)

In the 1970s the U.S. Army recognized a need to replace the aging M151 series vehicle. The Vietnam War made it clear that U.S. armed forces needed a newer, more versatile Tactical Wheeled Vehicle (TWV). By 1979, the Army had settled on a design, and the High Mobility Multipurpose Wheeled Vehicle (HMMWV) was delivered to the fleet in 1985. Presently, there are many different HMMWV variants, becoming the virtual backbone of the armed forces Light Tactical Wheeled Vehicle (LTWV) fleet.

The HMMWV replaced the M151 Military Utility Tactical Truck (MUTT) (1/4-ton), the M274 Mule (1/2-ton), the M561 Gamma Goat (1 1/4-ton), the M718A1 Ambulance, and the M792 Ambulance. Each replacement HMMWV variant assumed the mission role of the retiring vehicle. The current mission statement of the HMMWV is "to provide a light tactical wheeled vehicle for command and control, troop transport, light cargo transport, shelter carrier, ambulance, towed weapons prime mover, and weapons platform throughout all areas of the battlefield or mission area."[3]

Although there are many different HMMWV variants, every HMMWV carries some design similarities. The HMMWV is a highly mobile, diesel-powered, four-wheel-drive, and air-transportable vehicle that uses a common 4,400 lb payload chassis.[4] This allows HMMWVs to use common components, kits, and fuels. Each variant, however, has unique attributes and abilities. There are cargo/troop carrier, shelter carrier, armament carrier, ambulance, TOW missile carrier and scout-reconnaissance variants.

[3] U.S. Army Training And Doctrine Command Tactical Wheeled Vehicle Modernization. Operational Requirements Document (ORD) for the High Mobility Multipurpose Wheeled Vehicle (HMMWV). (Fort Eustis, VA: GPO, 2004), 1.

[4] Global Security. "High Mobility Multipurpose Wheeled Vehicle (HMMWV)."; available from http://www.globalsecurity.org; INTERNET.

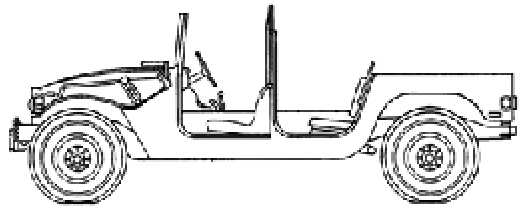

Figure 1. The M998 Series

The first HMMWV, the M998, serves as the baseline vehicle for all the variants. The M998, M998A1, M1038 and M1038A1 HMMWVs are light utility vehicles. They are equipped with basic armor and are used to transport troops and materiel. The cargo carrier is capable of a payload of up to 2,500 lbs. The troop carrier can support a two-man crew and carry up to eight passengers. The "A1" classification after any HMMWV indicates that it is a newer version of the same variant, updated with newer modifications.[5]

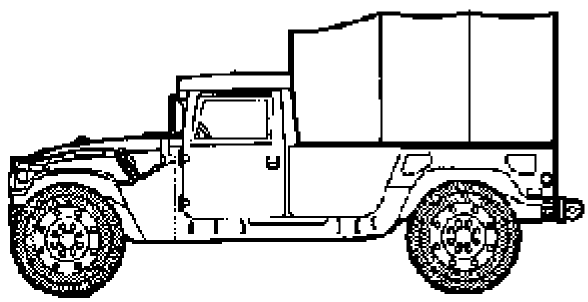

Figure 2. The M1097 Series

The M1097, M1097A1, M1097A2 are the heavy utility vehicles. Instead of the 2,500 lb. payload capacity of the light utility vehicles, the M1097 variants have a payload capacity of 4,575 lbs. Like the other cargo/troop carriers, it can support a crew of two with eight passengers. In addition to its cargo/troop carrying function, the M1097 can power shelter equipment.[6]

[5] Federation of American Scientists (FAS). "High Mobility Multipurpose Wheeled Vehicle (HMMWV) (M998 Truck)." (2000); available from http://www.fas.org; INTERNET.

[6] Ibid.

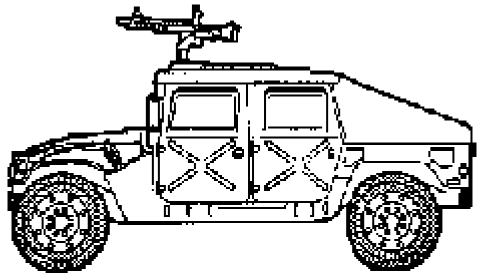

Figure 3. The M1025 Series

The M966, M1025, M1025A1, M1026 and M1026A1 HMMWVs are light armament carrier configurations in the HMMWV family. These variants are equipped with basic armor and a weapons mount, located on the roof of the vehicle. The weapons mount is adaptable and can accommodate the M60 7.62mm machine gun, M2 .50 caliber machine gun, or the MK 19 grenade launcher. The roof mount provides the weapons a 360-degree firing radius.[7]

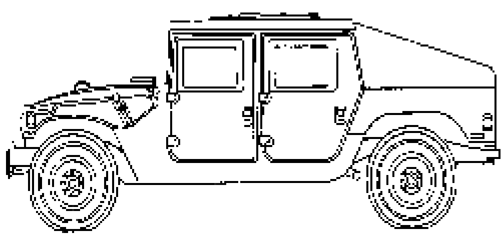

Figure 4. The M1043 Series

The M1043, M1043A1, M1044, and M1044A1 vehicles are heavy armament carrier configurations of the HMMWV family. The only major difference between the M1043 variants and the M1025 variants is that the M1043 variants boast supplemental armor.

7 Federation of American Scientists (FAS). "High Mobility Multipurpose Wheeled Vehicle (HMMWV) (M998 Truck)." (2000); available from http://www.fas.org; INTERNET.

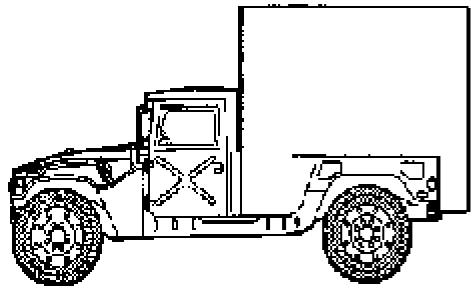

Figure 5. The M1037 Series

The, M1037, M1042, and M1113 HMMWVs are shelter carrier configurations. The M1037 and the M1042 are the light shelter configurations and the M1113 is a heavy shelter carrier configuration, differing in vehicle weights and payload capacity. The vehicles are equipped with basic armor and are used to transport the S250 shelter equipment. The vehicles possess a total payload capacity (including crew) of 3,600 pounds.[8]

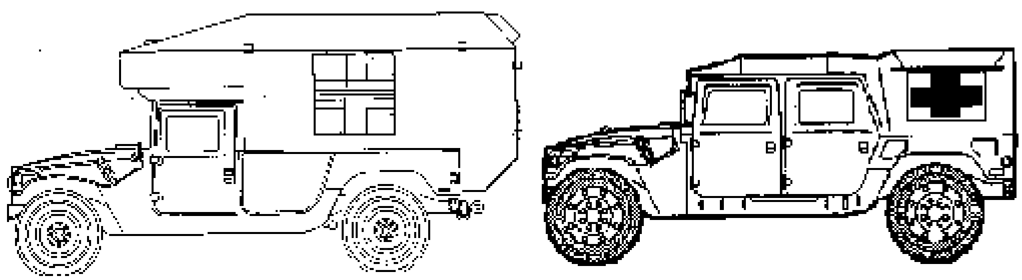

Figure 6. The M997 Series and the M1035 Series

The M996, M996A1, M997, M997A1, M997A2, M1035 and M1035A2 HMMWVs are the ambulance configurations in the HMMWV family. These vehicles are equipped with basic armor and used to transport casualties from the battlefield to medical-aid stations. The M996 and M996A1 are light ambulances and can accommodate either two litter patients, six sitting patients or a combination of the two. The M997, M997A1, and M997A2 are heavy ambulances and can accommodate either

[8] Federation of American Scientists (FAS). "High Mobility Multipurpose Wheeled Vehicle (HMMWV) (M998 Truck)." (2000); available from http://www.fas.org; INTERNET.

four litter patients, eight sitting patients or a combination. The M1035 and M1035A2 are soft-top ambulances. The M1035 is a light ambulance and the M1035A2 is a heavy ambulance. Each can accommodate up to two litter patients.[9]

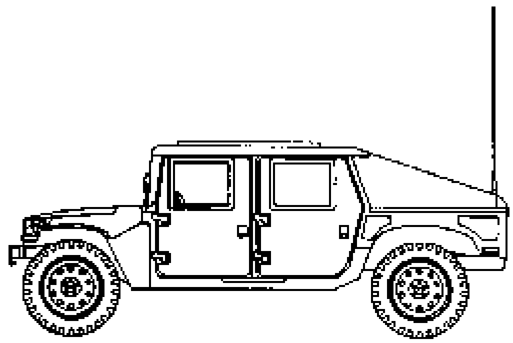

Figure 7. The M1114 Series

The M1109 and M1114 HMMWVs are up-armored armament carrier configurations in the HMMWV family. The primary function of the up-armored armament carrier is to perform reconnaissance and security operations. In addition to the basic armor, supplemental armor is attached to the sides and underbelly of the vehicle to protect occupants from small arms fire and mines. The creation of the up-armored HMMWV was motivated by the need to create a vehicle that could withstand Improvised Explosive Device (IED) attacks more adequately. However, these up-armored HMMWVs are 2,000 lbs. heavier, making them less maneuverable with a shorter cruising range than their lighter counterparts.[10] This trade-off is costly, as their main function is reconnaissance, for which mobility is critical. Like the other armament carriers, there is a roof weapons-mount capable of housing an M60 7.62mm machine gun, M2 .50 caliber machine gun, or an MK 19 grenade launcher.

[9] Federation of American Scientists (FAS). "High Mobility Multipurpose Wheeled Vehicle (HMMWV) (M998 Truck)." (2000); available from http://www.fas.org; INTERNET.

[10] Global Security. "High Mobility Multipurpose Wheeled Vehicle (HMMWV)."; available from http://www.globalsecurity.org; INTERNET.

The M1069 HMMWV is the prime mover variant, designed to transport the M119, 105mm Light Howitzer. The vehicle contains two seats and an open-air flatbed in the back, used to store the 105mm Howitzer ammunition.

A more concise reference of each HMMWV variant and its capabilities is listed below:

HMMWV Variant	Mission	Armor
M998	Cargo/Troop carrier	Basic Armor
M1038	Cargo/Troop carrier	Basic Armor
M966	Tow Missile carrier	Basic Armor
M1036	Tow Missile carrier	Basic Armor
M1045	Tow Missile Carrier	Supplemental Armor
M1046	Tow Missile Carrier	Supplemental Armor
M1025	Armament Carrier	Basic Armor
M1026	Armament Carrier	Basic Armor
M1043	Armament Carrier	Supplemental Armor
M1044	Armament Carrier	Supplemental Armor
M996	Mini-Ambulance, 2-Litter	Basic Armor
M997	Maxi-Ambulance, 4-Litter	Basic Armor
M1035	Soft-Top Ambulance, 2-Litter	Basic Armor
M1037	Shelter Carrier	Basic Armor
M1042	Shelter Carrier	Basic Armor
M1069	Prime Mover for M119 105-mm light gun	Basic Armor

Table 1. HMMWV Variant/Mission/Armor Rating Table

In 1995, HMMWV manufacturers introduced an "A2" configuration and the Expanded Capacity Vehicle (ECV). The A2 configurations contain a four-speed transmission and a 6.5 liter diesel engine, which improves mobility. The ECV variants handle an increased payload of up to 5,100 lbs. including their crews. The ECV can be used as the chassis for the M1114, an up-armored HMMWV used for reconnaissance. The ECV series is also used as the platform for missions that require payloads greater than 4,400 lbs.[11]

[11] Global Security. "High Mobility Multipurpose Wheeled Vehicle (HMMWV)."; available from http://www.globalsecurity.org; INTERNET.

Although the Army created the HMMWV to complete a wide range of missions, it has developed major weaknesses in recent years. The HMMWV was a revolutionary and useful technology in the 1980s, but it is an aging platform that is currently falling short of its expectation. In the Global War on Terrorism, the HMMWV has been pushed beyond its operational limits. With emerging warfare technologies, mission payloads are increasing and exceeding the current HMMWV capability. In order to meet current battlefield demands, the Army requires a more capable replacement for the HMMWV.

In OIF and the associated Iraq peacekeeping missions, U.S. Forces are using the HMMWV to conduct levels of combat that exceed vehicle design. Unfortunately, the basic armor kit on the HMMWV offers only slightly better ballistic and blast protection than its predecessor, the M151 MUTT. Any HMMWV model without the up-armor conversion kit is susceptible to almost any kind of fire including RPGs, AK-47s, IEDs and military-grade land mines. The armor kits include bullet-proof glass windows, and side, rear and underbelly armor plates. The up-armored kits provide protection from fire received from the side, but the armor plates on the underbelly of the vehicle do little to protect occupants from mine blasts that occur below the vehicle.[12] However, the increased weight of these kits significantly diminishes the vehicle's overall performance. The added weight of the kits makes vehicles incapable of traveling at standard convoy speeds, have less maneuverability, and have a lower payload capacity. Although helpful in protecting vehicles and its occupants, up-armor kits do not make HMMWVs meet the Army's increased mission requirements. In addition to falling short operationally, the HMMWV platform itself is an aging technology.

In 2005, the projected lifecycle of the average HMMWV was approximately 13 years.[13] However, because of combat, overuse, and harsh environments, HMMWVs last no more than two years in Iraq before either requiring major overhaul maintenance or scrapping. This poses a major problem for the Army. In their current employment, the HMMWV's projected lifecycle drops drastically. In addition to the projected lifecycle

[12] Global Security. "Up-Armored HMMWV."; available from http://www.globalsecurity.org; INTERNET.

[13] Global Security. "HMMWV Recapitalization."; available from http://www.globalsecurity.org; INTERNET.

being lowered, the average age of the HMMWV fleet is now well above its designed service life of 15 years. Since more than 50% of the current HMMWV fleet was made between 1985 and 1991, the average fleet age in FY 07 is now almost 17 years old.

The diminishing projected lifecycle and the ever-increasing average fleet age has rapidly increased Operations & Support (O&S) costs due to frequent malfunctions and breakdowns. The initial solution to curb the rising O&S costs was performing overhaul maintenance, thus returning the vehicle to a zero-mile condition. This “Resetting” of a vehicle added an additional 21 years to its lifespan and enhanced its performance. This resetting concept decreased O&S costs by creating more robust vehicles that required less frequent and less expensive maintenance.[14]

The Resetting program was established in 2000, with the overall goal to decrease rising O&S costs from the aging HMMWV fleet by maintaining the average fleet age below the 15-year planned service life. This program was abandoned in 2001 when Army leadership determined that the “reset” option was not cost effective. A more cost effective policy – the *Recapitalization program* – was developed. This program focuses only on fixing the older HMMWV combat variants. The Recap maintenance consists of a drive-train rebuild and a detailed inspect-and-repair process. The maintenance adds 10 years to the vehicles’ expected lifespan. The older M998, M998A1, M1037, M1038 and M1097A1 HMMWV variants are “recapped” to the M1097R1 vehicle. The new drive train supports an increased payload and allows for additional armor add-on. This recapping process takes place at Letterkenny Army Depot, Chambersburg, PA (LEAD), and Red River Army Depot, Texarkana, TX (RRAD).[15]

The Army Recapping Policy is necessary in order to continue using HMMWVs. The policy, however, is a temporary solution to the problem of the ever-increasing age of the LTWV fleet. The up-armor kits provide increased, but not sufficient crew protection; in addition they weigh down the vehicles, thus reducing mobility and payload performance. The armor, however, is required. The trade-off between performance and

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14 Global Security. “HMMWV Recapitalization.”; available from http://www.globalsecurity.org; INTERNET.

15 Ibid.

force protection means the HMMWV still cannot meet current mission requirements. The Army needs a new vehicle in order to lower the average age of the LTWV fleet, thereby meeting increased operational capabilities while achieving sufficient force protection.

B. Joint Light Tactical Vehicle (JLTV)

Beginning in 2006, U.S. Army and Marine Corps officials began researching the possibilities for creating a new LTWV to replace the aging HMMWV. Current U.S. military operations indicate that the future LTWV fleet must include increased expeditionary abilities as well as improved conventional combat capabilities. The United States' involvement in the Global War on Terrorism indicates a declining probability that U.S. forces will be involved in conventional large-scale combat operations. Instead, U.S. forces are more likely to be faced with "decentralized, small, unconventional, yet highly lethal forces."[16]

Fighting against insurgency operations requires increased mobility to cover an extended battlespace. The JLTV must provide concentrated combat power with a smaller, more mobile force. Additionally, the JLTV must meet the support and sustainability requirements of forces in remote areas. In the past, larger fighting vehicles such as the Stryker, Light Armored Vehicle (LAV), and Bradley fighting vehicle assumed the responsibility of the light tactical mobility mission. However, in the war against terrorism, that responsibility has now fallen upon the LTWV fleet. The lack of mobility and the Army's desire to project a peacekeeping image caused this shift.

The Ground Combat Forces Light Tactical Mobility Initial Capabilities Document (ICD) identified five gaps in current light tactical mobility transportation:

- Gap 1 – Inability to move mounted Infantry/Combat Arms forces via ground.
- Gap 2 – Inability to move mounted Combat Support (CS) forces via ground.
- Gap 3 – Inability to move mounted Combat Service Support (CSS) forces via ground.

[16] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), ii.

- Gap 4 – Inability to move Light Infantry (Airborne/Air Assault) via ground.
- Gap 5 – Inability to move Long Range Reconnaissance (undetected) via ground.

