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TACTICAL VEHICLES IN THE USMC GCTVS: A MULTI-CRITERIA EFFECTIVENESS STUDY

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THESIS

**TACTICAL VEHICLES IN THE USMC GCTVS:
A MULTI-CRITERIA EFFECTIVENESS STUDY**

by

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This research evaluated the effectiveness of the MRAP-All-Terrain Vehicle (M-ATV), joint lightweight tactical vehicle, and the High Mobility Multi-purpose Wheeled Vehicle (HMMWV) using multi-criteria effectiveness analysis within the context of the USMC Marine operating concept and National Security and Defense strategies. The Marine Corps is resource constrained and must carefully allocate resources. Having three vehicles perform the same mission is not efficient, nor a proper use of taxpayer dollars. A model was developed that quantifies how well a vehicle performs given the criteria of mobility, transportability, and protection per the Marine Corps ground tactical vehicle strategy (GCTVS). The model also factored in the identified future adversary and threat environments, applied those performance measures to the projected portfolio mix, and assessed the total efficacy of the GCTVS weighted for the given threat environment. The model predicted a cumulative 10% increase in portfolio efficacy through 2030 by restricting HMMWV use in the Middle East and divesting from the M-ATV no later than fiscal year 2021. If applied to the current GCTVS, this research could reshape the long-term profile of the Marine Corps' tactical wheeled vehicle fleet. The model developed could be applied to other Department of Defense portfolios to provide an objective quantitative measure beyond cost to evaluate and develop portfolio strategies.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAO	approved acquisition objective
AAV	amphibious assault vehicle
ACV	armored combat vehicle
CONUS	contiguous United States
DIME	diplomacy, information, military, economic
DoD	Department of Defense
EMD	engineering and manufacturing development
FMFM	Fleet Marine Force manual
FPI	Force Protection Incorporated
FY	fiscal year
GCC	geographic combatant commander
GCTVS	ground combat tactical vehicle strategy
HMMWV	High Mobility Multi-purpose Wheeled Vehicle
ICODES	integrated computerized deployment system
IDF	indirect fire
JERRV	joint explosive ordnance disposal rapid recovery vehicle
JLTV	joint lightweight tactical vehicle
LAV	light armored vehicle
LCAC	landing craft air cushion
LCU	landing craft utility
LHA	landing helicopter assault
LHD	landing helicopter dock
LPD	landing platform dock
M-ATV	MRAP- all-terrain vehicle
MAGTF	Marine air ground task force
MAP-K	MEU augmentation program – Kuwait
MCDP	Marine Corps doctrinal publication
MCPP-N	Marine Corps pre-positioning – Norway
MDSS II	MAGTF deployment support system II
MEF	Marine expeditionary force

MEU	Marine expeditionary unit
MOC	Marine operating concept
MOE	measure of effectiveness
MPH	miles per hour
MRAP	mine resistant ambush protected
MROC	Marine resource oversight council
MSC	military sealift command
MPS	maritime prepositioning ship
MPSRON	maritime prepositioning squadron
NATO	North Atlantic Treaty Organization
NDAA	national defense authorization act
NDS	national defense strategy
NSS	national security strategy
OCONUS	outside contiguous United States
R2C	route reconnaissance and clearance
STANAG	standardization agreement
TOW	tubular-launched optically-tracked wire-guided

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I. INTRODUCTION

Four U.S. Marines travel down a bumpy unimproved road somewhere in the middle of enemy-controlled territory on their way to a mission that could potentially loosen the grip of the enemy in the area. They are each wearing the latest flame-resistant uniform with infrared scattering technology underneath their lightweight small arms protective inserts plate carrier that will resist penetration by the 7.62mm projectile that is the preferred ammunition of the enemy. Communications with the rest of the platoon is encrypted and completely secure via the newest satellite communications technology, which also provides real-time geolocation tracking so leadership around the world can know exactly where the platoon's elements are within 10 meters. The automatic rifleman is carrying the infantry automatic rifle capable of laying down accurate small arms fire at 800 rounds per minute out to 800 meters. The other Marines are carrying their individual rifles complete with the newest optics and laser sighting system to enable accurate engagement of enemy targets out to 500 meters. Their weaponry is more effective than the enemy's by hundreds of meters, and their communications cannot be jammed. If struck by an enemy bullet, their protective equipment will save them. However, the vehicle they are riding in was designed 40 years ago and can be defeated by a milk jug filled with the proper mixture of farm fertilizer and cleaning supplies. Now imagine these same four Marines survived this mission, and years later are on a similar mission, but this time on the narrow urban streets of Italy or Hong Kong. They learned their lesson last time, so now they are in the newest vehicle with the best armor protection, but to achieve this, it is twice a big and three times as heavy as their last vehicle and cannot fit down the streets. In both cases, the vehicles were designed for such a specific mission that they were not effective in anything but that mission and consequently, failed the mission at hand.

In a perfect world with unlimited resources, the Marine Corps would simply buy the best vehicle for every mission type and use the appropriate vehicle as needed. However, in a resource-constrained world, every asset must be used to the greatest extent possible. The Marine Corps' tactical vehicle fleet is no exception, and if it continues to chase niche vehicle capabilities, the chances of the two scenarios described happening will continue to rise.

A. PURPOSE

This study examines the tactical vehicle strategy currently employed by the Marine Corps to identify inefficiencies or redundancies that may have been created given the recent publication of national and service-level strategy documents. By applying reasonable and logical evaluation methods, a recommendation can be made about the most effective combat tactical vehicle strategy within a resource-constrained environment. The study and conclusion will be organized to answer the following questions.

Research question: Given the current Ground Combat Tactical Vehicle Strategy and the Marine Operating Concept, what is the proper portfolio mix to be most effective in the anticipated threat environment through FY30?

Secondary questions: Is there a point in time at which the M-ATV or HMMWV will no longer be required as a tactical vehicle? If so, when?

B. SCOPE AND METHODOLOGY

Multi-criteria effectiveness analysis was used to evaluate the vehicles currently employed under the Ground Combat Tactical Vehicle Strategy (GCTVS) for overall effectiveness in a variety of regional environments. The total effectiveness model was based on three main criteria representing the key characteristics identified by the Marine Corps as essential for any vehicles to best support future operations (Walsh, 2018). The environments of concern were those identified by national leadership in the current National Security Strategy (NSS) and National Defense Strategy (NDS) (Mattis, 2018; Trump 2017). The effectiveness of each vehicle was calculated to conduct a final analysis of the tactical vehicle strategy as currently written through fiscal year 2030 (FY30). Finally, the effectiveness scores were interpreted in the context of the three specific threat regions over time, which led to the final recommendation.