Solutions to the gaps must be progressive, moving away from threat-based Cold War era garrison force to a responsive expeditionary force that focuses on mobility, survivability, flexibility and self-sustainability.[17]

The JLTV fleet will include variants responsible for Combat Arms (CA), Combat Support (CS), Combat Service Support (CSS) and Long-Range Surveillance. Depending on the mission, each of the variants will excel in different categories, but each variant must perform proficiently in the following characteristics:

- *Force Protection* (occupant protection): Concepts to achieve this include scalable armor to provide mission flexibility while protecting occupants.
- *Survivability* (vehicle survivability): Survivability includes mitigation of electronic IED defeat, shot detection/warning, self-recovery capability, running on flat tires, and instant fire suppression in engine and cabin.
- *Transportability*: Vehicle transportability by a range of lift assets, including rotary wing aircraft. Makes vehicles quickly deployable, an important characteristic in insurgency warfare.
- *Mobility*: Maneuverability to enable operations across the spectrum of terrain. Improvements on the HMMWV include increased maximum cruising range and speed, increased fuel efficiency, and less frequent refueling.
- *Net-Readiness*: Connectivity for improved Battlespace Awareness (BA) and responsive, well-integrated Command and Control (C2). Features include sufficient electrical power, long range On The Move (OTM) communications, and a tactical workstation.

[17] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 1-2.

- *Sustainability*: The ability to operate independently without support attachments for short periods of time. Features include two days of supplies and modularity of sustainment items to enable rapid replenishing and refueling capabilities.
- Payload: Increased ability to move cargo, troops and weapons relative to the HMMWV. Payload requirements must be met *after* the vehicle's armor is attached.[18] [19]

In the present proposal, there are five general JLTV types. Each general type of JLTV will have several different configurations. Within each configuration lie several sub-configurations, defined by the vehicle's mission requirements. Each sub-configuration corresponds to a separate JLTV variant. Among the five types there are a total of 18 sub-configurations, therefore 18 possible vehicle variants. The five general JLTV types are the Combat Tactical Vehicle (CTV), the Long Range Surveillance Vehicle (LRS), the Utility Vehicle Light (UVL), the Utility Vehicle Heavy (UVH) and the Ground Maneuver Vehicle (GMV).

Increment I in the JLTV Capability Development Document (CDD) states that the first set of JLTVs is scheduled to begin production by 2012. The initial procurement numbers for the Army are 5,500 JLTVs. Increment II of the JLTV CDD states that by 2016 updated JLTV variants should be fleet ready. Between Increment I and II, JLTV manufacturers are expected to research and to improve the design of Increment I JLTVs. Areas of focus include force protection, fuel efficiency, power generation, and net-readiness. Acquisition goals for Increment II indicate that a total of 33,137 JLTVs should be produced starting in 2016.[20]

The Combat Tactical Vehicle (CTV) will replace the M966, M966A1, M998, M998A1, M1025, M1025A1, M1025A2, M1026, M1026A1, M1038, M1038A1 and M1114 HMMWV variants. Like its namesake, the CTV will primarily be an armament

[18] Global Security. "Joint Light Tactical Vehicle (JLTV)."; available from http://www.globalsecurity.org; INTERNET.

[19] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 2.

[20] Ibid, 23.

carrier and a light fighting vehicle. The CTV configurations are a Close Combat Weapons Carrier and a Light Infantry Carrier. The sub-configurations of the Close Combat Weapons Carrier are the reconnaissance vehicle, heavy guns carrier, and anti-tank missile carrier. The sub-configurations of the Light Infantry Carrier are the infantry carrier, command and control (C2) vehicle, ambulance vehicle and utility vehicle. Because of its mission, the CTV will be a lighter vehicle, which increases its Measures of Performance (MOP) in mobility, such as maximum cruising range, maximum cruising miles per hour, top miles per hour, and fuel efficiency. The low Gross Vehicle Weight (GVW) increases its airlift transportability.[21]

There will, however, be a substantial amount of armor built into the CTV, adding to the GVW and decreasing payload capacity but significantly improving sustainability and force protection to shield the vehicle and its occupants. Design improvements, such as a V-shaped hull, are being considered to decrease damage sustained from an IED attack. Other improvements include more protection provided to the top mounted gunner. These improvements are best seen in Figure 8 below.

Figure 8. CTV conceptual design produced by Oshkosh Truck Corporation[22]

The Long Range Surveillance Vehicle (LRS) will replace the M1109 and M1114 HMMWV variants. The LRS only possesses one configuration, the Long Range

[21] Global Security. "Joint Light Tactical Vehicle (JLTV)."; available from http://www.globalsecurity.org; INTERNET.

[22] Defense Update. "Joint Light Tactical Vehicle." (2006); available from http://www.defense-update.com; INTERNET.

Surveillance configuration. There are two sub-configurations, the long range surveillance vehicle and the general purpose command and control (C2) vehicle. The important measures for the LRS design are mobility and net-readiness. In order to make the LRS more mobile the GVW will be lighter than any of the other JLTV variants, approximately 20,000 lbs. This will allow increased mobility, but, will lower payload capacity.[23]

The Utility Vehicle Light (UVL) will replace the M998, M998A1, M1038, M1038A1, M1037, M1042, M1069 light utility vehicles and the M996, M996A1, M1035 and M1035A1 light ambulance vehicles. The UVL has two configurations, the Light Cargo Carrier and the Light Prime Mover configuration. The Light Cargo Carrier configuration has three sub-configurations: the ambulance, the utility vehicle and the shelter carrier. The Prime Mover Light configuration only has one sub-configuration: the prime mover vehicle variant. The prime mover's job is to tow the 105mm Howitzer or the Q-36 Radar. The most important measure for the UVL is payload capacity. This means the UVLs will have a greater GVW but will possess a much higher payload capacity than either the CTV or the LRS (5,100 lbs vs. 4,000 and 3,500 lbs respectively).[24]

The Utility Vehicle Heavy (UVH) will replace the M1043 and M1044 heavy armament vehicles, M1097, M1097A1, and M1097A2 heavy utility vehicles, and the M997, M997A1 heavy ambulance vehicles. The UVH configurations are Heavy Troop Transport, Heavy Cargo Carrier, and the Heavy Prime Mover. The sub-configurations for the Heavy Troop Transport are the protected troop transport and the convoy protection platform. The sub-configurations for the Heavy Cargo Carrier are the ambulance/treatment vehicle, utility vehicle, and shelter carrier. There is only one sub-configuration for the Heavy Prime Mover, the prime mover sub-configuration. Like the

[23] Global Security. "Joint Light Tactical Vehicle (JLTV)."; available from http://www.globalsecurity.org; INTERNET.

[24] Ibid.

UVL, the UVH places its highest performance priority on payload capacity. The UVH will be a heavy utility vehicle, capable of a greater payload capacity and more seats than the UVL.[25]

The Ground Maneuver Vehicle (GMV) is the last in the JLTV family of vehicles. The GMV will replace the M1097, M1097A1, and M1097A2 heavy utility vehicles. Its production is not expected until Increment II, therefore little information is available. The GMV will be a heavily armored vehicle with a crew of two (operator and gunner), capable of transporting a nine man infantry squad with organic combat loads over long distances. The GMV will also be capable of mounting a crew operated weapon as well as be a host to a joint communication system.[26] A concise list of the JLTV variants and their missions are listed in the table below. For more detailed explanations of all the JLTV sub-configurations, see Appendix A.[27]

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[25] Global Security. "Joint Light Tactical Vehicle (JLTV)."; available from http://www.globalsecurity.org; INTERNET.

[26] U.S. Army Tank and Automotive Command. "Joint Light Tactical Vehicle Request for Information (JLTV RFI)."; available from http://contracting.tacom.army.mil; INTERNET.

[27] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 98.

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 Utiliity
Long Range Surveillance Vehicle	LRS1A	Reconnaissance
Long Range Surveillance Vehicle	LRS2A	C2
Utility Vehicle Light	UVL1	Light Ambulance
Utility Vehicle Light	UVL2	Light Utilty
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 2. JLTV Variant/Configuration/Sub-Configuration Table

The Army's motivation for developing the JLTV is to produce a LTWV capable of meeting the mission requirements of today and tomorrow. The JLTV will meet these mission requirements in its ability to excel in a decentralized battlefield.

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III. ANALYTICAL TECHNIQUES

This chapter explains the analytical techniques that were necessary to create our decision tool. These techniques explain the theory behind creating MODA models as well as the proper formulation of Linear Programs.

A. VALUE ANALYSIS

The goal of this research is to provide TACOM with a decision tool to model the LTWV modernization. This tool is a LP with a MODA driving the representation of each vehicle variant. LTWV modernization strategies require decisions between many alternatives (LTWV variants) with many competing objectives. Discussion of these competing objectives can be found on pages 14-15. Decisions of this type require MODA. The specific approach we use is, "Value-Focused Thinking."[28] This process flows from qualitative thinking to quantitative evaluation:

- Define the alternatives to quantify. In the decision context of LTWV modernization, the alternatives are LTWV variants.
- Identify the qualitative objectives that are relevant to the decision context and possible alternatives.
- Specify the quantitative attributes to measure each objective.
- Develop a framework combining objective values, resulting in an overall alternative value.

Value-focused thinking is at the center of this process. It approaches decision making in a non-traditional manner. It first identifies end-state characteristics before identifying suitable alternatives that encompass those characteristics. One can think of this method as a "top-down" approach, starting with objectives and ending with alternatives. This moves away from the traditional, alternative-based thinking, which

[28] Ralph Keeney. Value Focused Thinking. (Cambridge: Harvard University Press, 1992).

begins by identifying the available alternatives and then proceeds to choose the best. Value-focused thinking assigns values to each alternative, allowing ranking amongst them.

1. Objectives

Once a decision maker has a clear idea of what embodies an alternative, the objectives can be defined. "An objective is a statement of something that one desires to achieve… characterized by three features: a decision context, an object, and a direction of preference."[29] An objective does not need to be measurable or tangible, but just represent an ideal for which to aim. In other words, an objective is a qualitative measure of an alternative. For example, in the decision of purchasing a vehicle, safety could be an objective. In this case, the decision context is purchasing a vehicle, while the object is safety, and the direction is that more safety is preferred to less safety.

There are two distinct types of objectives, *fundamental objectives* and *means objectives*. "A *fundamental objective* characterizes an essential reason for interest in the decision situation…"[30] A *means objective* defines a means to achieve a fundamental objective. For example, safety is a fundamental objective, and crash avoidance is a means objective to safety. Fundamental objectives are essential in directing the decision making process and evaluating alternatives. Means objectives are useful for helping to break down fundamental objectives into quantitative measures. We use fundamental objectives for the VM to reduce the chances of redundancy, as means objectives may influence more than one fundamental objective.

Identifying objectives is the first step in the process of developing a value-focused model. Once a decision maker establishes a list of desired objectives, the objectives must be structured. This structuring distinguishes between fundamental and means objectives. Fundamental objectives may be drawn out by questions such as "Why is this objective

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[29] Ralph Keeney. Value Focused Thinking. (Cambridge: Harvard University Press, 1992), 34.

[30] Ibid, 34.

important?" If it is important because it is an "essential reason for interest in the situation," it may be a fundamental objective. To be a fundamental objective, the alternative also must completely control the qualitative measure.

Objective hierarchies can be developed either from the top down or the bottom up. Depending on the situation, one may be preferable to the other. An example pertaining to vehicle mobility will be used to demonstrate these concepts. A top-down, or objectives driven approach is appropriate when "alternatives are not well specified at the start of the analysis" and "start[s] with the overall objective and successively sub-divide[s] objectives."[31] The lower objectives that result from these subdivisions specify "what aspects of the higher-level objective are important."[32] Using the top-down approach, the objectives shown in Figure 9 would have been developed first by identifying "maximize mobility" as a fundamental objective, then decomposing this fundamental objective into two supporting fundamental sub-objectives. Maximizing speed and acceleration are fundamental to maximizing mobility. Decomposition breaks down an objective into its component objectives, for which individual attributes are found. Decomposition can help when there are multiple goals encompassed in an objective. Decomposition usually leads to clearer attributes; however it comes at the price of requiring more information. A bottom-up, or alternatives driven approach is appropriate when known alternatives are available. Starting at the lowest level, the objectives aim to capture the differences between the alternatives. The same example of mobility is developed by identifying that vehicle alternatives can be distinguished by their speed and acceleration. Then speed and acceleration would be grouped under the broader category of mobility. Hence, the bottom-up approach. The top-down approach is generally preferred to the bottom-up approach. However, using the bottom-up approach in conjunction with the top-down approach can produce useful results. Top-up, or starting from the top and looking upwards, identifies fundamental objectives from means objectives. Bottom-up is also a good tool to check the objective hierarchy structure and ensure the relationships between objectives are logical.

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[31] Craig Kirkwood. Strategic Decision Making. (San Francisco: Duxbury Press, 1982), 20.

[32] Ralph Keeney. Value Focused Thinking. (Cambridge: Harvard University Press, 1992), 71.

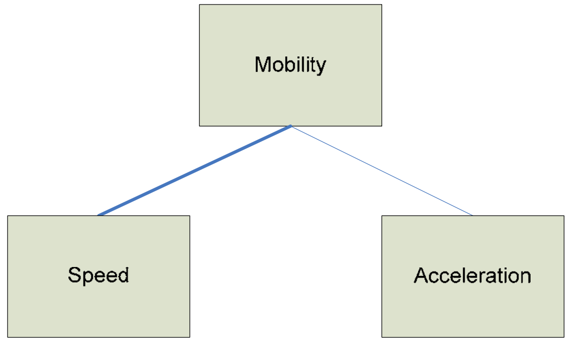

Figure 9. Mobility objectives

When defining an objective hierarchy, it should exhibit the following traits:[33] [34]

- Essentiality, requiring every objective to be important enough to include in the model
- Controllability, such that the alternative in question controls each objective
- Completeness, such that the objectives collectively embody the alternative
- Measurability, such that each objective is quantifiable
- Operability, making it feasible to collect the data to complete the analysis
- Independence, ensuring each objective may be treated separately
- Non-redundancy, avoiding any possible double-counting of a consequence
- Conciseness, making the hierarchy as simple as possible while completely representing the alternative
- Understandability, allowing potential users to understand each objective

Objective hierarchies alone have several benefits, both inside and outside of their role in forming value models. An objective hierarchy frames the scope of the problem at hand. Structuring objectives into a hierarchy allows the decision maker to spot any potential holes in the model. The model is then ready to be used in the value model formulation. It can assist in thinking about the model, analyze the role of each objective,

[33] Ralph Keeney. Value Focused Thinking. (Cambridge: Harvard University Press, 1992), 82.

[34] Craig Kirkwood. Strategic Decision Making. (San Francisco: Duxbury Press, 1982), 16.

and help specify appropriate attributes for each objective. It may also act as a guide in collecting information, to ensure that not only is the correct and necessary information collected, but that effort is not expended to collect excess information. Objective hierarchies give insight to the necessary performance of the alternatives.

2. Attributes

The next step in establishing a value model is adding attributes to the objective hierarchy. Each attribute quantitatively measures the achievement of a fundamental objective. An attribute should emphasize the intent of the objective. The three types of attributes are natural, constructed, and proxy. Each is addressed in detail below. Figure 10 shows an objective hierarchy with attributes. The objective hierarchy represents a vehicle purchase decision with respect to its environmental effects. Here, “maximize fuel efficiency,” “minimize decrease to quality of life,” and “maximize environmental protection” are attributes measuring the fundamental objective “minimize environmental effects.” The circles associated with each attribute are the measures used to define their scales. This example will be use used to clarify the concepts presented below.

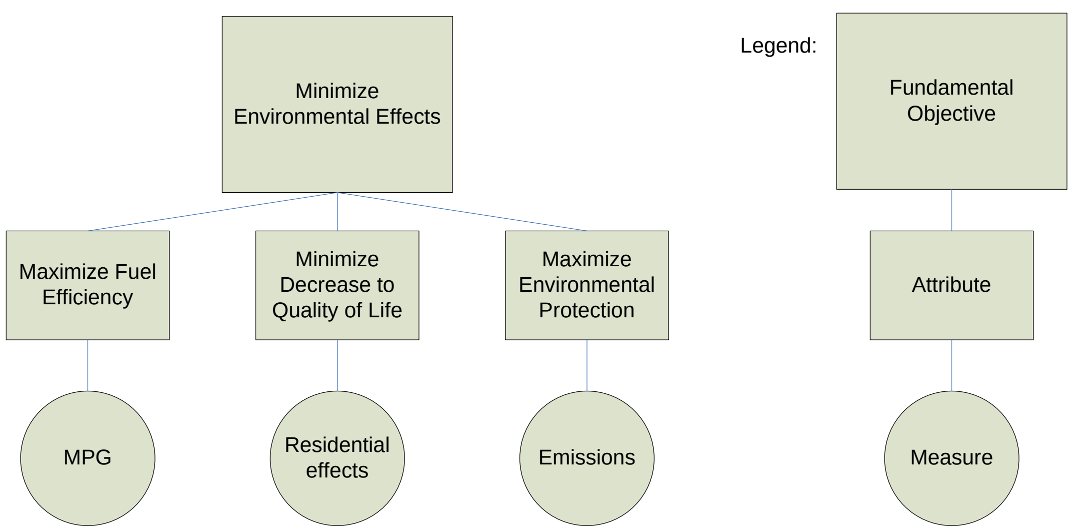

Figure 10. Objective hierarchy with corresponding attributes

a. Natural Attributes

Natural attributes "have a common interpretation to everyone."[35] Natural attributes are measured in understandable units, such as pounds or cubic feet. In the problem described in Figure 10, miles per gallon (MPG) could be a natural attribute to describe "maximize fuel efficiency." It's important to note that MPG is not the only possible attribute for "maximize fuel efficiency."

If possible, a natural attribute should be assigned to each objective. If a natural attribute is not available, options include a constructed attribute, or a proxy attribute.

b. Constructed Attributes

Every objective does not necessarily have a natural attribute. If a natural attribute is not available, a constructed attribute designed specifically for the objective may be used. A constructed attribute may help to describe a concept like quality of life, where there is no natural unit of measurement. Constructed attributes are only relevant within the problem they are developed for. Returning to the vehicle example of Figure 10, a survey measuring quality of life degradation due to increased vehicle pollution is an example of a constructed attribute. A survey specifically describes different levels of an objective in words, and associates them with a value. Well-known examples of constructed attributes include the Richter scale and the Dow Jones industrial average.

c. Proxy Attributes

A proxy attribute is used when the actual attribute that one wishes to apply is too difficult to measure. A proxy attribute is used in the actual attribute's place. In the vehicle example, emission levels could be a proxy for measuring the effect of a vehicle on environmental health. Proxy attributes reduce the effort necessary to gather data. However, proxy attributes should be

[35] Ralph Keeney. Value Focused Thinking. (Cambridge: Harvard University Press, 1992), 101.

used with caution, as they have less intuitive meaning. It is necessary to be very specific in the objective to ensure proxy attributes are used correctly.[36]

Attributes have three desirable properties. These properties ensure that each attribute clarifies the objective it measures. An attribute should be measurable, operational, and understandable.