C. ORGANIZATION

This thesis report begins by providing some background information on the source documentation that is used as the basis for the study's model. Additionally, background will be provided on each specific vehicle being evaluated. The background will be followed by a short discussion on the technique of multi-criteria effectiveness analysis. The model will be developed and the origin and purpose of each objective and attribute explained. In the analysis section, the developed model will then be applied to the identified vehicles three times across the regions in question. The analysis section will be followed by the results section wherein sensitivity analysis is used to identify any changes in effectiveness if some subjective values and other assumptions are altered. Finally, a conclusion and an accompanying recommendation will be provided to support future decisions regarding vehicle inventories and life cycle plans.

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II. BACKGROUND

A. UNITED STATES MARINE CORPS DOCTRINE

Marine Corps doctrine is derived from national level source documents starting at the highest level with the National Security Strategy signed by the president of the United States. The latest NSS, signed by President Trump in December 2017, identifies the vital national interests that must be protected to maintain the United States' power and influence in the world. The NSS identifies five specific threats to these interests: China, Russia, Iran, the Democratic People's Republic of Korea, and transnational threat groups (Trump, 2017). These have been referred to as the "4 + 1" (DeBoer, 2017). It then lays out some very high-level strategic initiatives to protect these national interests through foreign and domestic policies. National policies seek to employ the nation's tools of power through diplomacy, information, the military, and the economy, better known by the acronym DIME. The National Defense Strategy, signed by Secretary of Defense James Mattis, uses the NSS to develop what the Department of Defense's (DoD) strategy will be to combat the threats to the nation. The NDS is a classified document, but an unclassified summary provides the top-level strategic ideas and goals of the original document. The NDS summary states, "Long-term strategic competitions with China and Russia are the principal priorities for the Department, and require both increased and sustained investment, because of the magnitude of the threats they pose to U.S. security" (Mattis, 2018, p. 4). It also identifies three key regions - Indo-Pacific, Europe, and the Middle East - in which the U.S. must maintain control so as to not allow escalation to open conflict. The NDS is translated from strategic level goals to actionable tasks for each of the services through the National Military Strategy, also a classified document, signed by the Chairman Joint Chiefs of Staff. This document explains how the country will employ the "M" in DIME to secure those vital national interests.

These national-level documents provide each of the services with priorities and objectives at the highest level, and in the case of the Marine Corps, facilitate the publication of The Marine Corps Operating Concept (MOC) (Neller, 2016). The MOC has two main purposes: 1) Describe in broad terms how the Marine Corps will operate, fight, and win in

2025 and beyond as an extension of General Conway's work as published in The Marine Corps Vision and Strategy 2025; and 2) Shape our actions as we design and develop the capabilities and capacity of the future force (Conway, 2008; Neller, 2016). Since the publication of Fleet Marine Force Manual (FMFM) 1 Warfighting by Commandant Grey (1989), later renamed in 1997 as Marine Corps Doctrinal Publication (MCDP) 1 Warfighting, the Marine Corps has officially recognized maneuver warfare as the primary philosophy used to operate and fight. In this publication the Marine Corps defines maneuver warfare as, "a warfighting philosophy that seeks to shatter the enemy's cohesion through a series of rapid, violent, and unexpected actions which create a turbulent and rapidly deteriorating situation with which he cannot cope," (MCDP1 Warfighting, 1997, p. 59). The MOC acknowledges and reaffirms the Marine Corps' commitment to maneuver warfare in stating "[maneuver warfare] was, is and will remain our foundation" (Neller, 2016, p. 8).

In support of this foundation, the MOC identifies five critical tasks, one of which is as enhancing "our ability to maneuver," which will be necessary to change how the Marine Corps "organize[s], train[s], and equip[s]" (Neller, 2016, pp. 10). The MOC specifically discusses the need to maneuver from the sea by closely aligning with the Navy and using shipborne platforms to launch combat forces. These combat forces are expected to operate in complex urban terrain within littoral regions as the most likely scenarios to be encountered (Neller, 2016). The MOC also identifies the minimum agility capability level the Marine Corps must maintain as "sufficient protected mobility to support a division reinforced and Marine Expeditionary Force (MEF) requirements," and that these requirements should "take into account the highest-risk challenge against peer or near-peer competitors in urban littoral environments" (Neller, 2016, pp.22).

B. GROUND COMBAT TACTICAL VEHICLE STRATEGY

In support of the MOC, the Marine Corps has updated the comprehensive long-term plan, known as the GCTVS, for the acquisition, employment, sustainment, and disposal of all ground vehicles, tracked and wheeled, in the inventory (Walsh, 2017). This is the first time in three years the strategy has been updated. Lieutenant General Robert

Walsh, Deputy Commandant for Combat Development and Integration, signed the strategy document on 28 November 2017. The update is in response to the Marine Corps Resource Oversight Council (MROC) Decision Memorandum 16-2017 whereby it continues the original purpose of the GCTVS in providing a strategic vision for the tactical vehicle portfolio with a focus on the amphibian assault capability (Walsh, 2017).

The GCTVS notes that, "Marines require ground combat and tactical vehicles that are afloat ready…designed to be transportable by and integrated with naval shipping." (Neller, 2017, pp. 6). The strategy further requires the portfolio to be responsive to the range of military operations while favoring modernization over sustainment of legacy systems. As a result, the Joint Light Tactical Vehicle (JLTV) and Armored Combat Vehicle (ACV) have been assigned the lion's share, approximately 71%, of the Marine Corps' modernization budget (Walsh, 2017).

The Marine Corps' tactical vehicle inventory must meet characteristics in four specific areas (Walsh, 2017):

1. "Capabilities [must] balance **mobility, transportability, protection, and lethality** attributes" (p. 7). (emphasis added)

These are the four key characteristics any future vehicle systems must consider, but they require clear definitions to be useful.

Per the DoD dictionary, mobility is, "a quality or capability of military forces which permits them to move from place to place while retaining the ability to fulfill their primary mission" (DoD, 2018, p. 156). The places in which the Marine Corps is expecting to need this capability are "in mountainous, jungle, arctic, desert, and urban operating environments" (Walsh, 2017, pp. 3).