A measurable attribute defines the objective it measures in more detail than that provided by the objective alone. An attribute should emphasize what aspects of the objective are important.[37] Establishing measurability in natural attributes is fairly simple. Problems are more likely to occur with constructed or proxy attributes.[38] It can be unclear as to what exactly a constructed attribute accounts for, making it difficult to ascertain whether it is an appropriate attribute to measure an objective.

An operational attribute describes the possible levels of achievement associated with an objective. In other words, an attribute must be able to express relative preferences amongst the alternatives for different levels of achievement. Attributes may need a short description to make them operational. For instance, because measurements should be taken in consistent circumstances, these circumstances must be explained. Information pertaining to critical levels of the attribute is necessary to judge a level's desirability. For example, when judging the desirability of emission levels, knowledge of emission standards is necessary.

An attribute is understandable if there is no ambiguity in describing or interpreting an alternative in terms of its attributes.[39] This implies that there is "no loss of information" between one person's assignment of an attribute and another's interpretation of it. Creating an understandable attribute requires the ability to be precise in measurement.

[36] Ralph Keeney. Value Focused Thinking. (Cambridge: Harvard University Press, 1992), 120.

[37] Ibid, 113.

[38] Ibid, 113.

[39] Ibid, 116.

Attribute interaction affects whether a model is either additive or multiplicative. As proved by Keeney and Raiffa, each attribute $\{X_1, X_2, \ldots, X_n\}$ must be mutually preferentially independent for the resulting value function $v_i(x_1, x_2, \ldots, x_n)$ to be strictly additive.[40] This means that in an additive model, each attribute is associated with a single objective. Problems are most likely to occur with proxy attributes, which may influence more than one objective, violating mutual exclusivity. The TACOM value model is an additive model because all objectives are fundamental to the decision context, i.e., mutually exclusive and collectively exhaustive.

3. Quantitative Value Model

After development of the qualitative value model, i.e., the objective hierarchy and attributes, we next must develop the quantitative value model. The quantitative value model combines the objective hierarchy and attributes to give an overall value for an alternative. In the LTWV VM, each vehicle variant is a separate alternative.

The first step in the development of the quantitative value model is to determine a multiple dimension value function. This value function combines the values obtained from each of the single-dimension value functions (SDVF) for each attribute into a single value for each alternative. For each attribute *n*, it consists of two parts, a SDVF $v_i(x_i)$ and weight w_i. For an additive model, these are combined by Equation 1:[41]

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i), \quad \text{where } \sum_{i=1}^{n} w_i = 1 \tag{1}$$

An SDVF, $v_i(x_i)$, is specified for each attribute. The SDVF defines the relationship between the measured amount of an attribute and the degree to which that amount accomplishes the objective. The SDVF assigns a value for the level of accomplishment. The values from all attributes need to be compatible, so normalization is required.

The relationship between the measured amount of an attribute, i.e., its level, and its value may take any form. Common relationships include linear, increasing returns to

40 Ralph Keeney, L., H. Raiffa. *Decision Making with Multiple Objectives*. (Wisley, NY. 1976).

41 Ibid.

scale, and decreasing returns to scale. Returns to scale is the marginal value of each successive unit. A linear relationship shows constant returns to scale, as each successive attribute level has a constant marginal value. Increasing returns to scale implies that as the attribute level increases, the marginal value that each successive unit receives increases. Decreasing returns to scale is the opposite; as the attribute level increases, the marginal value that each successive unit receives decreases. The SDVF should include any insight from critical attribute levels. Critical attribute levels can include requirement, quota, or saturation levels. A method of determining the piecewise linear SDVF is discussed below.

A piecewise linear value function consists of several linear segments joined together. The value function relates an attribute's score or level (the measure input) to a value (the SDVF output). Values range along a scale, usually 0 to 1, to represent the range of the attribute. Though the most common scale is 0 to 1, other scales are permissible. We chose to use 0 to 10 so as to distinguish a value from a percent. A SDVF should be defined over the range of the worst to best levels received by available alternatives to maximize the ability to distinguish between them. The procedure for developing a piecewise linear function is as follows:

- Attach a relative value to each level of the attribute. For example, Level A, 10 pounds, is twice as valuable as Level B, 5 pounds.
- Assign the value of to *x* to the smallest relative value.
- Convert each level of relative importance into a multiple of *x*.
- Solve for *x* with the equation

$$\sum \text{Relative Values} = 10$$

- Plug in the value of *x* to each relative value to solve.

At this point, each level of the attribute has been assigned a value; however it is not yet a continuous function. Between each level, a straight line is drawn, and scores between levels are interpolated on that line. An SDVF must be developed for each attribute.

The assessment of the SDVFs is the most important part of building the quantitative model. As discussed previously, defining a SDVF for an attribute allows the decision maker to express returns to scale, as well as any other external critical attribute levels. These critical attribute levels can be anything from requirement to saturation levels. Subject matter expert input is critical at this phase of model development. The ability to associate levels of desirability with scores for a measure gives MODA its ability to accurately reflect factors in the outside environment and value judgments.

At this point, the individual attributes of an alternative can be measured and valued. The next step is to combine these attribute values together to give an overall value corresponding to the overarching fundamental objective.

a. Swing Weight Matrix

The attributes have a weighted impact on the overall fundamental objective value. The process of determining the weight of each attribute is known as the Swing Weight Matrix. Trainor et al[42] introduced the Swing Weight Matrix, and Ewing et al[43] extended and operationalized it in their 2005 Base Realignment and Closure analysis. The Swing Weight Matrix uses both an attribute's relative importance and as well as the variability within the data to assess its weight. As described by Ewing et al, the method has four steps:[44]

- Define the importance and variance dimensions.
- Place the value measures in the matrix.
- Assess the swing weights.
- Calculate the global weights.

42 T. Trainor, G. Parnell, B. Kwinn, J. Brence, E. Tollefson, R. Burk, P. Downes, W. Bland, J. Wolder, and J. Harris. "USMA Study Of the Installation Management Agency CONUS Region Structure". (West Point, NY, 2004).

43 P. Ewing, W. Tarantino, and G. Parnell. "Use of Decision Analysis in the Army Base Realignment and Closure (BRAC) 2005 Military Value Analysis." *Decision Analysis* (March 2006): 41.

44 Ibid, 41-42.

The first step is to define the importance and variance dimensions. Importance is a definition of precisely what is important in the decision context. For example, in Ewing et al's 2005 Base Realignment and Closure analysis, importance was defined as "the Army's ability to change an installation's attribute level."[45] Certain attributes in their model, such as acreage, were unchangeable, while others, like office space, could be modified by spending money. Variability refers to the change in value resulting from swinging an attribute from its lowest possible level to its highest. An attribute which does not possess much variability will not be useful in distinguishing between alternatives. Figure 11 is the Swing Weight Matrix for the 2005 BRAC example, with importance, or ability to change, increasing from right to left across the columns, and variability increasing from bottom to top along the rows.

← Ability to change →

Variation of scale (↕)

Mission immutable (very difficult to change)		Mission support (difficult to change without external support)		Mission enablers (change with army dollars)	
Heavy mnvr area Direct fire Brigade capacity 100	Light mnvr area Indirect fire 90	Int./partnering Area cost factor 75	*Housing avail.* *Crime index* *Maint./manuf.* *50*	*RDTE diversity* *20*	**Supply & storage** **Ops/admin** **Ammo storage** **10**
Force deploy Materiel deploy Airspace 90	Critical infrastr. Proximity Test ranges Mob. history 75	*Munitions prod.* *Accessibility* *Urban sprawl* *50*	*Connectivity* *Work force* *Availability* *20*	**MOUT** **10**	**Applied instructional** **General instructional** **5**
Buildable acres 75	*Soil resiliency* *Joint facilities* *50*	*Employment op.* *Water quantity* *Inst unit cost* *ENV. elasticity* *20*	**Medical avail.** **Noise contours** **Air quality** **In-state tuition** **10**	**C2 TGT facility** **5**	 **1**

Level of importance		
HIGH	*MEDIUM*	LOW

Figure 11. BRAC swing weight matrix [46]

The second step is to place the value measures in the matrix. The decision maker judges each attribute according to the criteria of importance and variability. More than one attribute may occupy a cell in the matrix. It is necessary to keep in mind that the

[45] P. Ewing, W. Tarantino, and G. Parnell. "Use of Decision Analysis in the Army Base Realignment and Closure (BRAC) 2005 Military Value Analysis." *Decision Analysis* (March 2006): 41.

[46] Ibid, 42.

definition of importance may not correspond to an attribute's criticality. In Figure 11, bold and italics are used to identify those attributes considered critical. Subject matter experts should be consulted at this step to ensure proper placement.

Step three assesses the swing weights. A matrix swing weight, f_i, is assigned to all cells in the matrix.[47] It is "important to ensure the proper range of weights [exists] between the highest and lowest weighted attribute[s]."[48] In, the 2005 BRAC example, swing weights range from 0 to 100. The highest, in this case 100, is placed in the upper-left corner, and the lowest, 1, is placed in the lower-right corner. A swing weight of 0 corresponds to no influence in the model, and is equivalent to not including that attribute at all. The rest of the matrix is filled in accordingly to reflect importance and variation.

The fourth and last step of the process calculates the global weight of each attribute. These weights, used in Equation 1, are calculated with Equation 2:[49]

$$w_i = \frac{f_i}{\sum_{i=1}^{n} f_i}, \text{ where } f_i = \text{matrix swing weight corresponding to attribute } i \qquad (2)$$

Ewing et al assert that the Swing Weight Matrix procedure has the following advantages over other weight assessment methods. By developing an explicit definition of importance, it gives a concrete interpretation of the weights and eliminates an element of subjectivity. It also "forces explicit consideration of the variation of measures."[50] As stated previously, if an attribute does not possess enough variation in

[47] P. Ewing, W. Tarantino, and G. Parnell. "Use of Decision Analysis in the Army Base Realignment and Closure (BRAC) 2005 Military Value Analysis." *Decision Analysis* (March 2006): 41.

[48] Ibid, 41.

[49] Ibid, 42.

[50] Ibid, 42.

the levels that objects achieve, it will not be useful for distinguishing between objects. The resulting framework allows for consistent swing weight assessments, which are then simply and easily justifiable.

The implementation of the model combines the raw data, the SDVF and the weights to produce an overall fundamental objective value for an alternative. For a given alternative, each of its attribute levels, x_i, is plugged into its respective SDVF, v_i, to find an attribute value. These values are combined, for each alternative, using Equation 1.

The meaning of this number can be thought of as the "proportion of the distance, in a value sense" the alternative is from the absolute worst alternative, which would receive a value of 0, and the ideal alternative, which would receive a value of 10.[51] The worst and best objects may only be hypothetical. Alternative values can be used for comparisons and decision making and works best when there are a limited number of alternatives. When decisions must be made between a large number of alternatives, or a *portfolio* of alternatives must be decided, then mathematical programming should be used to generate these portfolios.

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[51] Craig Kirkwood. Strategic Decision Making. (San Francisco: Duxbury Press, 1982), 74.

B. LINEAR PROGRAMMING

Linear Programming (LP) is the mathematical subject of optimizing (minimizing or maximizing) a linear *objective function* over a set of linear *constraints*. LP is an integral subject in operations research, enabling mathematicians to solve a wide range of problems from economics to engineering.[52]

An American named George Dantzig developed LP during World War II as a method to reduce expenditure costs while increasing damage dealt to the enemy. Dantzig published the formulation necessary to create LPs as well as an algorithm, called the *simplex method*, to solve them. The algorithm is an iterative method guaranteeing an optimal solution if one exists. It allows LPs, which previously took enormous amounts of time and computing power, to be solved quickly and efficiently. The methodology was declassified in 1947 and quickly became a tool for commercial optimization.[53]

There are many uses for LP. Among others, the subject applies to economics, business management, finance management, and project management. This thesis uses LP to find a feasible modernization strategy for the LTWV fleet that meets budgetary and operational constraints.

The standard form for expressing LPs is to state which direction you are optimizing (minimizing or maximizing), what you are optimizing (the objective function), followed by the constraints which the solution must meet. In the end, a LP looks as follows:

$$\text{Maximize (or Minimize) } c^T x$$
$$\text{Subject to } Ax \leq b$$
$$\text{Where } x \geq 0$$

"x" represents the vector of variables. "c" represents the coefficients associated with each variable. "A" and "b" make up the coefficients for the constraints.

52 J. Noyes and E. Weisstein. "Linear Programming." (2005); available from http://www.mathwworld.com/LinearProgramming.html; INTERNET.

53 Ibid.

Geometrically, the linear constraints in the problem define a convex region known as the *feasible region*. Because the objective function must also be linear, the local optimal solution must be the global optimal solution. In other words once you find *an* optimal solution to the objective function, it is guaranteed to be *the* optimal solution to the problem. Also, because of the linearity of the objective function, the optimal solution is guaranteed to lie on the boundary of the feasible region. An example of a feasible region is seen in Figure 12.

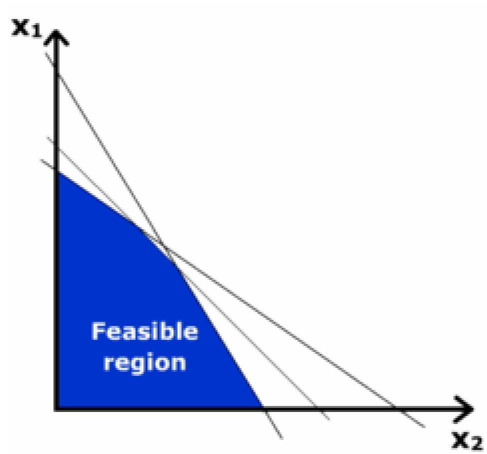

Figure 12. A Graphical Representation of a Feasible Region

LPs can be formulated where no optimal solution exists. If constraints contradict each other there is no feasible region. Therefore the LP has no solution. Also, constraints in an LP can create an unbounded feasible region, where ever increasing higher or lower (depending on if the problem is maximizing or minimizing) solutions can always be found. This clearly creates a situation where no optimal solution exists. The unbounded feasible region would not be a polyhedron but rather a plane. However, if the feasible region is a convex polyhedron (as seen in Figure 12) there exists an optimal solution.

A series of linear constraints intersect to create the feasible region. Any combination of values within that region creates a feasible answer, and an optimal answer exists along the borders of the feasible region, most likely at an intersection of two or more constraints.[54]

The simplex algorithm, developed by Dantzig, solves LPs by iteratively testing possible optimal solutions. Dantzig proved that if a LP is capable of possessing an optimal solution, that optimal solution must lie on the boundaries of the feasible region. In most cases, that solution lies in a vertex of the feasible polyhedron, or the intersection of two or more constraints. The algorithm uses that theorem and walks along the boundaries of the feasible region, looking for an optimal solution.

If all of the decision variables in a particular linear program are required to be integers, then the program is further classified as an Integer Linear Program (ILP). ILPs are sometimes very difficult for a computer to solve because of the combinatorial nature of the problem. Because LPs with continuous decision variables are easier to solve, we have formulated our problem as an LP where we allow for fractional solutions. This approach is acceptable for our problem because the magnitudes of our decision variables (numbers of vehicles bought, recapped, and retired) are such that rounding of these variables will not affect the prescribed policies. For example, the number of recapped vehicles or new vehicles proposed by the LP will most likely be in the hundreds in any given year. In other words, rounding from 102.6 to 103 vehicles will have very little effect on the solution.

The LTWV LP was implemented using the General Algebraic Modeling System (GAMS), a high level algebraic modeling language designed for professional level optimization. GAMS is capable of solving Linear, Non-Linear, Integer and Mixed Integer Programs when coupled with an appropriate solver. The solver used with our test problem was CPLEX; the best general purpose linear programming solver available.[55]

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[54] J. Noyes and E. Weisstein. "Linear Programming." (2005); available from http://www.mathwworld.com/LinearProgramming.html; INTERNET.

[55] The General Algebraic Modeling System (GAMS). "The GAMS System."; available from http://www.gams.com; INTERNET.

IV. METHODOLOGY

A. LTWV VALUE MODEL

1. Objective Hierarchy

The development of the LTWV value model addresses the situation of quantifying a LTWV for the purpose of making fleet inventory decisions. The model was developed from HMMWV and JLTV requirements documents as well as subject matter experts in order to accurately reflect important aspects, capabilities, and requirements of these vehicles.

The qualitative model was developed using the procedure and guidance specified in Keeney's *Value Focused Thinking* and Kirkwood's *Strategic Decision Making* (see Chapter III). Information was gathered from the HMMWV Operational Requirements Document and the JLTV Capability Development Document to identify objectives and attributes. A top-down approach was used, starting from the Key Performance Parameters (KPPs) of the JLTV CDD. These KPPs, Mobility, Transportability, Net-Readiness, Force Protection, Survivability, Payload, and Materiel Availability, are the basis of the model, and served as the initial objectives.[56] We divided objectives into sub-objectives until attributes could clearly be assigned. Subject matter experts LTC Lee Ewing and LTC Stuart Rogers were then consulted to ensure the objectives and attributes accurately represented a vehicle. LTC Ewing is an expert in the field of decision analysis, and LTC Rogers an expert in TWVs. LTC Rogers gave us recommendations for our single-dimensional value functions (SDVF) and weights. LTC Ewing ensured the value model accurately reflected those recommendations. We used the swing weight matrix to assess weights from the bottom up. Each attribute was weighted individually and combined resulting in the overall weights for each fundamental objective. The resulting objective hierarchy with attributes is below:

[56] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 22-23.

Legend

- *Capability*
    - **Attribute (units)**

- *Mobility*
    - *Vehicle mobility*
        - *Speed*
            - **Maximum cruising range (miles)**
            - **Top MPH (miles per hour)**
            - **Acceleration (seconds, 0 – 60 mph)**
        - *% Incline*
            - **Maximum speed on 5% grade (miles per hour)**
            - **Maximum % grade (% grade)**
        - **Fuel efficiency (ton miles per gallon)**
        - *Maneuverability*
            - **Maximum fording depth (feet)**
            - **Turning radius (feet)**
    - *Transportability*
        - **Air (tons, gross vehicle weight)**
        - **Sea (volume, vehicle space occupied)**
- *Net-Readiness*
    - *Alternator size (amps)*
- *Survivability*
    - *Force protection (inhabitants)*
        - **Force protection (protection level 1-4)**
    - *Vehicle safety*
        - **Crash survival (% GVW supported in rollover)**
        - **Crash avoidance (% go given dry normal conditions)**
    - *Payload*
        - *Capacity*
            - **Maximum weight (pounds)**
            - **Cargo area (cubic feet)**
            - **Number of seats (count)**
        - **Towing capacity (pounds)**
    - *Sustainability*
        - **Reliability (MMBOMF)**
        - **Total ownership (FY08$)**
        - **Maintenance (operational availability)**

Figure 13. Objective Hierarchy of Attributes

We chose every objective and attribute carefully to accurately represent a vehicle capability in the context of the performance requirement in the CDD. The remainder of this section will be devoted to the justification and explanation of each objective and attribute in this model. The version of the model presented here is as complete as possible, and includes all objectives on which vehicles are scored. Though these objectives are all valid, in the end, some were dropped from the final model used in this analysis for reasons of redundancy, lack of data, or lack of variation within the data. It should be clarified that if an objective is dropped for lack of variation within the data, this does not imply that the objective is not important, but instead that the objective provides no additional insight into distinguishing between vehicles. The final inclusion or exclusion of each objective is addressed within the individual sections below. We assessed each of the following attributes by using a piecewise linear SDVF approach. Value increments were assessed through subject matter expert input from various sources. The assessments were not conducted in person; however, they were conducted over conference phone calls and the results staffed by the U.S. Army Combined Arms Support Command (CASCOM).

a. Mobility

Mobility is one of three of the top-tier objectives, encompassing both the mobility of a vehicle itself and the transportability of a vehicle. The mobility objective is designed to represent a vehicle's tactical and operational mobility. It is crucial to mission fulfillment that a vehicle have excellent tactical mobility, as it "will be employed across the range of military operations and must be capable of precise, decisive maneuver, horizontal and vertical, day and night, in all terrain and weather conditions."[57] A vehicle's operational mobility or transportability is an expression of the need to "support inter-theater strategic deployment and intra-theater operational maneuver."[58] It is advantageous if a vehicle can be being transported by existing Army assets in a timely manner.

Within vehicle mobility, sub-objectives include speed, performance on incline, fuel efficiency, and maneuverability. Speed is a critical aspect of a vehicle's

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[57] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 20.

[58] Ibid, 22.

ability to complete missions and succeed operationally. Vehicles need to be able to operate for prolonged periods of time at speeds ranging from cruising to sprint. The following attributes aim to capture both parts of this speed requirement.

- Maximum cruising range, measured in miles, is described in the JLTV CDD as the "distance traveled on level paved surface roads at GVW on single tank of fuel."[59] It reflects a vehicle's ability to travel for a long period of time at a constant, non-sprint speed. This would include convoy travel and routine movement. Vehicles must have the required range to be "consistent with other Army motor wheeled vehicles."[60] Inability to do so "may result in additional fueling stops and possible unacceptable reduction in current logistics support efficiency."[61] Maximum cruising range's SDVF has increasing returns to scale, reflecting the increasing marginal value in each successive unit of cruising range. An increased cruising range indicates a decreased refueling need, making the vehicle more time and cost effective.

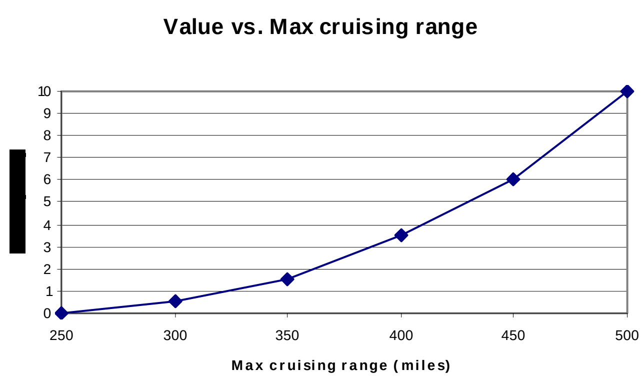

Figure 14. Value vs. Maximum cruising range

[59] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 27.

[60] U.S. Army Training And Doctrine Command Tactical Wheeled Vehicle Modernization. Operational Requirements Document (ORD) for the High Mobility Multipurpose Wheeled Vehicle (HMMWV). (Fort Eustis, VA: GPO, 2004), 17.

[61] Ibid, 17-18.

- Top speed of a vehicle, measured in miles per hour, is the maximum sustained speed a vehicle at GVW can achieve over flat paved surfaces.[62] This attribute captures a vehicle's sprint ability, and attainment of a high value in it is crucial to a vehicle having "superior tactical mobility."[63] Vehicles must "achieve higher road/convoy speeds in response to ongoing operational lessons learned," and this attribute aims to reflect this.[64] The SDVF for top speed is piecewise linear, with the key point being at 45 mph, the speed of modern convoys. The inability to keep up with convoys renders the vehicle useless in that context.

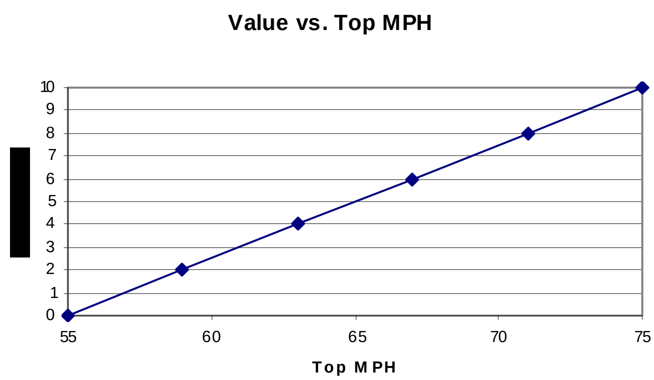

Figure 15. Value vs. Top MPH

- Acceleration, measured as the seconds necessary to accelerate from 0 to 60 mph, captures a vehicle's ability to increase its speed. Without a reasonable amount of acceleration, a vehicle with an ideal top speed is not very operationally useful. Over the range of the data, acceleration has

62 Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 33.

63 Ibid, 33.

64 Ibid, 33.

constant returns to scale. However, the data did not have enough variability to significantly distinguish between variants, and was not included in the final model.

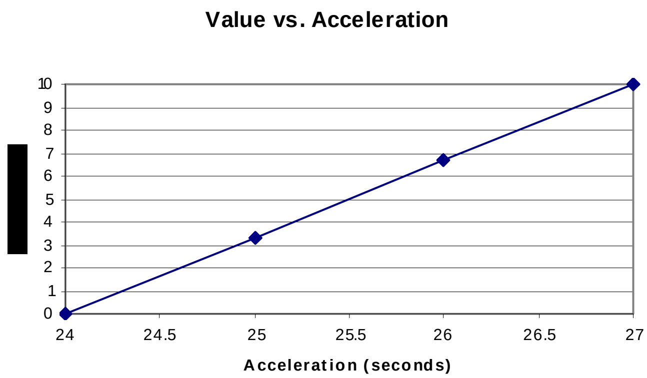

Figure 16. Value vs. Acceleration

Vehicles must be able to perform on inclines ranging from hilly to mountainous terrain to meet operational needs for which they are designed. These needs range "from utility in nature to direct action to convoy escort to patrolling," and the ability to maintain sustained high speed over graded terrain "allows the Joint ground forces to control and drive the operational tempo and operate inside the enemy decision cycle."[65]

- Maximum speed on 5% grade at GVW was chosen as an attribute because 5% represents "an operationally relevant description of hilly to mountainous terrain, and it is important that vehicles be able to maintain speed on grade for the variety of missions described above."[66] This attribute's SDVF shows constant returns to scale, with the same knee in the curve as in top speed. This break at 45 mph marks convoy speed, with vehicles unable to keep up rendered useless in this role.

65 Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 34.

66 Ibid, 34.

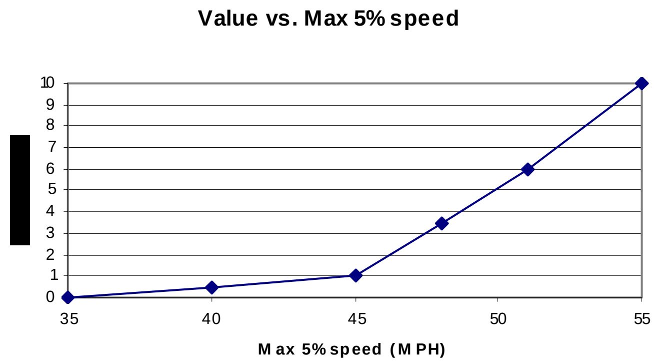

Figure 17. Value vs. Maximum 5% speed

- Maximum percent grade represents the amount of dry, hard-surfaced longitudinal slope that a vehicle can ascend, descend, start and stop on at GVW without loss of stability, malfunction, or degradation of stated requirements.[67] Vehicles must park with the engine off for long enough duration "as to assure that there shall be no loss of fluids or other malfunction while parked."[68] This requirement assures that vehicles will be able to operate in any possible steep terrain conditions that operations demand. The negotiation of "these slopes is essential for the emplacement of towed weapons, communications shelter systems, and overall battlefield maneuverability."[69] The SDVF for maximum percent grade has constant returns to scale; within the range of variation there is no justification for anything else.

[67] U.S. Army Training And Doctrine Command Tactical Wheeled Vehicle Modernization. Operational Requirements Document (ORD) for the High Mobility Multipurpose Wheeled Vehicle (HMMWV). (Fort Eustis, VA: GPO, 2004), 11.

[68] Ibid, 12.

[69] Ibid, 12.

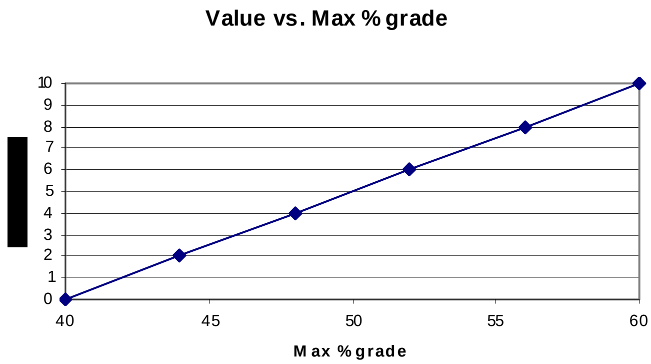

Figure 18. Value vs. Maximum % grade

Fuel efficiency is a matter of utmost importance to overall operations. "After water, fuel is the highest demand, largest throughput commodity on the battlefield;" therefore "even comparatively small reductions in fuel consumption have large scale effects across the force because of the reduction in fuel movement requirements."[70] Reductions in fuel needs "provide commanders greater freedom of action and reduce the vulnerability of logistical elements on the battlefield because they have to move less [fuel]."[71] Executive Order 13423 recognizes this by "mandating that future vehicles achieve 2% annual improvements relative to their baselines for fiscal year 2005."[72]

- Fuel efficiency, measured in ton miles per gallon, is its own natural attribute. Its SDVF has increasing returns to scale, as a result of increased gains per successive unit of efficiency achieved. Increased gains in value are achieved by reducing the amount of money spent on purchasing it, time and effort spent logistically transporting it, and dependence on fossil fuels in accordance with national goals.[73]

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70 Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 26-27.

71 Ibid, 26.

72 Ibid, 26.

73 U.S. Army Training And Doctrine Command Tactical Wheeled Vehicle Modernization. Operational Requirements Document (ORD) for the High Mobility Multipurpose Wheeled Vehicle (HMMWV). (Fort Eustis, VA: GPO, 2004), 18.

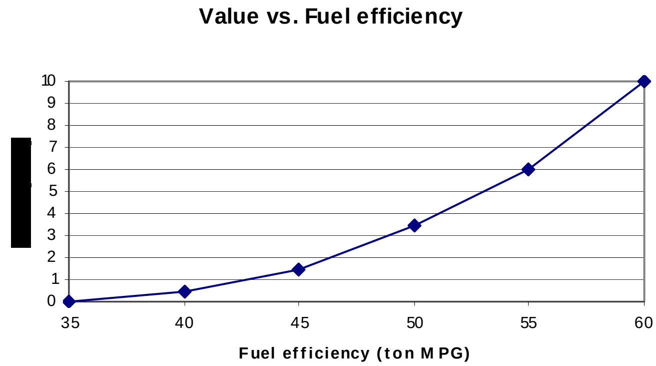

Figure 19. Value vs. Fuel efficiency

Maneuverability, defined as "the ability to negotiate obstacles found in the complex battlespace (natural, man-made, limited space), including all terrains (jungle, forest, mountain, desert, urban, etc.) found in the mission profile," is essential to operational success.[74] Vehicles should be capable of handling this complex battlespace, to include having the capability to "traverse slopes, ford, turn (control direction), cross vertical obstacles, breach light natural or manmade obstacles (saplings, gates/fences), cross ditches, and push like-sized obstacles from lanes of maneuver."[75]

- Maximum fording depth, measured in inches, represents the depth a vehicle at GVW shall be capable of fording in hard bottom salt-water obstacles without preparation.[76] This capability is required such to "allow operations where water fording and amphibious landings are required," and ensure the vehicle is designed to "withstand the most vigorous of environmental conditions."[77] This attribute of maneuverability measures a vehicle's ability to handle environmental obstacles. The SDVF for this attribute has decreasing returns to scale, as the Army's needs are limited to

[74] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 36.

[75] Ibid, 33.

[76] Ibid, 60.

[77] U.S. Army Training And Doctrine Command Tactical Wheeled Vehicle Modernization. Operational Requirements Document (ORD) for the High Mobility Multipurpose Wheeled Vehicle (HMMWV). (Fort Eustis, VA: GPO, 2004), 13.

a 30 foot fording capability, leaving any additional depth desirable, but unnecessary and less valuable than attainment of 30 feet. The data showed that every vehicle is designed to meet this 30 foot requirement, eliminating variation, and justifying its exclusion from the final model.

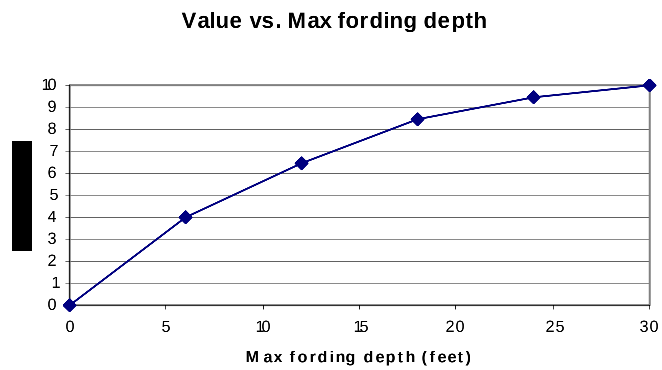

Figure 20. Value vs. Maximum fording depth

- Curb to curb turning radius is another attribute of maneuverability, capturing a vehicle's movement ability without regard for obstacles. It is measured in feet, and its SDVF shows constant returns to scale in the range of data variation. The data for this attribute did not show enough variability to justify its presence in the final model; without variability, the attribute could not distinguish between variants.

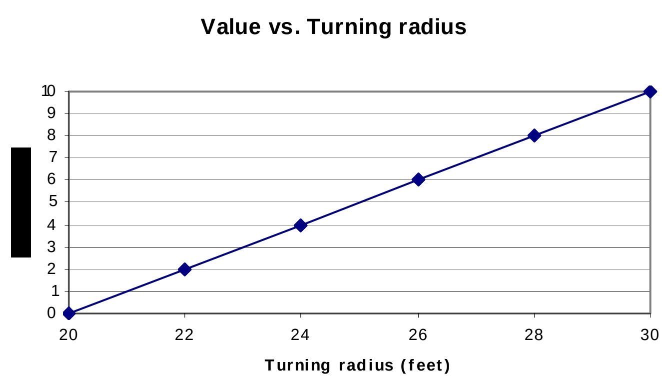

Figure 21. Value vs. Turning radius

It is important to note that while neither of maneuverability's attributes was included in the final model, this does not imply that maneuverability is not important. Instead, it indicates that they were not useful attributes in distinguishing between the different variants.

Transportability includes sub-objectives which maximize air and sea transport. These capabilities "provide flexibility for entry operations (permissive and non-permissive) to counter threat anti-access strategies by using multiple austere entry points to bring in combat configured units."[78]

Air lift capability is crucial to current operational demands. "Use of fixed wing aircraft permits rapid deployment of forces to (and within) a hostile forward operating area. Rotary wing aircraft allow rapid deployment of forces in a hostile forward operating area in support of maneuver."[79] "Movement of Joint forces via rotary wing provides the Services an essential vertical envelopment capability critical to the execution of their individual service missions."[80] In this model, we chose to focus on tactical mobility utilizing rotary wing aircraft, not because fixed wing are unimportant, but because fixed wing do not present much variation between variants.

- GVW is the main determinant of air-lift capability, limiting transport through an aircraft's maximum payload limit. It shows constant returns to scale, emphasizing the criticality of each pound equally. Aircraft can sling-load more than one vehicle if their combined weights are under the maximum payload, and every pound of a vehicle's weight contributes equally towards that limit.

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78 Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 22.

79 Ibid, 22.

80 Ibid, 22.

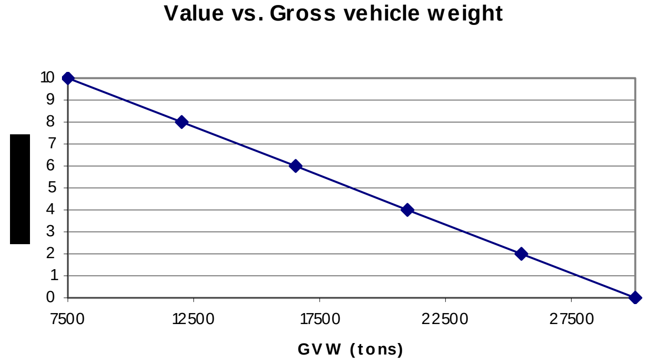

Figure 22. Value vs. Gross vehicle weight

"Sealift allows world-wide deployment of JLTV, supporting pre-positioning, Sea Basing, and Amphibious force projection capabilities."[81] With the wide range of current military operations, it is critical to have the ability to transport forces and equipment over large distances.