Platforms used in shipping the tactical vehicles like amphibious class ships, maritime prepositioning ships, Military Sealift Command (MSC) vessels, and USMC-owned transport aircraft (C-130, CH-53, MV-22) are the basis for defining transportability (Walsh, 2017). Measurable characteristics such as width, height, and weight are driving factors in determining transportability, as these attributes are what limit a vehicles' ability to be lifted by or fit in an aircraft or ship.

The military definition of protection is "Preservation of the effectiveness and survivability of mission-related military and nonmilitary personnel, equipment, facilities, information, and infrastructure deployed or located within or outside the boundaries of a given operational area" (DoD, 2018, p. 189). The internationally accepted criteria to evaluate effectiveness of protection as it relates to vehicles is STANAG 4569 (NATO Standardization Agency [NSA], 2012).1 However, U.S. manufacturers have adjusted the testing methods prescribed by the STANAG document and the protection levels are now commonly referred to as "MRAP-levels" of protection. These levels are similar to, and the MRAP levels are based on, the STANAG levels (Bertuca, 2010).

Lethality is the vehicle's ability to support various weapons platforms employed by infantry battalions including medium and heavy machine guns as well as missile and rocket launching systems.

2. "Closely managing transport weights and inventory positions – interface with connectors, amphibious class ships, maritime prepositioning ships (MPS), Military Sealift Command vessels, and transport aircraft (C-17, CH-53and M-22)" (p. 7).

The GCTVS incorporates inventory management both in where the inventory is located and what type of vehicles will be maintained at specified inventory levels across time. Inventory location must be balanced among the MSC vessels, the Marine Expeditionary Unit (MEU) inventory aboard amphibious ships, CONUS and OCONUS storage facilities.

[1] STANAG 4569 stands for the North Atlantic Treaty Organization (NATO) Standardization Agreement (STANAG) 4569. STANAG 4569 is a classified set of test parameters that define how armored vehicles are to be evaluated for resistance to attack. Vehicles are evaluated on resistance to direct fire weapons, indirect fire (IDF) weapons, and underbelly mine/IED attacks. The vehicles ability to protect occupants depending on proximity to IDF detonations, the caliber of direct fire weapons, or the explosive weight of mine/IED attacks determines the STANAG level. STANAG 4569 is categorized into two classifications; mine threats and kinetic energy protection. The mine threat protection levels range from 1 to 4b with the letter M preceding the level. The kinetic energy protection levels range from 1 to 6 with K preceding the protection levels.

3. “Provide capacity to meet and sustain worldwide Marine Corps commitments in support of geographic combatant commanders” (p. 7).

The total number of vehicles within the Marine Corps’ inventory must be enough to support the missions required of the Marine Corps by the six geographic combatant commanders (GCC). The Marine Corps, like all services, is a force provider to the GCC. As part of the Title 10 responsibilities to execute those, “other missions as required by the President,” the Marine Corps supplies the personnel and equipment to execute missions for the GCCs (United States Marine Corps, 1956). The GCTVS lists the capacity as the need to support forcible entry operations by two Marine Expeditionary Brigades.

4. “Modular and able to incorporate growing technology to meet future threats across the electromagnetic spectrum” (p. 7).

As warfare continues to be executed using more technically sophisticated equipment, the tactical vehicles of the Marine Corps must be capable of receiving upgraded technology and employing the latest electromagnetic spectrum weapons and defensive measures.

C. TACTICAL WHEELED VEHICLES

Within the GCTVS, all ground vehicles, including wheeled and tracked, that are used to execute tactical missions are included in the strategy. Tracked vehicles such as tanks and armored personnel carriers are referred to as combat vehicles (Walsh, 2017). This study only includes the three main wheeled vehicles used for general purpose and tactical support to these combat vehicles. The wheeled vehicles included in the study are the High Mobility Multi-Wheeled Vehicle, the Mine Resistant Ambush Protected – All-Terrain Vehicle, and the Joint Lightweight Tactical Vehicle.

1. High Mobility Multi-purpose Wheeled Vehicle (HMMWV)

The oldest and lightest vehicle in the GCTVS is the HMMWV, pictured in Figure 1, which has been in the Marine Corps inventory since the mid-1980s when AM General received a $1.2B contract in 1983 (NY Times, 1983). The HMMWV was a replacement for the Jeep and had been used as the prime tactical vehicle for everything from troop transport and weapons system platforms to ambulance duties (Seabough, 2017). As a direct replacement for the jeep, the HMMWV was never designed nor intended for use as a combat vehicle in direct contact with the enemy. However, this platform was used throughout Desert Storm and again during the opening years of the OIF/OEF conflicts.

Figure 1. High Mobility Multi-purpose Wheeled Vehicle. Source: Jane's by IHS Markit (2018c).

After the initial invasion into Iraq in 2003, additional armor kits were installed on the HMMWVs in response to the lack of survivability during enemy attacks (Solis, 2006). Marine Corps officials reported that these upgrades to 1,169 HMMWVs in the Marine Corps inventory were delayed due to supply availability; interim armor was installed as a stopgap measure, providing ballistic protection but little IED protection. By September 2004, 1,438 HMMWVs were retrofitted with add-on armor that met the required IED protection levels using 3/8 inch rolled homogenous steel (Solis, 2006). While in theory this "up-armor" improvement was going to provide additional layers of ballistic protection from small arms fire, it did little to protect against attacks from below the vehicle while adding thousands of pounds to the vehicle weight and reducing its mobility (Seabough, 2017). The additional armor proved to be ineffective against IEDs, and casualty numbers began rising leading to increased coverage by the media followed by public demand for the military to protect the servicemen and women from this danger (Jacobs, 2007). Congress also began to focus on the combat vehicles after receiving reports from Congressional Research Service (CRS) authored by Andrew Feickert (2007) and testimony from military leaders leading to authorization for the DoD to develop a materiel solution in the National Defense Authorization Act of Fiscal Year 2006.

There are approximately 17,000 HMMWVs still in the Marine Corps inventory with a valid mission requirement. They were never intended to be front line combat vehicles, so those valid missions are on bases/stations or in the rear echelon of a conventional combat zone. Seabough (2017) noted in his article, "Oshkosh JLTV First Drive Review," that the addition of armor and other equipment over the past 30 years has left the HMMWV overweight and underpowered. Arakere, Bell, Haque, Grujicic, and Marvi (2009) point out the additional armor designed to provide more protection to the occupants significantly undermined the original performance characteristics. They found this reduction in performance was particularly acute in off-road performance where braking distance was increased as was potential for rollover (Arakere et al., 2009), confirming what field experts had known for years as reported by the Associated Press and published in the *Washington Post* in 2006 (Associated Press, 2006). With the addition of armor, the payload supportable by the suspension system was also necessarily reduced by the weight of the armor leaving the vehicle useless as a troop transport or cargo carrying utility vehicle (Seabough, 2017). The development of a new vehicle to replace the HMMWV was underway as early as 2006 with the lessons learned from Iraq and Afghanistan fresh on the DoD's mind (Dimascio, 2006). Therefore, the requirement for a lightweight tactical vehicle that can provide a comparable level of force protection to the MRAP and the agility of the original HMMWV was given to the tactical vehicle industry (Dimascio, 2006). The answer was the Joint Light Tactical Vehicle (JLTV).