- Volume is the main determinant of sealift ability, limited by a ship's cargo area. It shows constant returns to scale, with each cubic foot weighted equally, following the same logic of airlift capability. Ships may carry several vehicles at a time, provided they all fit in the cargo area, and each cubic foot of volume contributes equally towards that limit.

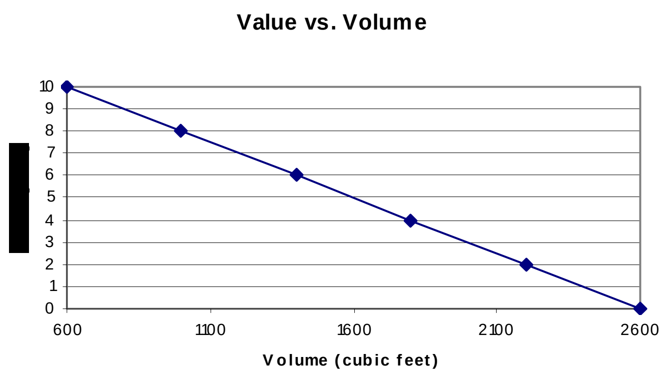

Figure 23. Value vs. Volume

[81] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 22.

b. Net-Readiness

The second top-tier goal is net-readiness, allowing the fleet to "achieve interoperability through the seamless integration of Joint and Service C4I systems."[82] With this in mind, the fleet needs to be able to "operate as part of a joint team and… share information both vertically and horizontally throughout the force and across boundaries."[83] Current situations predict that vehicles will need "to operate in units during distributed as well as close combat operations, mandating that units be able to quickly develop, synchronize, and adapt plans to integrate the effects of ISR, Fires and Maneuver."[84] "Timely, accurate collaboration is essential to maintaining decision superiority over enemy combatants as well as in non-hostile situations…made possible by [the ability to] seamlessly share information."[85] Net-readiness is measured by alternator size, a proxy for the power available for transmission equipment, such as radios.

- Alternator size represents net-readiness in this context, in that all radios and electronic equipment must be powered from the alternator. A larger alternator implies a larger power source, enriching this capability. HMMWVs are powered by a 60, 100, 200, or 400 amp belt-driven alternator.[86] However, it has been shown that a 400 amp alternator is not sufficient to "power all on-board systems while at or near engine idle (600-900 RPMs)."[87] To ensure that JLTVs are not subject to this limitation of belt-driven alternators, research is being done on alternative technologies, including power take-off, in-line, and parallel hybrid propulsion alternators. As these will not be implemented unless they can meet the on-board power requirements, the model represents them as a

[82] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 23.

[83] Ibid, 23.

[84] Ibid, 23.

[85] Ibid, 23.

[86] Ibid, 53.

[87] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 53.

400 amp alternator, which gives a value of 10. The SDVF has an odd shape to represent the ability of a 200 amp alternator to meet 75% of a vehicle's needs. Leading up to 200 amps, there are constant returns to scale. Above 200 amps, there are also constant returns to scale; however the rate of return decreases, as there is less percent satisfaction of the goal to be gained per additional amp.

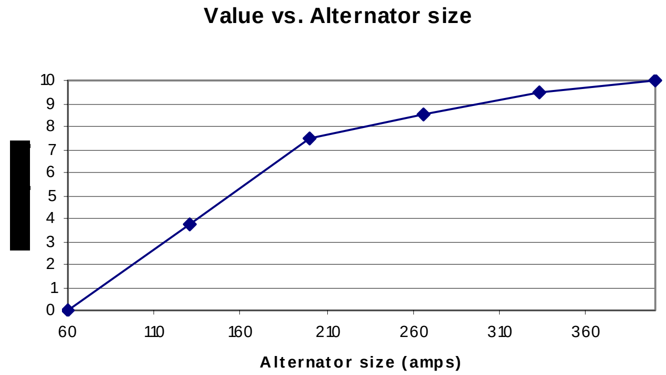

Figure 24. Value vs. Alternator size

c. Survivability

The third top tier goal, survivability, encompasses vehicle force protection, safety, payload, and sustainability. These distinct sub-objectives represent a vehicle's safety and payload.

Force protection describes the ability of a vehicle to survive an attack. "Conducting irregular warfare against an unconventional enemy on a battlefield without front lines and secure areas requires an emphasis on protection for the light tactical vehicle fleet supporting maneuver forces."[88] "Protected light tactical mobility protects… personnel from the effects of kinetic, non-kinetic, chemical, biological, nuclear, explosives, projectiles, and directed energy weapons."[89] This is very important in the realm of operational use, as it ensures the "ability to operate and survive within the threat

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88 Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), Force Application Appendix 1.

89 Ibid, 5.

environment, providing mission assurance and continuity of operations."[90] This model represents all attack types together, to avoid any possible redundancies that may occur by double-counting the same protection measures, such as armor, that protect against several attack types.

- Force protection is measured in levels of 1 to 4, corresponding to different levels of an attack that a vehicle may survive. A vehicle's level is not classified, but what type and intensity of attack the level corresponds to is. This corresponds to the system used to rate protection in the JLTV CDD; however due to difficulties obtaining the data, this attribute is not included in the final model used here. The attribute is too important to be removed from the model as a whole, and should data become available, it should be reinstated. The SDVF shows increasing returns to scale, as it grows more important to be able to withstand an attack as the size of the attack increases.

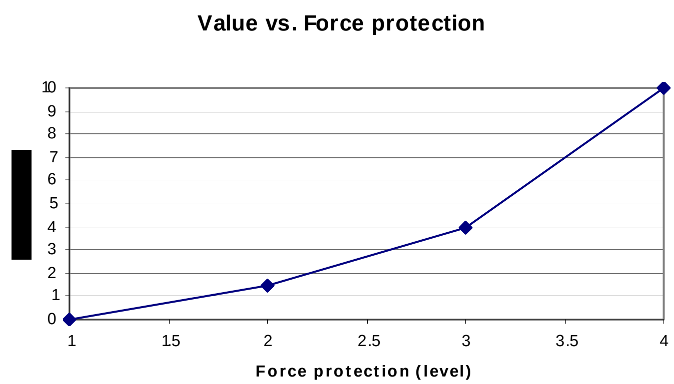

Figure 25. Value vs. Force protection

Safety measures the protection a vehicle offers its inhabitants in both a battle and non-battle context, broken down into two parts, avoiding and surviving accidents. Several factors contribute to accidents, including "top heavy armored vehicles,

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90 Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), Force Application Appendix 1.

poor road conditions, inexperienced drivers, high speed, poor visibility, chaotic civilian drivers and a high threat environment."[91] Equipping vehicles with the means to avoid and survive potential crashes is critical.

- Crash survival is measured by percent rollover, which is the percent of its own GVW that a vehicle's roof can support. The goal is to "provide a crashworthy vehicle structure capable of maintaining structural integrity in a rollover" by quantifying the crush resilience of the roof structure.[92] "Rollover protection is required in both training and operational settings, [as] vehicle accidents / mishaps, caused by non-hostile or hostile action, significantly contribute to loss of combat power."[93] Additionally, "IEDs and other threat attacks are causing secondary rollovers after detonation."[94] The SDVF for crash survival shows constant returns to scale. It may seem that vehicles unable to support their own weight, or have a percent rollover of less than 100% should not give constant returns to scale; this is accounted for in the range that this function spans over. The minimum value of 0 is awarded to a vehicle which can support 100% GVW. The data for this measure shows that all vehicles are capable of scoring a 10 in this objective, with no variation, justifying its exclusion from the final model.

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91 Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 24.

92 Ibid, 24.

93 Ibid, 24.

94 Ibid, 24.

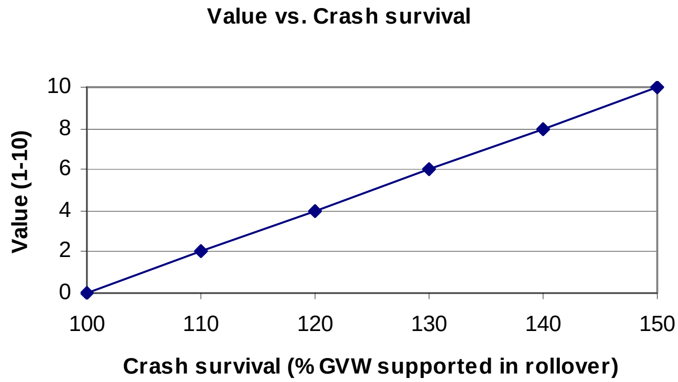

Figure 26. Value vs. Crash survival

- Crash avoidance is measured by the % go (100% minus % no go) on the NATO Reference Mobility Model, for dry normal conditions in Al Mafrag, Jordan. The NRMM makes predictions "using terrain characteristics (e.g., soil strength, vegetation, slope, roughness), vehicle attributes (e.g., tractive effort curve, weight, aerodynamic properties, dimensions), and scenario parameters (e.g., dry, wet, snow, sand)."[95] For example, "traction, ride quality, and visibility" may limit vehicle speed.[96] This location and conditions were chosen to represent the current operational demands on the TWV fleet. Vehicles are judged based on "performance speeds, soft-soil mobility, and trafficability."[97] This scale represents the ability of a vehicle to maneuver, which is a proxy for safety in that a more maneuverable vehicle is more likely to avoid accidents. The SDVF for crash avoidance shows constant returns to scale, as each successive increase in safety is weighted equally.

95 U.S. Army Modeling and Simulation Resource Repository (MSSR). "NATO Reference Mobility Model."; available from http://www.msrr.army.mil/index.cfm?RID=MNS_A_1000379; INTERNET.

96 Ibid.

97 Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 21.

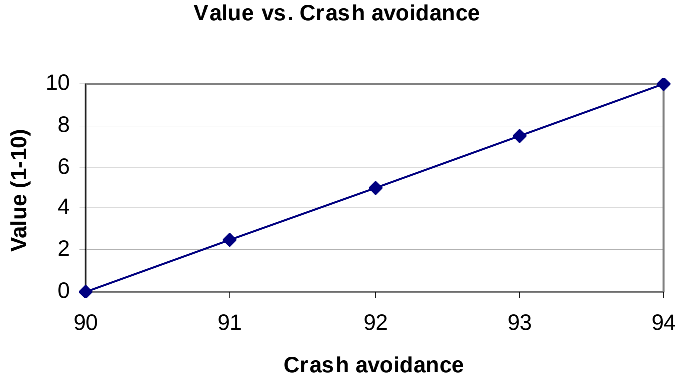

Figure 27. Value vs. Crash avoidance

The payload of a vehicle measures its carrying ability, in passengers, weight, volume, and towing. Payload might be better applied under a separate main objective, perhaps called "Utility". However, in this model it is located under the survivability objective because of sponsor preference. Updating this in the VM is one possibility for further research.

"Current operations highlight the need for increased payload in the light tactical fleet. Maneuver units need this payload in order to carry and employ the weapons and combat enablers required on the modern battlefield."[98] "A critical need exists for a high mobility, multi-capable LTWV capable of transporting greater payloads and for providing… protected troop transport."[99] To this end, it is beneficial to have more of each of the above abilities; however, there is often a tradeoff between payload and other attributes. "Although protection is the highest priority, it can not take away from the payload required" of the vehicle.[100] Payload encompasses two sub-objectives, capacity and towing. Capacity refers to a vehicle's internal carrying ability, including maximum weight, cargo area, and number of seats, while towing refers to a vehicle's external carrying ability and includes maximum towing weight.

98 Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), Force Application Appendix 1.

99 Ibid, 25.

100 Ibid, Force Application Appendix 1.

- Maximum weight is defined to include "occupants and their personal equipment with individual weapon, sustainment items, [and] mission essential equipment."[101] These elements will factor into the next two attributes, cargo area and number of seats; however each attribute limits the capability differently and thus need to be accounted for. The SDVF for maximum weight has decreasing returns to scale, justified by the fact that space is more commonly the limiting factor than weight; decreasing the marginal value of higher successive pounds.

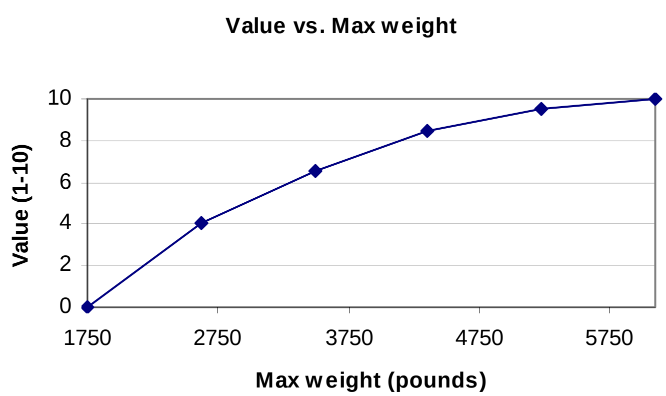

Figure 28. Value vs. Maximum weight

- Cargo area refers to the space available for cargo, exclusive of passengers. Inherently, there is thus a tradeoff between cargo area and number of seats, as well as cargo area and any additional equipment a vehicle may carry. The SDVF for cargo area has increasing returns to scale, reflecting its increasing importance as it often is limiting factor in carrying capacity.

[101] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 25.

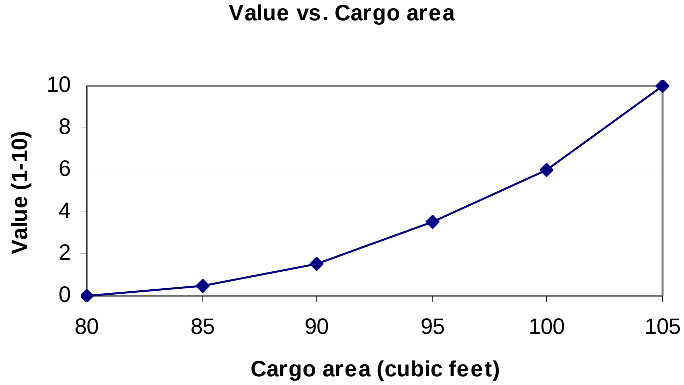

Figure 29. Value vs. Cargo area

- The number of seats available in the vehicle includes the seats allotted for the driver, gunner, operators (e.g. medics in an ambulance), passengers (e.g. squad transport) and litter patients. The attribute could alternatively measure whether a vehicle had enough seats for its mission role, but that would not reflect the seats as a space allotment. The SDVF is linear to show the equal importance given to each seat.

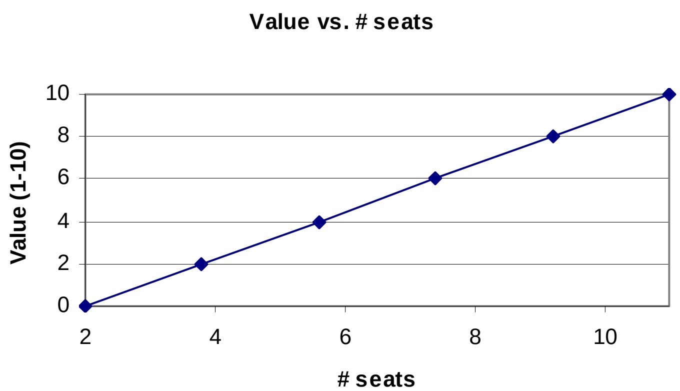

Figure 30. Value vs. Number of seats

Towing is an important capability for a vehicle, allowing for additional material to be carried, external of the space constraints of the vehicle, and increasing the effective payload capability. Towed material can include howitzers, trailers, or, with a standard Army 5-ton wrecker tow bar, a like vehicle.[102] Towing capacity can be measured either by weight, or, if it is a like vehicle being towed, distance. This model focuses on towing supplies, and therefore measures ability by weight.

- Towing capacity includes payload of any towed material, as well as the tongue and pintle, and is measured in pounds. Its SDVF is linear, as each additional pound gives the same amount of value and is not subject to other limitations such as space.

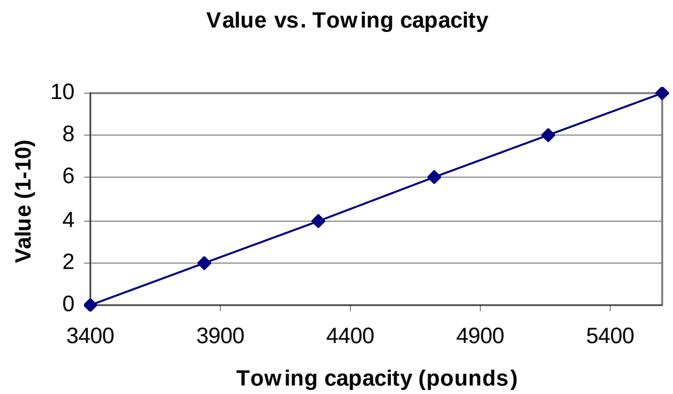

Figure 31. Value vs. Towing capacity

The sustainability of a vehicle contributes towards survivability by ensuring that vehicles are reliable, affordable, and low-maintenance. Vehicles have become a crucial element to today's operations, and achieving the three aspects of sustainability assures that the fleet is not limited by accessibility to operational vehicles.

- "Reliability is the probability that [a vehicle] will perform its intended mission functions under stated conditions for a specified period of time or distance."[103] It is measured in Mean Miles Between Operational Mission Failure (MMBOMF), defined as "a critical failure event rendering a system incapable of continuing its mission, deadlining the system, and

[102] U.S. Army Training And Doctrine Command Tactical Wheeled Vehicle Modernization. Operational Requirements Document (ORD) for the High Mobility Multipurpose Wheeled Vehicle (HMMWV). (Fort Eustis, VA: GPO, 2004), 27

[103] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 26.

requiring immediate (maintenance) attention to return the system to an operational condition."[104] Currently, prolonged operations need to operate at extended ranges, and the changing global environment makes it critical for vehicles to have a high level of reliability.[105] The SDVF for reliability shows increasing returns to scale, with the increased value resulting from the longer missions a vehicle is eligible for given a higher reliability rating.