The HMMWV is scheduled to remain in the Marine Corps' inventory until 2030, with an authorized fielding inventory of approximately 17,000 vehicles. Table 1 provides the predicted inventory requirements as projected in the GCTVS through FY30, which illustrate how inventory levels will decrease over time as the JLTV is fielded.

Table 1. Projected Inventory Levels for HMMWV (All Variants). Adapted from USMC (2017).

	Qty per Fiscal Year (FY)											
	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
HMMWV	17056	15371	13551	11701	10665	9765	8865	7965	5974	3983	1992	0

2. Joint Light Tactical Vehicle (JLTV)

As early as 2006, the Army and Marine Corps were exploring solutions to replace the HMMWV as was reported by Jen Dimascio for *Inside Defense* (Dimascio, 2005). After a year without complete consensus regarding requirements by the two services, the 2006 National Defense Authorization Act (NDAA) "encouraged" them to work together in finding a common solution (NDAA, 2006). Starting in 2008, the DoD published a request for proposal for three tactical vehicle contractors with BAE and NAVISTAR, General Tactical Vehicle [a joint venture between General Dynamics and AM General], and Lockheed Martin Systems being awarded the technology development contracts (Feickert, 2017). The contract award decision was protested by Northrop Grumman-Oshkosh and the Boeing-Textron teams in November of 2008, stopping work on the JLTV until the protests were dismissed by the Government Accountability Office in February 2009 (Censer, 2008; Wasserbly, 2009).

The two-year technology development phase was extended by a one-year delay due to changing requirements calling for more under vehicle protection and the cancellation of the six-man variant (Bertuca, 2011). This delay forced the engineering and manufacturing development (EMD) phase contract to be awarded in August 2012 rather than 2011, as planned (Feickert, 2017). Three companies were awarded the EMD contract requiring each company to produce 22 vehicles prototypes for operational testing to last 14 months (Feickert, 2017). Following the 33-month EMD phase, the low rate initial production contract was awarded to Oshkosh to produce the first 16,900 JLTVs, pictured in Figure 2, for the Army and Marine Corps (Gould, 2015). Lockheed Martin protested the decision and caused some contracting delays, but the program is scheduled to be fielded to the priority units starting in 2019 (Feickert, 2017).

Figure 2. Joint Lightweight Tactical Vehicle. Source: Jane's by IHS Markit (2018d).

Despite the contracting issues and protests, Bill Mooney, an Oshkosh regional vice-president, said the JLTV is to have better mobility than up-armored HMMWVs yet the force protection of an MRAP (Business Wire, 2016). The JLTV developed by Oshkosh has focused on three main attributes. Per the brochure available on the Oshkosh website, the JLTV provides a "Net ready" connection, a state-of-the-art suspension system, and a fully integrated armor protection system (Oshkosh, 2017).

To meet the needs of the future warfighting environment, the connectivity of the vehicle must be adaptable. Oshkosh (2017) claims the JLTV's communications suite can be reconfigured in the field to meet the demands of the mission. It also says the mechanical and electrical interface was optimized for quick integration and can operate independently or as part of a common communications architecture. While the communications system is a very important design of any of today's vehicles, the protection and mobility were the chief complaints of the HMMWV and MRAP. The braking system has also been upgraded to outperform the HMMWV or MRAP. Finally, the JLTV is protected by a fully integrated system Oshkosh calls the Core1080.

While numerous public statements by DoD officials and contractors have declared that the JLTV is not going to be a one for one replacement to the HMMWV, the GCTVS directly counters these statements: "The HMMWV will be incrementally replaced on a one-for-one basis by the JLTV starting in FY19" (Walsh, 2017, pp. 36). The authorized fielding strength of HMMWVs is currently 17,056 vehicles and, over the duration of the JLTV fielding plan, that number remains as the sum total of HMMWVs and JLTVs authorized as shown in 0 (Walsh, 2017). This shows that there is exactly a one-for-one replacement plan.

Table 2. Fielding Plan and Sunset Plan for JLTV/HMMWV. Adapted from USMC (2017).

Qty per Fiscal Year (FY)												
	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
HMMWV	17056	15371	13551	11701	10665	9765	8865	7965	5974	3983	1992	0
JLTV												
Inct I	0	1685	3505	5355	5500	5500	5500	5500	5500	5500	5500	5500
Inct II					891	1791	2691	3591	3591	3591	3591	3591
Inct III									1991	3982	5973	7965
Total	17056	17056	17056	17056	17056	17056	17056	17056	17056	17056	17056	17056

The design of the JLTV will come in four variants; general purpose, heavy guns carrier, utility carrier, and close combat weapons carrier (Gilmore, 2016). All but the utility variant will carry four occupants with the utility variant seating two with a large cargo bed in place of the two rear seats. These same three variants will also be able to mount weapons systems, although that option is determined by the end user. David Dierson, vice president and general manager of joint programs for Oshkosh, noted that the JLTV was designed with modularity in mind (Keller, 2017). He said the vehicle is designed to be adjustable according to missions now, but also modular with respect to future developments. New technology over the lifespan of the vehicle will be able to be incorporated in the vehicle with minor adjustments by engineers. The JLTV's weapon systems supported range from small individual weapons to large caliber machine guns. In October of 2017, Oshkosh unveiled the automated turret with Hellfire missiles and a coaxial .50 caliber mounted for air defense against unmanned aerial vehicles and fixed-wing aircraft (Judson, 2017, Keller, 2017).

The JLTV will have a payload range of 3,500 to 5,100 pounds across the four variants (Gilmore, 2016). Additionally, according to the JLTV brochure available on the Oshkosh website (https://oshkoshdefense.com) it is designed to have an operational range of 300 miles at up to speeds of 70 miles per hour. The suspension system is said to allow 70% faster speeds off-road with 20 inches of wheel travel. That is four more inches of wheel travel than the Oshkosh-made M-ATV. All of this capability fits within a package weighing only 14,000 pounds before adding the various armor kits and is required to fit in all of the same storage locations aboard amphibious shipping as the HMMWV. There are two levels of armor kits, with kit A being the base model and intended for low threat use. Level B armor is additional armor that will be attached for higher threat-level conflicts providing added small arms, and underbody protection from mines and IEDs (Gilmore, 2016).

3. Mine Resistant Ambush Protected (MRAP)

Mine resistant ambush protected vehicles have been a controversial topic since their inclusion in the Marine Corps inventory of tactical vehicles. The study conducted by Rohlfs and Sullivan called into question whether the price being paid for the new MRAPs was worth what they concluded was no more effective at reducing casualties than the up-armored HMMWVs (Rohlfs & Sullivan, 2013). A rebuttal by Marine Corps analyst F.J. Gayle questioned the methodology and conclusions of the Rohlfs-Sullivan study and suggested that the vehicles were in fact safer many times over (Gayle, 2013). The Lamb, Schmidt, and Fitzsimmons article argued, “that MRAPs are a valid irregular warfare requirement,” despite the numerous counter arguments they cited throughout their article (Lamb et al., p. 76, 2009). One such criticism, cited in their article, was by retired U.S. Army General Barry McCaffrey who claimed the MRAP to be the wrong vehicle for a situation that was under control (Lamb et al., 2009). Tom Vanden Brook is a journalist for *USA Today,* which chronicled much of this controversy via his articles: Pentagon balked at pleas for safer vehicles (Eisler, Morrison, Vanden Brook, 2007); Gates: MRAPs save ‘thousands’ of troop lives (2011); Estimate of lives saved by MRAPs lowered (2012); Mattis, Marines balked at lifesaving vehicle (2016). The MRAP was originally acquired through a rapid fielding acquisition process driven by public outcry, continuous media coverage (Vanden Brook, 2007; Gilsinan, 2007; Atkinson, 2007), and congressional pressure (CSPAN, 2005) ultimately leading to Secretary of Defense Robert Gates, in June 2007, to issue a memo to DoD acquisition officials that the MRAP is the DoD’s number one acquisition priority (Rutherferd, 2007). The direction from Secretary Gates resulted in the expedited acquisition of the MRAP via the rapid fielding process. These vehicles saw some success in combating the IED threat compared to HMMWVs. The inventory numbers grew quickly, and the MRAP became a ubiquitous sight on any U.S. installation in Iraq or Afghanistan.

This family of vehicles had a variety of makes and models that were used over the next decade for a variety of purposes including models from manufacturers BAE, Force Protection Inc (FPI), Caiman, MaxxPro, and Oshkosh (Eisler, Morrision, Vanden Brook, 2007). FPI is the producer of the Cougar family of MRAPs that are still in the Marine inventory. They come in two varieties: a 4x4 and 6x6 variant. Both are used for troop transport although the 6x6 was originally intended as a delivery vehicle for combat engineer missions (Gayle, 2013). It was designated the Joint Explosive Ordnance Disposal Rapid Recovery Vehicle (JERRV) and was specifically equipped to conduct engineer route reconnaissance missions (Gayle, 2013).

The Cougar MRAP is extremely large with the smaller 4x4 version spanning 20 feet 8 inches, the 6x6 is 24 feet 7 inches in length, and both are just under nine feet wide and without a turret or other attachments they stand ten feet tall (Force Protection, 2007). When turrets or electronic warfare devices are installed, vehicle heights can exceed 14 feet. The 4x4 variant weighs around 34,000 pounds while the 6x6 weighs an average of 45,000 pounds (Force Protection, 2007). Both vehicles have similar construction with a V-shaped hull and armor plating able to uphold the same protection levels.

In addition to the troop-carrying variants, route reconnaissance and clearance (R2C) variants were developed and employed by both the Army and Marine Corps (Gayle, 2013). The largest of these variants is known as the Buffalo and is a 45,000 – 84,000 pound vehicle with an articulating arm designed to interrogate mines and other buried explosive hazards (Force Protection, 2007).

Another MRAP variant with a very specific task is the Husky. The Husky provided mine and IED detection using a variety of ground penetrating sensors. The vehicle's latest variant, the Husky 2G, is a two-man operated vehicle with a driver and a systems operator (Critical Solutions, 2015). This concept is very similar to military aircraft with a pilot and Naval Flight Officer or "back-seater" that employs all other systems of the aircraft while the pilot only concentrates on flying. The Buffalo and Husky together with two R2C Cougars and three CAT I Cougars make up a route clearance package and are not considered troop transport options although high profile dignitaries have been escorted in the Buffalos and Cougars of R2C packages due to the safety, visibility afforded and comfort of the passengers (Walsh, 2017).

Over time, the mobility and maintainability of these MRAPs came into question (Bertuca, 2010). These vehicles are extremely heavy with a high center of gravity making traversing off-road conditions questionable. Because many missions required off-road travel, maintenance of these vehicles became troublesome. The need for a new lighter and more agile version was identified. The MRAP-All-Terrain Vehicle (M-ATV), Figure 3, was created and began to supplant the existing older and heavier versions.

Figure 3. MRAP All-Terrain Vehicle. Source: Jane's by IHS Markit (2018g).

The M-ATV was designed to be 30% lighter at a curb weight of 24,000 pounds (Feickert, 2011). The independent suspension and improved steering provide better handling and turn radius giving the M-ATV the ability to negotiate a 30% side slope and climb a 60% grade (Oshkosh, 2016). Additionally, it retains the same survivability threshold as the MRAP CAT I, II, and III vehicles (Walsh, 2017). The new M-ATVs were immediately deployed to Afghanistan in November of 2009 with more than 3,500 in theater by June of 2010 (Bertuca, 2010). These improved performance measures are available in five variants seating anywhere from four to eleven service members (Oshkosh, 2016). Because of the lighter frame and improved power plant and drive train, the M-ATV boasts a top speed of 65 miles per hour with an average range of 320 miles (Oshkosh, 2016). The improved suspension and reduced weight also give the M-ATV a 4,000-pound payload (Oshkosh, 2016).