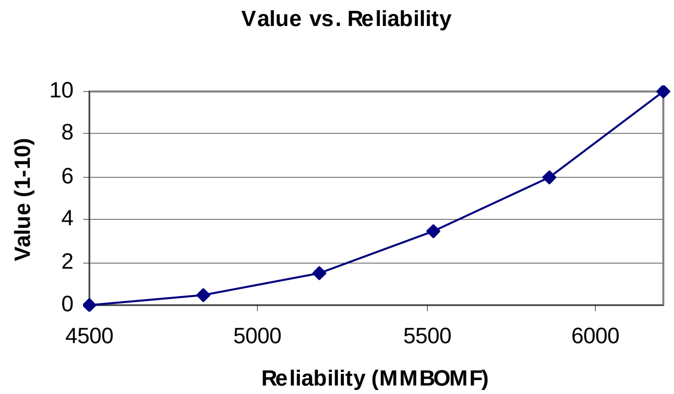

Figure 32. Value vs. Reliability

- Total ownership measures the cost of a vehicle over its lifetime, in FY08$, including procurement and Operations & Support (O&S) costs. Procurement costs refer to all "cost elements such as nonrecurring production, recurring production, data, training, system engineering/program management, etc," and do not include RDTE costs.[106] O&S costs refer to all costs accrued over a vehicle's assumed 20 year useful life, and "comprise a major portion of the overall life cycle cost and the cost of maintaining and supporting the current TWV fleet."[107] It therefore is important to minimize the "cost of maintaining and

[104] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 26.

[105] Ibid, 26.

[106] Ibid, 62-64.

[107] Ibid, 26.

supporting the family of vehicles…to free up resources for other critical war fighting requirements."[108] Total ownership has decreasing returns to scale, focusing on cutting the cost of less expensive and more common vehicles.

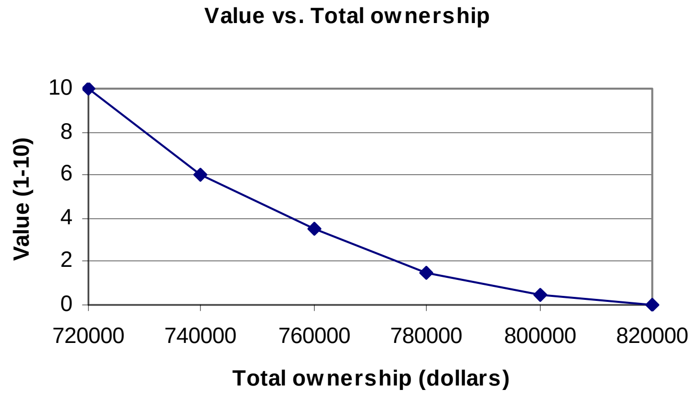

Figure 33. Value vs. Total ownership

The amount of maintenance a vehicle requires affects the lifetime cost and availability of a vehicle. Lifetime cost is accounted for above; this attribute focuses on operational availability. Operational availability affects a vehicle's ability to "maximize available combat power, minimize maintenance force structure, and minimize exposure and dispersion requirements for crews and maintenance personnel."[109]

- Operational availability is the percent of time a vehicle is operational, defined as "up time / total time."[110] Its increasing returns to scale reflect the increased gain as vehicles require less cost and effort to maintain.

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[108] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 25-26.

[109] U.S. Army Training And Doctrine Command Tactical Wheeled Vehicle Modernization. Operational Requirements Document (ORD) for the High Mobility Multipurpose Wheeled Vehicle (HMMWV). (Fort Eustis, VA: GPO, 2004), 24.

[110] Joint Requirements Oversight Council. Capability Development Document (CDD) for the Joint Light Tactical Vehicle (JLTV). (Washington, D.C.: GPO, 2007), 25.

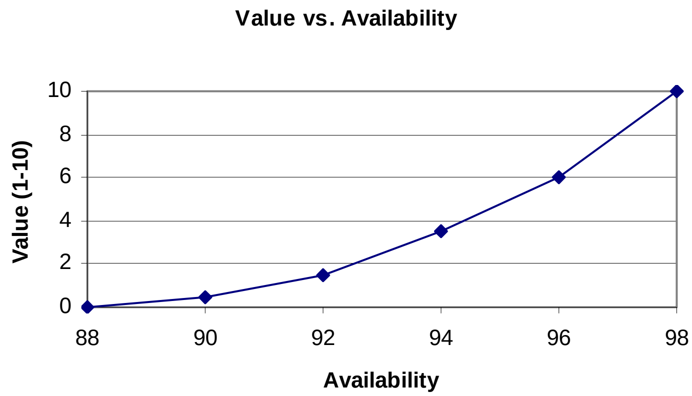

Figure 34. Value vs. Availability

2. Swing Weight Matrix

The last part of the model assessment was the weights. Following the swing weight matrix method, attributes were placed in a matrix according to their variability and essentiality, in terms of controllability. "Variability" here is not used in the statistical sense; instead refers to the amount of value gained from swinging an attribute from its worst to best value. "In terms of controllability" refers to whether an attribute can be planned around. In combat, if a vehicle must rely on an attribute, having not been able to make prior arrangements, this attribute is "important." For example, number of seats would receive a low essentiality matrix weight, as number of seats is known and can be accounted for by only assigning appropriate vehicles to missions that require a lot of seats. Force protection would receive a high essentiality matrix weight, as a vehicle cannot control for an attack; the most it can do is prepare for it. Matrix swing weights were defined from 1 to 100 and assigned to each cell. The resulting matrix can be found below.

	Least	← Controllability →	Most
	Uncontrollable		Controllable through planning measures
Most	Top MPH Fuel efficiency Airlift ability Max payload weight Availability *100*	Max cruising range Max 5% speed Net-readiness Cargo area *75*	# seats Sealift ability *30*
← Variability →	Crash avoidance Reliability Total ownership *75*	Max % grade *45*	Towing capacity *15*
Least	[Force protection] [Acceleration] *30*	[Crash survival] [Turning radius] *15*	[Max fording depth] *1*

Figure 35. Swing weight matrix

This matrix includes all measures from the complete model, including those not in the final model. Measures excluded from the final model are indicated in brackets, and are not included in further calculations. From here, each attribute was assigned a global weight by normalizing over each of the matrix swing weights assigned above, and rolled up to the main objectives. Mobility received a weight of 0.459, net-ready 0.066, and survivability 0.476. The details of the weights can be found in Appendix B.

B. RESULTS

The VM assigns the following values to vehicles, on a scale of 1 to 10. The "Ideal" vehicle achieved a 10 in every attribute, and serves as a source of comparison. Vehicle values can be interpreted as the "proportion of the distance, in a value sense, the alternative is from the (possibly hypothetical) alternative with an overall value of zero to the (also possibly hypothetical) alternative with an overall value of 10."[111]

[111] Craig Kirkwood. Strategic Decision Making. (San Francisco: Duxbury Press, 1982), 74.

The values below reflect, as expected, that the JLTV shows significant improvement over the HMMWV in all objectives. Both the average values and the percent of the ideal vehicle achieved show this. This observation is reassuring, as it proves the LTWV fleet is moving in a direction of improving operational ability. By addressing capability gaps observed with HMMWVs, the JLTV has earned higher values.

	Total	**Mobility**	**Net-ready**	**Survivability**
IDEAL	10.000	4.585	0.655	4.760
HMMWV	4.471	2.377	0.373	1.720
% Ideal	44.71%	51.84%	57.02%	36.14%
JLTV	6.499	3.541	0.655	2.303
% Ideal	64.99%	77.23%	100.00%	48.39%

Table 3. Comparison of HMMWV and JLTV scores, by objective

1. Mission Variant Comparison

Observations can be made by comparing the different mission variants of the LTWV fleet, armament, reconnaissance, and utility vehicles. Both HMMWVs and JLTVs can be divided into these categories. A vehicle’s mission affects its attributes, and its design reflects its combat role. For example, an armament vehicle may have more armor and less cargo area than a utility vehicle. The results are broken down by mission role below, and complete results may be found in the Appendix C.

a. Armament Vehicles

Armament vehicles are primarily light fighting vehicles. The CTV will be a lighter vehicle to increase its mobility. Each armament vehicle and its values are shown in Figure 36, broken up into contributions from the achievement of each objective.

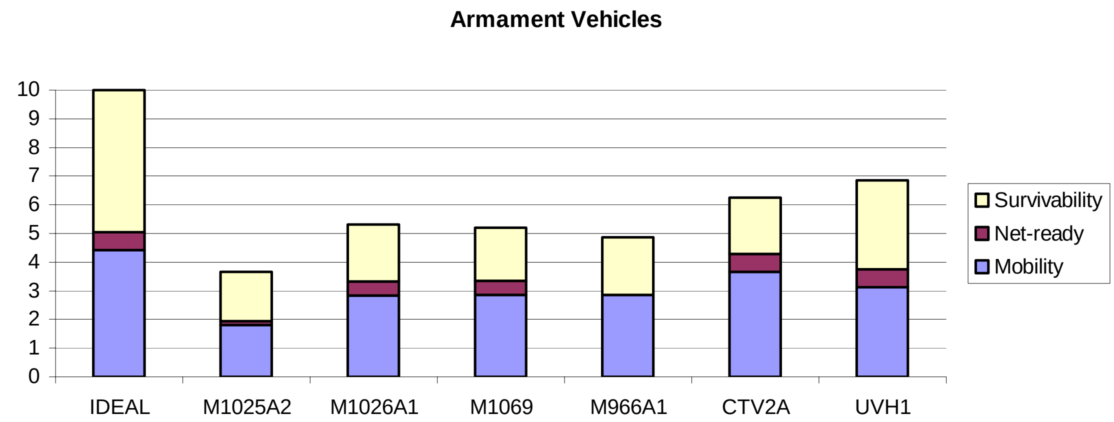

Figure 36. Armament vehicle values broken down by objective

	Total	**Mobility**	**Net-ready**	**Survivability**
IDEAL	10.000	4.412	0.630	4.958
M1025	3.499	2.195	0.000	1.304
M1025A1	3.597	2.277	0.000	1.320
M1025A2	3.655	1.808	0.135	1.712
M1026	5.230	2.760	0.473	1.998
M1026A1	5.312	2.842	0.473	1.998
M1069	5.206	2.867	0.473	1.867
M966	4.774	2.762	0.000	2.012
M966A1	4.869	2.849	0.000	2.020
CTV2A	6.248	3.664	0.630	1.954
CTV3A	6.220	3.664	0.630	1.926
UVH1	6.856	3.127	0.630	3.098
Average	5.043	2.801	0.313	1.928

Table 4. Armament vehicle scores, by objective

b. Reconnaissance Vehicles

Reconnaissance vehicles are designed for battlespace awareness, and emphasize net-readiness. It is important to note that this category of mission variant has a higher proportion of JLTVs to HMMWVs than other categories, perhaps skewing the data in an upward direction with the higher JLTV values.

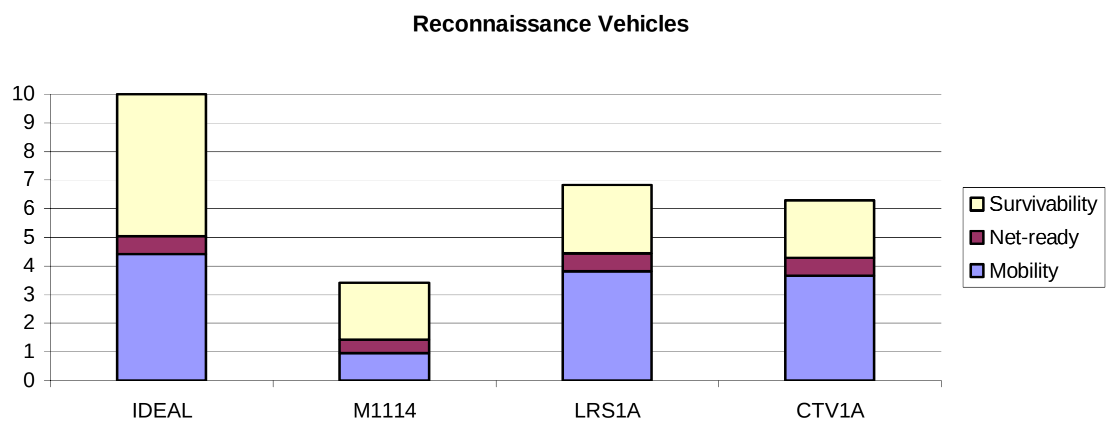

Figure 37. Reconnaissance vehicle values, broken down by objective

	Total	Mobility	Net-ready	Survivability
IDEAL	10.000	4.412	0.630	4.958
M1114	3.410	0.952	0.473	1.985
LRS1A	6.839	3.808	0.630	2.401
LRS2A	6.839	3.808	0.630	2.401
CTV1A	6.304	3.664	0.630	2.010
CTV5A	6.248	3.664	0.630	1.954
Average	5.928	3.179	0.599	2.150

Table 5. Reconnaissance scores, by objective

c. Utility Vehicles

Utility vehicles are intended for moving both people and cargo, and are designed with mobility and high payload capacity in mind. In this model, a payload capacity is included in the survivability objective.

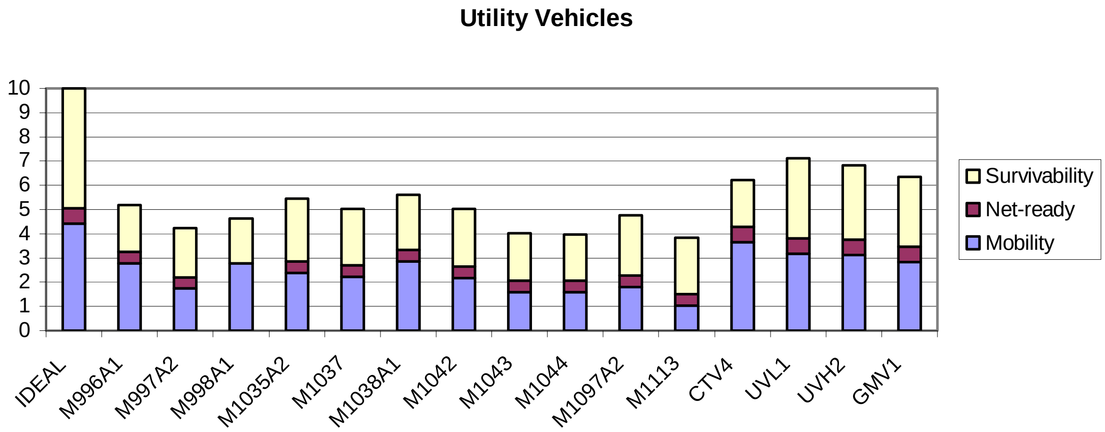

Figure 38. Utility vehicle values, broken down by objective

	Total	Mobility	Net-ready	Survivability
IDEAL	10.000	4.412	0.630	4.958
M996	5.094	2.701	0.473	1.920
M996A1	5.180	2.788	0.473	1.920
M997	4.409	2.159	0.473	1.778
M997A1	4.406	2.156	0.473	1.778
M997A2	4.222	1.736	0.473	2.013
M998	4.619	2.776	0.000	1.843
M998A1	4.622	2.779	0.000	1.843
M1035	5.366	2.784	0.473	2.110
M1035A2	5.443	2.383	0.473	2.587
M1037	5.034	2.221	0.473	2.340
M1038	5.535	2.781	0.473	2.281
M1038A1	5.620	2.867	0.473	2.281
M1042	5.020	2.180	0.473	2.367
M1043	4.022	1.599	0.473	1.950
M1044	3.970	1.597	0.473	1.901
M1097	5.153	2.193	0.473	2.488
M1097A1	5.153	2.193	0.473	2.488
M1097A2	4.760	1.800	0.473	2.488
M1113	3.847	1.030	0.473	2.344
CTV4	6.220	3.664	0.630	1.926
CTV6	6.164	3.664	0.630	1.870
CTV7	6.192	3.664	0.630	1.898
UVL1	7.123	3.182	0.630	3.311
UVL2	7.095	3.182	0.630	3.283
UVL3	7.095	3.182	0.630	3.283
UVL4	7.095	3.182	0.630	3.283
UVH2	6.828	3.127	0.630	3.070
UVH3	6.828	3.127	0.630	3.070
UVH4	6.828	3.127	0.630	3.070
GMV1	6.343	2.830	0.630	2.883
Average	5.510	2.622	0.499	2.389

Table 6. Utility vehicle scores, by objective

d. Comparison

The strengths of each mission variant are compared using the average percent of ideal. It is difficult to compare achievement across objectives and vehicles with the weighting system, as the highest value possible varies. Taking the percentage of ideal normalizes to account for this. Average percent ideal is the amount that the average value of a mission variant objective achieves of its ideal value. It can be thought of as a proportion of ideality that a mission variant achieves, per objective. Looking at Table 7, the LRS receives the highest value the highest overall, by a slight margin. The high ratio of JLTVs to HMMWVs may have an affect, as JLTVs as a whole receive higher values. As expected, within each objective, each variant receives the highest value in its main mission role. The armament vehicles do the best in mobility, reconnaissance vehicles in net-readiness, and the utility vehicles in survivability.

	Total	**Mobility**	**Net-ready**	**Survivability**
IDEAL	100.00%	44.12%	6.30%	49.58%
Armament	53.16%	69.52%	63.10%	37.34%
Reconnaissance	56.96%	64.74%	91.67%	45.63%
Utility Vehicle	54.84%	57.30%	77.68%	49.75%

Table 7. Average percent ideal

The results of this analysis will provide input data for the LTWV LP. Each vehicle contributes a certain amount of each objective to the overall fleet, giving the LTWV LP a way to measure the fleet as a whole.

C. THE LTWV LINEAR PROGRAM FORMULATION

1. Objective Function

The LTWV model is a LP which prescribes recaps, retirements, and new purchases for the U.S. Army LTWV fleet for the next 15 years. Through elastic constraints, the LTWV LP models operational requirements, budget, capacity and age. Elastic constraints can be violated at a penalty set by the decision maker. These requirements ensure that the fleet maintains readiness throughout the modernization process, while staying within budget. The objective function of the LTWV LP is the minimization of the sum of the penalties incurred by violating constraints. This forces the model to search for a feasible modernization strategy. Modernization strategies will be a combination of recaps, new purchases, and retirements for the vehicle variants, spread over the 15 year timeframe.

Elastic constraints offer advantages over traditional fixed constraints. The use of elastic constraints results in a flexible feasible region, enabling the decision maker to identify and manipulate violated constraints. Control over the associated penalties may offer insight to the decision maker on which constraints are most important to meet. This provides the Army with invaluable insight on what the best decision choices will be in the future as the LTWV fleet modernization is underway.

2. Constraints

The Army requires that the LTWV fleet be operationally capable at all times. Operational capability is measured in units of value, and uses the results of the VM. Overall fleet value in mobility, net-readiness, and survivability must be maintained. The LTWV LP models fleet capability value as the sum of individual vehicle capability values. Operational requirement constraints ensure the fleet has a diverse range of capabilities at all times. When vehicles retire or go to the depot for recapping, they are not operationally available, limiting the number that may be out of service at once. Constraints in the LTWV LP capture the maintenance downtime associated with recapping a vehicle.

Capacity constraints govern how many vehicles can undergo recapping at once. There are maximum capacity constraints that control the number of vehicles receiving maintenance at any given time. Each depot has a maximum capacity of vehicles it can process per year, limiting the number of recaps the fleet can have in progress at any given time.

There are also capacities associated with purchasing and retiring vehicles. The amount of new vehicles which can be produced each year from suppliers determines the upper limit on the number of purchases that can be made. The JLTV CDD also offers some insight as to when JLTVs are scheduled to be introduced into the fleet. This timeline as well as procurement numbers offer an upper and lower bound on how many new JLTVs can be procured per year. The upper limit on retiring vehicles expresses a limit on how many of each type of vehicle may be retired each year, to control fleet turnover. Currently, the Army has no official policy on the maximum number of vehicles that can be retired every year. The present solution is to continue fixing vehicles until they are no longer serviceable, and only then retire them. However, with the procurement of every new JLTV, a subsequent retiring of a HMMWV of the same mission will be permitted at one-to-one rate. So although there is no current upper bound on the number of vehicles that can be retired, the actual number should be dictated by the arrival of the JLTV replacements.

The overall fleet age must be between the minimum and maximum desired fleet age, as designated by TACOM. Overall age varies throughout the modernization process, and is an average of the age of all vehicles operational at the time. This does not include vehicles undergoing recaps.

The Army has a finite budget each year to devote to the LTWV modernization. Over each year, the budget must be adhered to, and cover all operations and modernization. More specifically, this refers to all operating costs associated with the current fleet, as well as all of the costs incurred from recaps, retirements, and new purchases during the time period. In the LTWV LP the budget is a hardwired constraint. However, since the budget for this project has yet to be determined past the six year point, if possible, the budget constraints should be modified in order to better reflect changing budget allocations. Also, because the budget is an elastic constraint, decision makers will be able to better judge future budget needs in order to maintain operational requirements while replacing the HMMWVs with JLTVs. For the complete formulation of the LTWV LP see Appendix D.

Once the model is optimized, the output states the fleet composition, per vehicle variant. The sum-product of the fleet inventory and the value assigned to each variant from the VM gives an overall fleet value. The LTWV LP maximizes that overall fleet value at the end of the 15 year point, given the constraints provided. The overall fleet value changes depending on the constraints, thus affording TACOM the ability to shift constraints and see how that affects the fleet composition as well as its value.

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V. ANALYSIS

A. IMPLEMENTATION

The LTWV Optimization Model uses data from a myriad of publications and area experts. Professor Dell developed the LTWV LP and implemented it in GAMS. We ran the VM to obtain the objective coefficients for the LTWV LP, collected, formatted, and quality controlled the data, and analyzed the results of the LTWV LP.

Most of the data sets are modularized and created for LTWV LP to read-in. This allows for easy addition of data if more becomes available; or if the decision maker wishes to manipulate data to observe outcomes. We programmed some parameters directly into the LTWV LP, but they are easily manipulated within the GAMS implementation. The objective function of the LTWV LP comes directly from the results of the VM, as was the data for the constraints pertaining to the three main capabilities, mobility, net-ready, and survivability. The objective function coefficients as well as the capabilities coefficients are written in separate files, from which the LTWV LP reads-in the data.

We enhanced the LTWV LP to better simulate the JLTV replacement of the HMMWV: Each HMMWV and JLTV was classified by the mission that they are designed to perform. Those missions are:

- Reconnaissance
- Light Armament
- Heavy Armament
- Light Utility
- Heavy Utility
- Light Ambulance
- Heavy Ambulance
- Light Shelter

- Heavy Shelter
- Prime Mover
- Command and Control (C2).

In the LTWV LP, we added a caveat such that a newly procured JLTV should replace a HMMWV with a matching mission role. The underlying motivation is to maintain the fleet operational capability. For example, we designed this constraint to prevent Light Ambulance JLTVs replacing Heavy Armament HMMWVs.

We categorize the initial LTWV fleet inventory by variant and age. This allows the program to try to minimize the average age of the fleet as well as indicate which vehicles to retire once they were too old. It also provides a base case computation of the overall fleet value, calculated as the product of the value of any given vehicle variant and the number of vehicles of that type in the current LTWV fleet. The sum of all the variant values yields the overall fleet value.

As is always the case in analytical undertakings, we make assumptions when data for the constraints either did not exist or were otherwise unobtainable. We specify these assumptions below.

1. Assumptions

Our first assumption is putting upper-bounds on the age an individual vehicle or the average age of the fleet before forcing individual vehicles to retire. The Army currently practices the method of only retiring vehicles if they are no longer serviceable, regardless of age. However, with the upcoming integration of the JLTV, HMMWV vehicles that are still serviceable will be retired to save on O&S costs. Initially, we set the maximum age of any given HMMWV or the average fleet age to 25 years. We increased the age to 35 years because when the program ran, HMMWVs were being forced to retire before the JLTVs could replace them.

A facet of the program we did not utilize was modeling the time it took to recap a vehicle. Professor Dell designed the program to accept a decimal value between 0 and 1, representing the fraction of a year a vehicle is available after being recapped. Upon inquiry, we found that the depot facilities are currently overflowing with vehicles needing maintenance. No data has been collected on the average time it takes to recap a HMMWV. Therefore we set that that value to 0, stating that it took exactly 1 year to recap a vehicle.

We make approximations for the cost associated with recapping a vehicle. We searched for the costs associated with recapping each vehicle variant the recap program applies to. We only found data on the average recap costs per recap depot (Red River Army Depot (RRAD), and Letterkenny Army Depot (LEAD). The average recap cost applied to every vehicle undergoing a recap is $50,960. Decision makers can easily incorporate data on the cost to recap individual variants, if it becomes available.

We also assume the values for the overall budget. Ideally the program's overall budget would consist of the sum of the budgets allotted for:

- New HMMWV procurement
- The HMMWV Recapitalization program
- New JLTV procurement
- Operating costs for both HMMWVs and JLTVs.

We would list these budgets per year, extending to Fiscal Year 2022 (FY22) (the 15 year point where we end the model). However, much of this data is unavailable. Although we found budgets for the HMMWV procurement and the Recapitalization program for FY07, there was no published information on how that budget is going to shift in the next 15 years. Also, the JLTV is still in its concept design phase so only estimations exist for the JLTV procurement budget and no information at all exists on their projected operating costs. Therefore, we used one number for all 15 years of budgets. This number, 15.8 Billion FY08$, is the projected budget for the JLTV program as stated in the JLTV CDD. As the years pass and budgets are published for these programs, decision makers can easily update the budgets.

The last critical assumption we make concerns the lower and upper bounds for the procurement numbers for both the HMMWV and the JLTV. In other words, the bounds on the number of vehicles the Army is allowed to purchase. There are separate boundary values for each variant over the 15 year modeling time frame. Although these values are assumptions, we base them upon estimations and averages computed from actual data.

First, we will discuss the lower and upper bounds for the HMMWV procurement. The lower bound for each of the HMMWV vehicles for each year is 0, stating that the Army is not required to procure any HMMWVs in any given year. HMMWV procurement estimates vary significantly among the experts, some as high as 4,000 units annually. In some cases, these estimates are greater than the upper-bounds we use, and would therefore make the LTWV LP infeasible. Consequently, we selected a lower bound procurement number of 0. Decision makers can easily increase the lower bound, if they wish.

We were only able to gather data for the upper-bound of the planned number of HMMWV procurements through the year 2013. The data came listed as an aggregated form per year, not broken down by HMMWV variant. We converted this data into a usable form by distributing total procurement numbers evenly over every HMMWV variant still in production. From the year 2013 on, we assume that the HMMWV will no longer be in production, as the Army plans on procuring the first batch of JLTVs in the year 2012.

The JLTV CDD contains procurement timelines and planned quantities for the JLTV. The Army plans on implementing Increment I, the first procurement of JLTVs, in 2012, with a production of 5,500 vehicles. In 2016, the second phase of production, Increment II, will begin. This includes 3,986 LRS vehicles, 15,794 CTV vehicles and 13,494 vehicles, totaling to 33,274 JLTV vehicles.

We divided Increment I procurement data over a four year period – from 2012-2015 – and evenly over every JLTV variant. We divided Increment II data over a three year period – from 2016-2018 – and over each JLTV variant. The distribution simulates procurements over several years to take into account maximum plant production capabilities as well as budget capabilities.

The JLTV procurement numbers, ranging from 2012 to 2018, serve both as lower and upper bounds in the LTWV LP. We implement this equality to force the shift in the LTWV fleet from HMMWVs to JLTVs. Before 2012, we set the upper bound for the

JLTV to 0 because JLTVs will not yet be eligible for production. After 2018, the lower bound per year on the JLTV is 0, with no upper bound. We did this to simulate the JLTVs heavy production and to meet the goal of completely retiring the HMMWV.

Every assumption we make is either based upon real data or notional data drafted from area experts and official publications. The LTWV LP presents the data in such a way that notional data is easily updatable with more accurate data. Insights from the model can still be drawn even though some notional data drives it.

B. ANALYSIS

The Linear Program's beta test included six runs. Each run, we varied the inputs slightly, and analyzed the results. We performed a simple sensitivity analysis on the overall allotted budget, the allowed maximum HMMWV age, and delays in the JLTV procurement schedule. We considered our base case to be a 15.8 Billion FY08$ budget, a maximum HMMWV age of 35 years, and an on time JLTV procurement.

1. Fleet Value Comparison

Each year, the LTWV fleet will have a new fleet value based upon the value the VM assigns to each vehicle variant and the fleet's current inventory. Implementing *recap, buy new* and *retirement* options on each vehicle, the fleet's composition changes year to year. We ran an analysis to investigate the effect that the modernization process has on the overall fleet value. It is important to note that the LTWV LP aims to maximize the overall fleet value. The fleet value is computed in Year 1, and set as a lower bound on subsequent years. This ensures the fleet maintains at least its current value and operational readiness. A higher optimal solution might exist if we allow the fleet values to dip below the value of the first year. However, the repercussions of not having ready vehicles to use adversely impacts combat readiness. The current fleet value for year one of the fifteen year program is 328,495. Below are the fleet values over the 15 year analyzing period for three separate budgets.

The first graph is for the 15.8 Billion FY08$ per year budget. This budget is the base case.

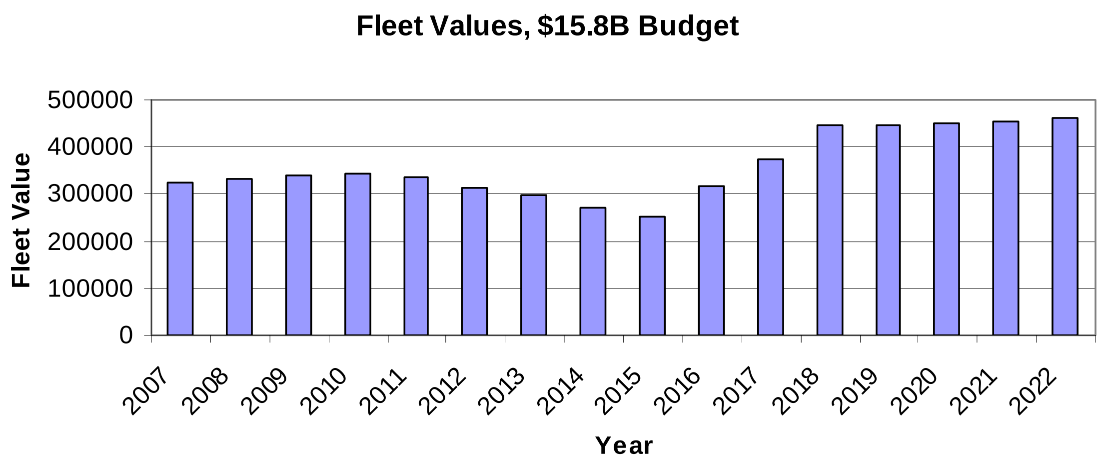

Figure 39. Fleet Values for a 15.8 Billion FY08$ Budget

Note the steep increase in the fleet value in 2016. The implementation of the Increment II, the start of a procurement of approximately 33,000 JLTVs, accounts for this increase. This also shows that the JLTV, in theory, will be a much more capable vehicle than the HMMWV. The highest fleet value is reached in 2022 with a value of 460,730. The average fleet value of the 15 year period is 364,116.

The second graph is the same analyzing except the budget was restricted to 10.8 Billion FY08$ per year.

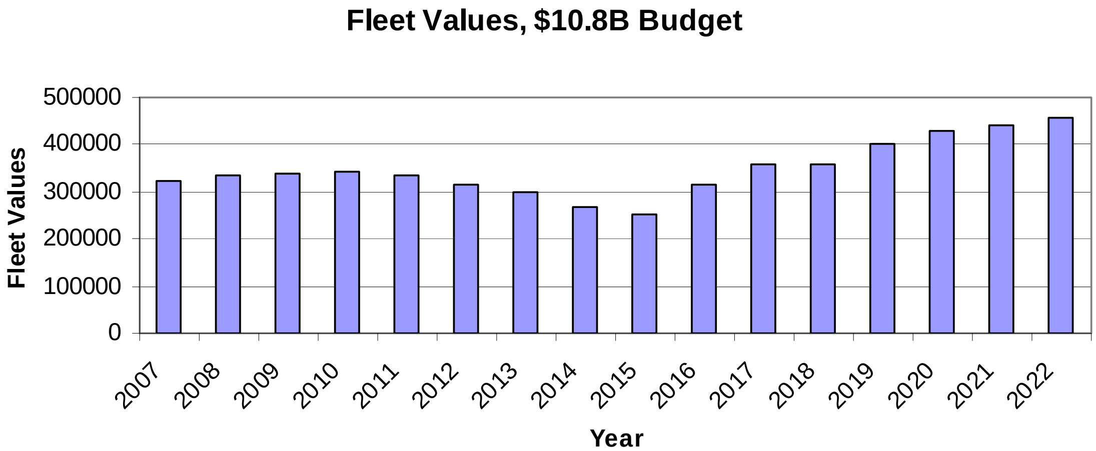

Figure 40. Fleet Values for a 10.8 Billion FY08$ Budget

Notice that in comparison to the $15.8 Billion budget, these fleet values are significantly lower. The maximum fleet value for this iteration is only 455,677 and the average is 354,183. This average is 9,933 less than the average fleet value given a $15.8 Billion budget. These dips in the fleet value indicate to decision makers that the budget should not be lowered if they want to maximize overall fleet effectiveness.

The third graph observes the fleet value with an increased budget of 20.8 FY08$ Billion per year.

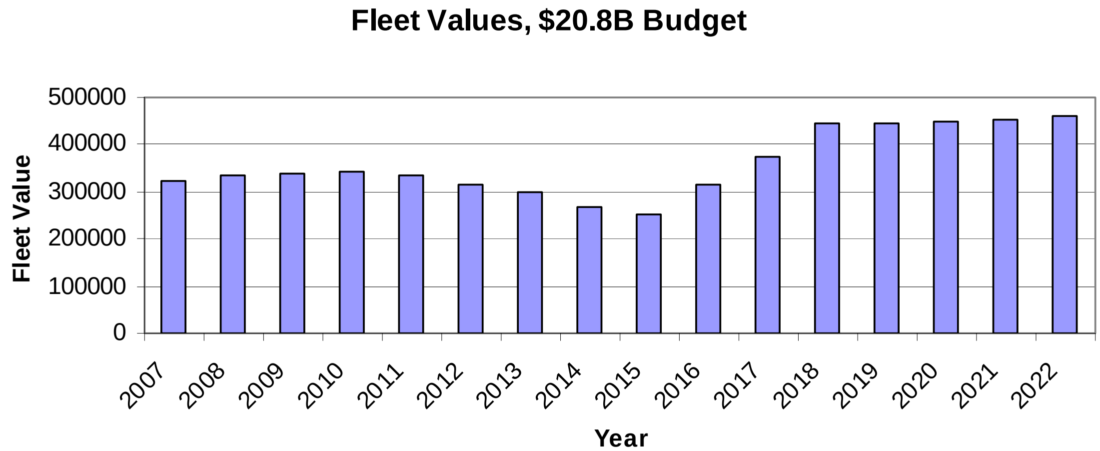

Figure 41. Fleet Values for a 20.8 Billion FY08$ Budget

The fleet values do not increase as the budget increases from $15.8 Billion to $20.8 Billion. At $20.8 Billion, the maximum fleet value stays steady at 460,730 with an average fleet value of 364,116. The rapid drop off of returns to scale as the budget increases indicates that the limiting factor bounding fleet value is not its available funds. Therefore, there would be no benefit to increasing the budget. The factor limiting the fleet value must be another constraint. Investigating within our model, we found that the procurement rate is bounding fleet value growth. That is, we specify exactly how many JLTVs to procure each year. A more interesting result from increasing the budget might exist if a decision maker changed that assumption.

2. Delayed Procurement Analysis

A second analysis ran was simulating a delay in the procurement timeline. This analysis illustrates the possible drawbacks if the integration of the JLTV is delayed. The base case of a 35 year maximum allowable age of any vehicle and a $15.8 Billion budget was compared to an identical case save year that the JLTV integration began. Instead of the planned 5,500 unit procurement beginning in 2012 and the 33,000 unit procurement beginning in 2016, the 5,500 unit procurement was pushed back to begin in 2014 and the 33,000 unit procurement to begin in 2018. Figure 42 is a graphical comparison of the base case vs. the delayed production.