And while the M-ATV shows marked improvement over both older MRAPs and HMMWV performance they are not completely compatible with amphibious shipping. The Marine Corps uses an automated information system called the Integrated Computerized Deployment System (ICODES) (Mills, 2013). Embarkation specialists upload the appropriate Marine-Air-Ground Task Force Deployment Support System II (MDSS II) data into the ICODES program and it develops an optimized load plan from which the specialists adjust to meet mission specific requirements (Mills, 2013). The ICODES program shows that the MRAPs fit in all vehicle stowage space on Landing Helicopter Assault (LHA) ships while its' size prevents loading on upper or lower vehicle holds of a Landing/Platform Dock (LPD) ship and the lower vehicle hold of a Landing Helicopter Dock (LHD) ship. These restrictions prevent the stowing of the M-ATV in two-thirds of the available space on a MEU, thus reducing the transportability of the vehicle and limiting the limiting the number of vehicles delivered by a MEU.

A combination of some legacy MRAPs and the new M-ATVs were placed into the permanent vehicle inventory with an expected service life through 2030 (Walsh, 2017). Not all of which are assigned to operational fleet units, instead a portion are stored in a ready state with other combat items that collectively are known as war reserves. The three types of war reserves are stateside depots, overseas depots, and in operational/supporting units. The stateside depot is located in Barstow, California. Overseas depots include the Marine Corps Pre-Positioning- Norway (MCPP-N), the MEU Augmentation Program – Kuwait (MAP-K), and two Maritime Pre-positioning Squadrons (MPSRON)s (Haviland, 2011, Hudson, 2014). MAP-K is a program designed to maintain from 410 to almost 1,700 MRAP vehicles in an operational status so that they may support theater security cooperation activities within CentCom (Hudson, 2014). The vast majority of the MRAP fleet are maintained in war reserves around the globe with 844 maintained in MAP-K and 912 maintained in the stateside depot (Vergenz, 2017).

The Marine Corps has published a total MRAP requirement of 2,007 vehicles across all variants (Walsh, 2017). That total is subdivided into authorized quantities, as listed in Table 3. Using the totals from Table 3, the two war reserve locations contain 85% of MRAPS with 10.5% assigned to operational and supporting establishment units.

Table 3. 2018 MRAP Inventory. Adapted from USMC (2017).

Type	TAMCN	Qty
CAT I, Cougar	D0025	943
CAT I, Cougar, TOW	D0040	34
CAT II, Cougar	D0027	230
CAT II, Cougar R2C	D0051	46
CAT II, Cougar, Ambulance	D0023	19
CAT III, Buffalo	B0035	30
M-ATV	D0036	705
Total		2007

This extended life cycle comes at a cost to maintain an aging and worn out fleet of vehicles. Marine officials have estimated that MRAPs cost 86% more annually to maintain and operate than HMMWVs (Vergenz, 2017). The operations and maintenance costs associated with MRAPs assigned to operational units is $50,000 per vehicle per year, while the cost associated with maintaining MRAPs overseas according the KBR Wyle's report of 2017 is approximately $20,000 per vehicle per year (Vergenz, 2017). Maintaining the vehicles in stateside depots in a level "A" status where that entails the vehicles being stored outdoors without climate control would cost $12,000 per vehicle per year (Vergenz, 2017).

D. REGIONS AND EXPECTED ENEMY

Within the NDS, under the heading "Prioritizing preparedness for war," three key regions are identified, "deter aggression in three key regions – the Indo-Pacific, Europe, and Middle East" (Mattis, 2018, p. 6). The base assumption for this thesis is that those efforts to deter aggression failed in one of the regions and open conflict with the most likely enemy is now likely to occur. The most likely enemies as stated in the NSS and NDS are China, Iran, North Korea, Russia, and transnational terrorist organizations (i.e., ISIS, Al Queda) (Trump, 2017; Mattis, 2018). Each of the regions are characterized by distinct geographical features that can influence or restrict the use of military tactics and equipment. Likewise, the most likely enemy within the region will also influence the type of warfare and equipment used to conduct military operations.

1. Indo-Pacific

The Indo-Pacific region boasts the greatest percentage of water to land over all other combatant commands with many island nations and a large percentage of coastline per nation (Central Intelligence Agency [CIA], 2018). This necessarily means that movement to any location of conflict will require a ship or aircraft. A conflict in this region is likely to center around the two enemy threats of China and North Korea (Mattis, 2018). As seen in the Pacific campaign of WWII quite often arriving by ship was the only option until airfields on the islands were secured.

2. Europe

Europe is a highly developed region with mature infrastructure and a complex road network that is modern (CIA, 2018). Some cities have very narrow streets with large populations. The landscape outside of cities is rolling hills and forests with mountains throughout (CIA, 2018). The associated enemy threat is Russia (Mattis, 2018). Under this assumption, the type of weaponry, equipment, and tactics used will be conventional. This will drive the use of maneuver warfare on the part of U.S. forces, which requires deadlier and more mobile assets.

3. Middle East

This region is characterized by underdeveloped infrastructure with a poor road network across mostly barren desert landscape (CIA, 2018). It is punctuated by rough terrain in the form of mountains and has minimal prominent water features with minimal coastline (CIA, 2018). The main enemy threats are Iran and those non-state actors (Mattis, 2018).

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III. METHODOLOGY

This thesis uses a multi-criteria effectiveness analysis to explore the tradeoffs between various attributes in the vehicle's performance in specified regions. The three vehicle types were evaluated using four main objective categories; mobility, transportability, protection, and lethality.

According to Kirkwood (1997) in his *Strategic Decision Making: Multi-Objective Decision Analysis with Spreadsheets* text, multi-criteria effectiveness analysis is a common technique used when multiple conflicting objectives exist for a set of alternatives. This technique allows an analyst and the stakeholders to place value on individual desirable attributes through varying techniques and ultimately calculate a measure of effectiveness (MOE) for each alternative that is being considered enabling a ranking of alternatives from best to worst. The technique is well-known and used across many industries and disciplines such as identifying optimal locations for manufacturing plants (Alam et al, 2015), evaluating risk in the cyber environment (Kelic et al., 2013), or in artificial intelligence as used by Hsueh and colleagues (2010). However, the commonality among these applications is they are used before large investments have been made. The Marine Corps finds itself in a position where very large decisions have been made and billions of dollars have already been invested by the American taxpayer. To protect this investment the vehicles will be used for the duration of the vehicle's useful life regardless of changing threat environments or mission requirements. This research applies a multi-criteria effectiveness model in a post-hoc manner using the emerging requirements and identified characteristics desired in vehicles to supports the Marine Corps mission.