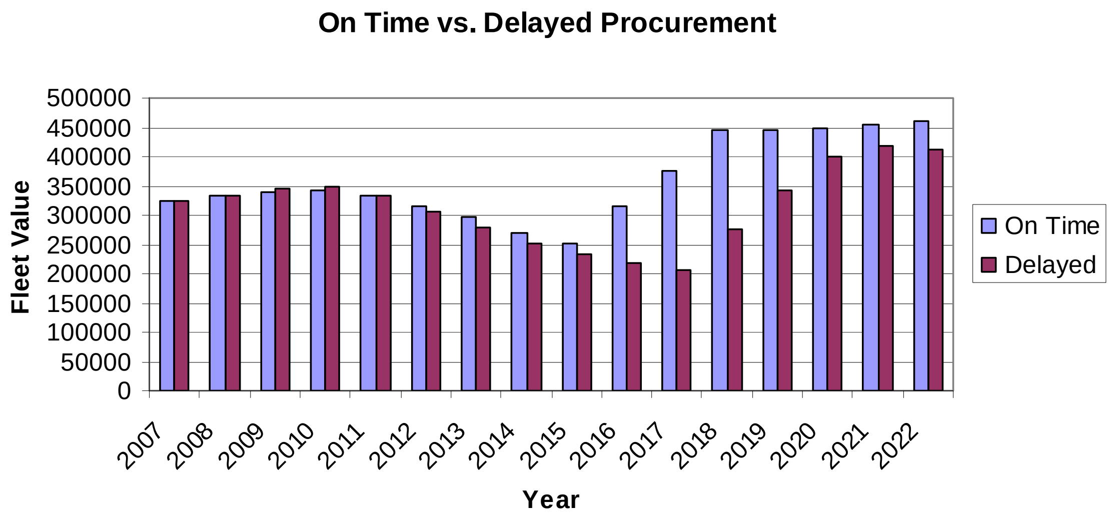

Figure 42. On time procurement vs. delayed procurement

It becomes apparent that a delay in the procurement of the JLTV vehicles causes the fleet value to suffer considerably. In fact, the fleet value for the delayed procurement dips below the original fleet value of 328,495 in a total of eight of the 15 years that the program is operated. This number represents the overall operational capability of the LTWV fleet, with the goal of the JLTV program to raise that operational capability, not lower it. It is suspected that the cause of this sharp decrease in the fleet value is due to a sudden forced retirement of many HMMWV vehicles. The HMMWV fleet ages too much before the JLTV can be implemented to replace them. Failure to implement the JLTV program on time without creating viable alternatives to further extend the lifespan of the HMMWV fleet could lead to disastrous consequences for the LTWV fleet and its operational capabilities.

3. Recommendations

From the cursory analysis that we ran using the LTWV LP we derive several insights concerning future modernization strategies. According to our model, the proposed budget of $15.8 Billion to cover the cost of procuring new JLTVs is acceptable. After testing the fleet values with a $5 Billion budget decrease, results showed a dramatic drop in the overall fleet values. Alternatively, an increase of $5 Billion in the budget showed no increase in the overall fleet values. The inability of the fleet to produce a higher average fleet value with additional funds indicates that the budget is not the limiting factor. In fact, it may be possible to further lower the budget without affecting fleet value. To increase the fleet value beyond that achieved with a $15.8 Billion budget, it is necessary to increase the upper bounds on procurement numbers.

The analysis that was ran simulating a delay in the JLTV procurement also lead to interesting results. With the delay, the overall fleet values dropped dramatically, sometimes below the initial fleet value. That is to say that the operational effectiveness of the entire LTWV fleet will be diminished while waiting for the JLTVs to arrive. Too many HMMWVs reached their maximum age and were forced to retire without any JLTVs to replace them.

In conclusion, it would be wise for the Army to draft contingency plans for extending the life-span of the HMMWV fleet. These plans could include preparing to create more recap depots, increasing the capacity of the Recapitalization program. The Army could also expand the Recapitalization program to apply to more vehicle variants. The Army could continue to refuse to retire vehicles depending on their age, but rather solely based upon their operability until the JLTV can be released. However, as described earlier, the HMMWV fleet is in dire need of relief. The HMMWV is a 1980s technology which is being expected to serve in a war fighting role in the 21st century. Further delays in the JLTV program could lead to disastrous effects on the battle field and unnecessary loss of lives for American soldiers. We gain a powerful insight on the importance of introducing the JLTV as scheduled and on time.

There are many more analyses that can be run using the LTWV optimization model. For instance, the model is capable of mapping the changes in the fleet composition every year. It output would document how many and which variant LTWVs were recapped, retired and purchased. We did not investigate these changes because based upon our assumptions we already knew exactly how many JLTVs the Army procured every year. Investigating when the LTWV LP forces HMMWVs to retire is a prime example of how versatile this decision tool is.

This model does not provide an infallible prediction on what the exact composition of the LTWV fleet will be in 15 years. It does, however, provide invaluable insight on possible pitfalls that lie in modernization strategies. The model is also very capable of expanding to become more accurate as notional data is replaced with concrete data. Overall, the LTWV optimization model is already a capable decision tool for decision makers at TACOM, and has yet to reach its full potential.

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VI. CONCLUSIONS AND FUTURE RESEARCH

A. CONCLUSIONS

The Light Tactical Wheeled Vehicle fleet faces a period of transition. The HMMWV is aging and deteriorating, approaching the point of unsuitability for operational use. To meet increased operational demands, the Army will develop and introduce a new vehicle, the JLTV. The JLTV will eventually replace the HMMWV as the Army's new LTWV, but its integration presents challenges. The JLTV is still in the design phase so the vehicles will not be available for several more years. Intelligent planning is required to manage the extension of the lifespan of the HMMWV fleet until the JLTV can be integrated.

The Army has developed programs to extend the lifecycle of the HMMWV fleet while the JLTV is being designed and implemented. The current U.S. Army HMMWV lifecycle extension program is the Recapitalization Program. "Recapping" upgrades a HMMWV to a new, more robust variant. Currently, the Recap Program only applies to older HMMWV variants that perform combat missions. In to order optimally manage the Recap Program and the integration of the JLTV, decision makers must consider all aspects of the modernization process, from operational requirements to budgetary constraints.

The U.S. Tank-Automotive and Armament Command (TACOM) requested a decision tool to aid in optimizing the sustainment of the HMMWV and the integration of the JLTV. Our thesis serves as a conceptual framework for that decision tool. The decision tool itself takes form as an LP which maximizes the value of the LTWV fleet per year for the next 15 years while meeting operational and budget constraints. "Value" is measured by a MODA, the VM, in which each vehicle is measured by its achievement of competing operational objectives. The operational objectives the VM addresses are *mobility, net-readiness, and survivability*. The optimum fleet value is constrained every year by budget constraints, operational requirements, and replacement options.

Our analysis demonstrates the power the decision tool possesses. Our analysis uses a combination of real and notional data, and is not designed to make specific recommendations for future decisions, but rather to demonstrate the tool's versatility and evolutionary capabilities. Any notional data we use is logical, and follows subject matter expert recommendations. To this end, analytic results are generally, but not specifically, valid. Care should be taken in using the results; we recommend further analysis before any of these recommendations are implemented as policy.

Regardless of the accuracy of the data, we were still able to make interesting observations using the model. Perhaps the most interesting observation we noted was when we imposed a delay in the implementation of the JLTV. With just a two year delay in the JLTV procurement timeline our model showed potentially disastrous declines in the overall value of the LTWV fleet. Should the JLTV be delayed, contingency plans such as an expanded Recap Program would to minimize the decreases in the fleet values. We based this observation upon notional data, however it is still gives real insight to potential repercussions.

B. FUTURE RESEARCH

There are many ways to further develop this work. While the decision tool is conceptually complete and operational, the model requires concrete data to strengthen it. There are several places where more detailed data would make the model considerably more accurate.

The decision tool can extend to include more vehicles, should other options become available. Should policy makers place a different value on objectives, the model can evolve to reflect this by re-assessing the SDVFs and weights in the VM. The LTWV LP can evolve to incorporate any additional constraints that arise in the future.

The uncertainty of budgets, operational tempo, and emerging technologies create a complex environment for the decision makers at TACOM. This tool will facilitate planning and exploring potential courses of action for the coming years. This conceptual framework and analysis will aid decision makers in better planning the future of the LTWV fleet.

APPENDIX A: JLTV SUB-CONFIGURATIONS

Functional Concept	Mission	Role	Mission Role Variant (MRV)	Configurations	Sub-Configurations: Description and Assets Requirement	Payload Category: Capacity
Battlespace Awareness (BA)	ISR	Move Recon / Surveillance Team	Long Range Surveillance (LRS)	Long Range Surveillance	Long Range Surveillance (LRS) (4 seats) Increment II Assets: TBD	**Payload Category A** **Threshold**: on vehicle 4500 lbs w/o B kit 3500 lbs with B Kit On Trailer: 3400 lbs **Objective**: on vehicle 4000 lbs w /B kit On Trailer: 4200 lbs
					General Purpose C2 Variant (4+Gunner) Increment II Assets: TBD	
Force Application (FA)	Maneuver		Combat Tactical Vehicle (CTV)	Close Combat Weapons Carrier	Reconnaissance (1+4) (Armored Scout: Knight/FIST/CBRNE) Increment I Assets: TBD Increment II Assets: TBD	**Payload Category B** **Threshold**: Marine Corps CTV= 4000lbs On Trailer: 4200 lbs Army CTV=4500 lbs On Trailer: 4200 lbs **Objective**: Marine Corps CTV= 4326lbs On Trailer: 5600 lbs Army CTV=5000 lbs On Trailer: 4200 lbs
		Move Weapons w/Infantry & Move Security Forces			Heavy Guns Carrier (4+Gunner) (MP, Mounted Patrol; Convoy Escort) Increment I Assets: TBD Increment II Assets: TBD	
					Anti-Tank Missile Carrier (4 seats) (TOW ITAS) Increment I Assets: TBD Increment II Assets: TBD	
		Move Infantry - Fire Team		Infantry Carrier - Light	Infantry Carrier - Fire Team – USA CTV (2+5) (also 120mm Mortar prime mover) Increment I Assets: TBD Increment II Assets: TBD	
					Infantry Carrier - Fire Team – USMC CTV (1+5) (also 120mm Mortar prime mover) Increment I Assets: TBD	

Functional Concept	Mission	Role	Mission Role Variant (MRV)	Configurations	Sub-Configurations: Description and Assets Requirement	Payload Category: Capacity
					Increment II Assets: TBD	
		Move Tactical C2			C2OTM (4 seat) (Tactical Maneuver Brigade C2) Increment I Assets: TBD Increment II Assets: TBD	
		Carry light MEDEVAC support			Ambulance - B (3 crew + 2 litters or 4 ambulatory patients) Increment I Assets: TBD Increment II Assets: TBD	
		Carry light cargo (non-shelter)			Utility – B (2 seat) Increment I Assets: TBD Increment II Assets: TBD	
Focused Logistics (FL)	Maneuver Sustainment - Light	Carry medium MEDEVAC support	Utility Vehicle – Light (UVL)	Cargo Carrier - Light	Ambulance – C (3 Crew + 4 Litters or 6 ambulatory patients) Increment II Assets: TBD	**Payload Category C**: **Threshold**: 5100 lbs On Trailer = 5600lbs **Objective**: 5500 lbs On Trailer = 10,000 lbs
		Carry light cargo (non-shelter)			Utility – C (2 seat) Increment II Assets: TBD	
		Carry light / standard shelters			Shelter Carrier – C (2 Seat) (Standard shelters - Maintenance, Communications) Increment II Assets: TBD	
	Maneuver Support	Move Combat Support Elements		Prime Mover - Light	Prime Mover – C (2 Seat) (105mm Howitzer, Q-36 Radar) Increment II Assets: TBD	
Focused Logistics (FL)	Maneuver Support	Transport Light Maneuver Forces	Utility Vehicle – Heavy (UVH)	Troop Transport Heavy	Protected Troop Transport (2+9) Increment II Assets: TBD	**Payload Category D**: **Threshold**: 6100 lbs On Trailer = TBD **Objective**: 6700 lbs On Trailer = TBD
					Convoy Protection Platform (2+gunner fore and aft) Increment II Assets: TBD	
		Carry heavy		Cargo Carrier -	Ambulance/Treatment Vehicle – D: -Heavy Ambulance	

Functional Concept	Mission	Role	Mission Role Variant (MRV)	Configurations	Sub-Configurations: Description and Assets Requirement	Payload Category: Capacity
		MEDEVAC support		Heavy	and Heavy Treatment Vehicle (Ambulance crew of 3 Medical Personnel /Treatment crew of 4 Medical Personnel) Increment II Assets: TBD	
		Carry heavy cargo (non-shelter)			Utility – D (2 seat) Increment II Assets: TBD	
		Carry heavy shelters			Shelter Carrier – D (2 seat) (Heavy Shelters - Data Interchange) Increment II Assets: TBD	
		Move Fire Support		Prime Mover - Heavy	Prime Mover – D (2 seat) (Light Howitzer Ammunition Carrier; LW155) Increment II Assets: TBD	

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APPENDIX B: ATTRIBUTE SWING WEIGHTS

	Variability	Essentiality	Local weight	Global weight
Max cruising range	3	2	75	0.066
Top MPH	3	3	100	0.087
Max 5% speed	3	2	75	0.066
Max % grade	2	2	45	0.039
Fuel eff.	3	3	100	0.087
Air	3	3	100	0.087
Sea	3	1	30	0.026
Alternator size	3	2	75	0.066
Crash avoid	2	3	75	0.066
Max wt	3	3	100	0.087
Cargo area	3	2	75	0.066
# seats	3	1	30	0.026
Towing	2	1	15	0.013
Reliability	2	3	75	0.066
Total Own.	2	3	75	0.066
Availability	3	3	100	0.087

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APPENDIX C: COMPLETE VM RESULTS

	Mobility	Net-ready	Survivability	Total Value
IDEAL	4.585	0.655	4.760	10.000
M1025	2.281	0.000	0.962	3.243
M1025A1	2.367	0.000	0.979	3.346
M1025A2	1.879	0.140	1.387	3.406
M1026	2.868	0.491	1.683	5.043
M1026A1	2.954	0.491	1.683	5.128
M1035	2.893	0.491	1.800	5.184
M1035A2	2.477	0.491	2.295	5.264
M1037	2.309	0.491	2.039	4.839
M1038	2.890	0.491	1.978	5.359
M1038A1	2.979	0.491	1.978	5.448
M1042	2.265	0.491	2.068	4.824
M1043	1.662	0.491	1.633	3.787
M1044	1.660	0.491	1.582	3.733
M1069	2.979	0.491	1.548	5.018
M1097	2.279	0.491	2.192	4.962
M1097A1	2.279	0.491	2.192	4.963
M1097A2	1.871	0.491	2.192	4.554
M1113	1.070	0.491	2.043	3.605
M1114	0.990	0.491	1.670	3.151
M966	2.871	0.000	1.698	4.568
M966A1	2.961	0.000	1.707	4.667
M996	2.807	0.491	1.603	4.901
M996A1	2.897	0.491	1.603	4.991
M997	2.244	0.491	1.454	4.190
M997A1	2.241	0.491	1.454	4.186
M997A2	1.804	0.491	1.699	3.995
M998	2.885	0.000	1.522	4.407
M998A1	2.889	0.000	1.522	4.411
CTV1A	3.808	0.655	1.696	6.159
CTV2A	3.808	0.655	1.638	6.101
CTV3A	3.808	0.655	1.609	6.072
CTV4A	3.808	0.655	1.609	6.072
CTV5A	3.808	0.655	1.638	6.101
CTV6A	3.808	0.655	1.551	6.014
CTV7A	3.808	0.655	1.580	6.043
LRS1A	3.957	0.655	2.103	6.715
LRS2A	3.957	0.655	2.103	6.715
UVL1	3.307	0.655	3.048	7.010
UVL2	3.307	0.655	3.019	6.981
UVL3	3.307	0.655	3.019	6.981
UVL4	3.307	0.655	3.019	6.981
UVH1	3.250	0.655	2.827	6.732
UVH2	3.250	0.655	2.798	6.703
UVH3	3.250	0.655	2.798	6.703
UVH4	3.250	0.655	2.798	6.703
GMV1	2.941	0.655	2.603	6.199

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APPENDIX D: LTWV LP FORMULATION

SUBSCRIPTS 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*

FORMULATION

Objective function:

Minimize $\sum$*Penalties incurred for violating elastic constraints*

Subject to the following constraints:

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

Balances the inventory over time, for all non-new vehicles

$$I_{atv} = \sum_{a',r,v'\in AF_v} E_{a'r,t-1,v'v} + P_{t,v} \qquad \forall\ a=0, t>1, v$$

Balances the inventory over time, for all new and recapped vehicles

$$I_{atv} = ii_{av} \qquad \forall\ a, t = 0, v$$

Establishes the number of vehicles of each type and age at the start of year 0

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

Ensures number of vehicles undergoing recap is less than the maximum recap capacity for each time period and vehicle type

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

Ensures number of vehicles being retired is less than the maximum retirement capacity for each time period and vehicle type

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

Ensures number of vehicles purchased falls between the minimum requirement and maximum capacity for each time period and vehicle type

$$\sum_{a} \underline{fage}_{tv} \left(I_{atv} + \sum_{a,r,v'\in AF_v} aval_{artv'v} E_{artv'v} \right) \dot{\le} \sum_{a} a\, I_{atv} \qquad \forall\ t, v$$

Forces overall fleet inventory age to be older than the minimum for each time period and vehicle type

$$\sum_{a} a\, I_{atv} \dot{\le} \sum_{a} \overline{fage}_{tv} \left(I_{atv} + \sum_{a,r,v'\in AF_v} aval_{artv'v} E_{artv'v} \right) \qquad \forall\ t, v$$

Forces overall fleet inventory age to be younger than the maximum for each time period and vehicle type

$$\sum_{a,v} map_{actv} I_{atv} + \sum_{a,r,v,v'\in AF_v} map_{0ctv} aval_{artv'v} E_{artv'v} \dot{\ge} dem_{ct} \qquad \forall\ c, t$$

Ensures demand for each capability is met by the current operational fleet for each time period

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

Ensures the modernization strategy does not exceed the budget for all time periods

$$I_{atv} \geq 0 \ \ \forall atv;\ \ E_{artvv'} \geq 0\ \forall artvv';\ \ P_{tv} \geq 0\ \forall tv;\ \ R_{atv} \geq 0\ \forall atv;$$

Ensures non-negativity

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.

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