A. IDENTIFY OBJECTIVES AND ATTRIBUTES

To begin a multi-criteria effectiveness analysis, the objectives that define the MOE and their relationship must be identified. These objectives are called the ends objective of the alternative being evaluated. Ends objectives represent the qualities that are important in making the decision and are not always directly measurable and may be constructed of means objectives and attributes. The relationship between objectives and attributes will produce a chart similar to Figure 4. Each chart will be unique to the decision context and could be smaller or much larger depending on the complexity and level of detail required for the model. Keeping the model as small as possible while still achieving the level of detail required to differentiate between alternatives is critical to avoid "watering down" all the evaluation attributes. According to Kirkwood (1997), there are five desirable properties to consider when developing an effectiveness model. He lists these properties as completeness, non-redundancy, independence, operability, and size. To achieve completeness the model must adequately represent and measure the desired qualities identified as relevant to the decision. Non-redundancy means the model's attributes should be collectively exhaustive and mutually exclusive as described by Kirkwood (1997). The independence of the model characteristics is best described as the lack of value interaction between evaluation criteria. While the non-redundancy criteria appears similar, it simply directs that an attribute cannot be counted twice while independence says the level of one attribute cannot influence the value contributed by another. The fourth desirable property is the operability of the measures. The measures must be understood by those that will be using the model and making the decisions.

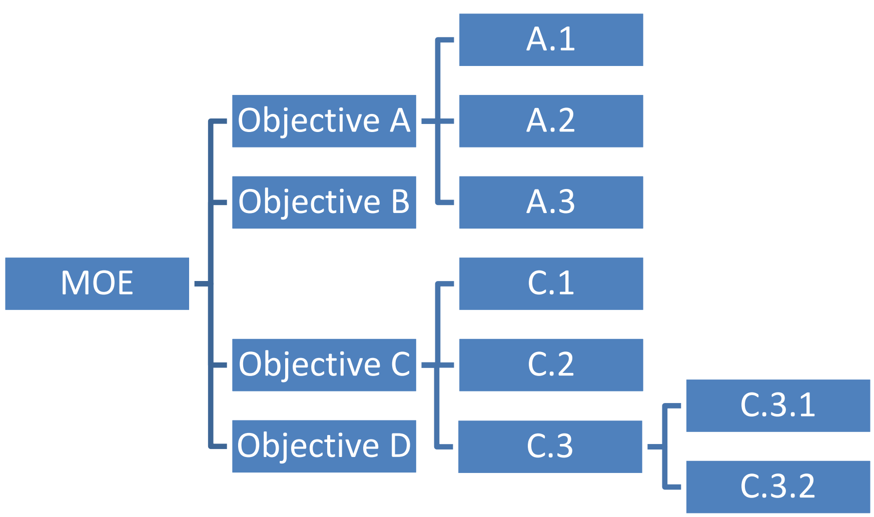


Figure 4. Measure of Effectiveness Example

B. DEFINE VALUE FUNCTIONS

After defining the objectives and attributes that make up the model, the measurement scales for each attribute must be defined. An attribute can be measured using two types of scales according to Kirkwood (1997): Natural and constructed. Natural scales are those scales that are generally accepted and understood by everyone, while constructed scales are created to value a specific attribute in a decision (Kirkwood, 1997). These two scales can then be further categorized as direct or proxy scales. A direct scale can measure the level of performance of an alternative with respect to a specific attribute and be directly measured. A proxy scale is used when the attribute cannot be measured and instead is replaced by an associated attribute(s) (Kirkwood, 1997). Natural measurement scales are preferred and, when available, should be used to reduce the complexity of the model taking advantage of the existing knowledge of those performing the analysis and the decision-makers using the output from the analysis. If a natural scale does not exist and a suitable proxy cannot be identified, only then should a constructed measurement scale be developed.

The alternative's MOE can be represented mathematically by a value function as described by Kirkwood (1997). The generic value function V(x) for the system in Figure 4 with seven attributes (A.1, A.2, A.3, C.1, C.2, C.3.1, C.3.2) will take the form of Equation 1 as adapted from Kirkwood (1997) in his discussion on value functions. In this value function, X represents the measured attribute, v is the value for that measured attribute given the best-case attribute measurement, while the w represents the weight of that attribute relative to the other attributes.

$$V(x) = \sum w_i v_i x_i \tag{1}$$

The values of each measured attribute usually follow one of three types of functions. Kirkwood refers to this degree of preference per unit change in the attribute as "value increment" (Kirkwood, 1997, p. 64). Values can increase linearly where a single unit increase anywhere within the measured range is preferred as much as any other single unit increase. Value increases can also be increasingly preferred as values increase or conversely, decreasingly preferred as values increase. To determine these value increments for nonlinear functions, an exponential constant ρ can be calculated using the normalized midpoint. This ρ is then used in Equations 2 or 3 to generate the value increment v(x) for each attribute. Both Equations 2 and 3 are derived by Kirkwood (1997, p. 66). Two equations are needed for the two occasions: 1) Equation 2, when the v(x) is increasing with an increasing value of x 2) Equation 3, when the v(x) is decreasing with an increasing value of x. If the mid-value is the mathematical midpoint then standard normalization techniques can be used.

$$v(x) = \left\{1 - exp\left[-\left(High - x\right)/\rho\right]\right\} / \{1 - exp[-\left(High - Low\right)/\rho \tag{2}$$

$$v(x) = \left\{1 - exp\left[-\left(x - Low\right)/\rho\right]\right\} / \left\{1 - exp[-\left(High - Low\right)/\rho\right\} \tag{3}$$

C. DEVELOP WEIGHTS

Finally, to complete construction of the model, weights for each attribute and objective must be established. Weights represent the comparative desirability of attributes or objectives under a common objective. Weights can be determined outright by the decision-maker or by using a technique called swing weighting as described by Kirkwood (1997, p. 71).

Once all characteristics in the model have been measured for each alternative the final MOE can be calculated. This will produce the MOE for each alternative that will allow comparison of alternatives as defined by the measurable characteristics. The MOE will be a number from 0 to 1 where the ideal solution would have an MOE of 1 and can be used in cost effectiveness analysis. Each alternative will have an associated cost and that can be plotted against the MOE for each alternative. The cost can be any measure of resources used to gain the system. This cost need not be monetary and can be personnel costs, unit cost, annual cost, time cost, etc.

IV. ANALYSIS

To compare the effectiveness of each vehicle operating in specific regions, a multi-criteria model was used to generate a common quantitative value called a measure of effectiveness (MOE) for all subject vehicles. The MOE is a summation of the criteria deemed most relevant by Marine Corps leadership and published in the GCTVS. There are four main ends objectives listed in the GCTVS that construct the MOE: mobility, force protection, lethality, and transportability (Walsh, 2017). Lethality was considered for this model and determined to be not applicable to tactical wheeled vehicles as detailed in the Chapter III, Section A; Identify Objectives and Attributes. The remaining three objectives were divided into means objectives and attributes to most accurately and thoroughly represent each vehicle. The model is depicted in Figure 5. The value function for each attribute was developed using common maneuver warfare tactics and standard Marine personnel and equipment doctrine. Each value was then weighted per each region's characteristics, the most likely enemy's doctrine, and the preference of decision-makers. When each ends objective value for each vehicle was calculated, it was used to construct the final measure of effectiveness for each vehicle in each region.

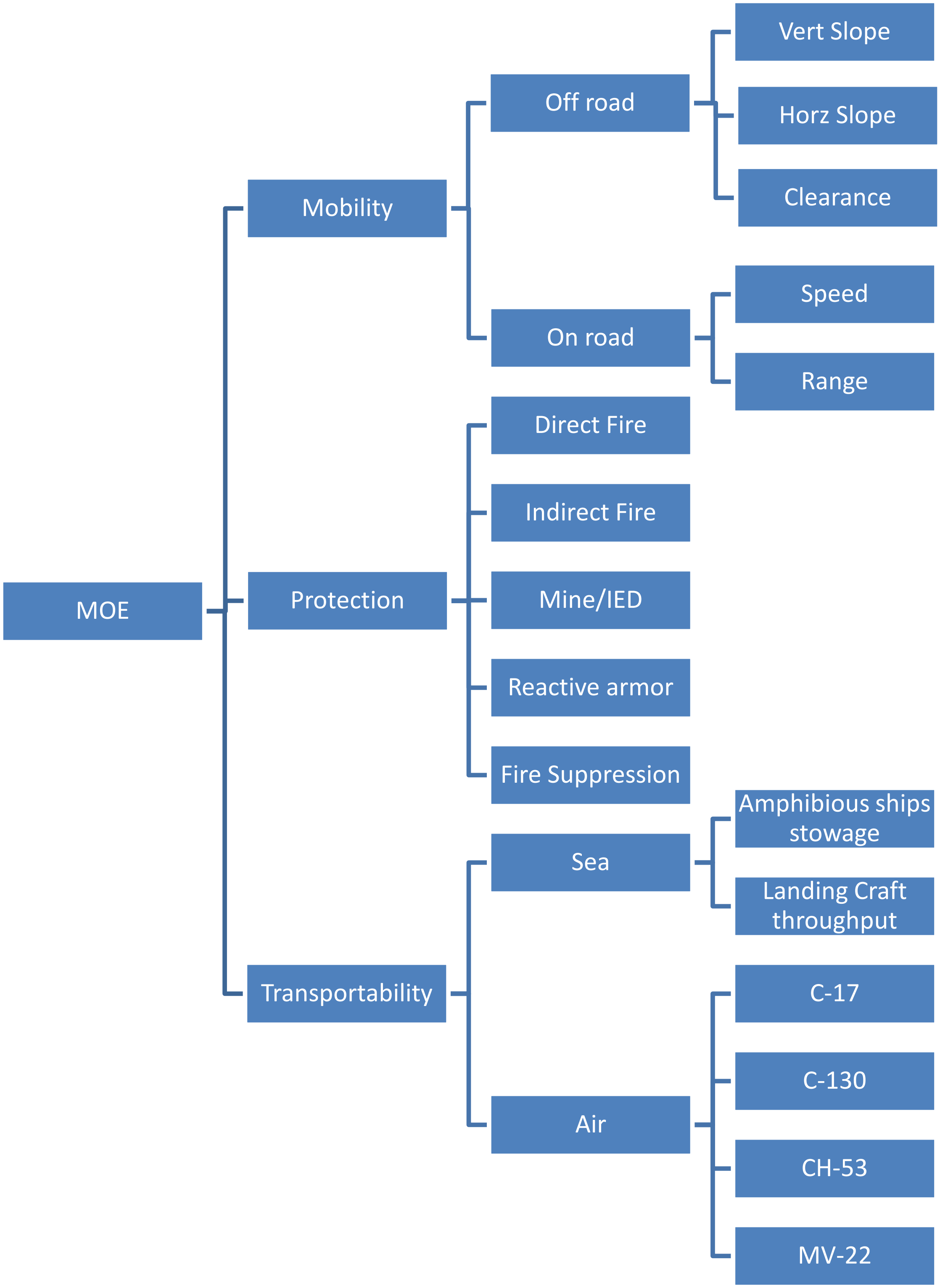


Figure 5. Measure of Effectiveness Model

A. IDENTIFY OBJECTIVES AND ATTRIBUTES

The ends objectives of the model are mobility, transportability, and protection. While it is impossible to directly measure any of these objectives, they do represent the critical characteristics of a tactical vehicle as determined by Marine Corps leadership. Therefore, each objective is subdivided into means objectives and/or attributes.

1. Lethality

To operate effectively in a combat environment, a vehicle must employ the weapon systems found in a standard Marine infantry battalion. There are four machine gun platforms that the Marine infantry company employs: M2 .50 caliber MG, Mk-19 automatic grenade launcher, the M240 series medium MG, and the automatic infantry weapon or light MG. In addition to the machine guns, the infantry battalion also employs a Tubular-launched Optically-tracked Wire-guided missile (TOW) system. Each of these systems can mount in a standard turret and engage enemy targets while stationary and moving as required. The vehicles being evaluated are produced with a turret to accommodate these weapon systems and none of them are equipped with additional weaponry to distinguish them from the other vehicles. Oshkosh did display a variant of the JLTV that employed Hellfire missiles at the 2017 Association of the U.S. Army convention and demonstrated a 30mm chain-gun variant in January 2017 in Arizona as reported by Jen Judson (2017). However, these variants were designed for employment by the Army as a possible substitute for the Stryker and its' air defense mission. There are no plans by the Marine Corps to incorporate this variant into the GCTVS. As a result, lethality is determined to be a non-discriminating factor when evaluating these tactical vehicles and has been removed from the model.

2. Mobility

Mobility is not directly measurable, so some proxy factors must be identified that best represents this capability. Off-road and on-road mobility are the two best categories that are collectively exhaustive yet mutually exclusive. The most relevant characteristics that represent on-road mobility are sustained speed and the vehicle's range.

a. Off-Road

To adequately represent a vehicle's ability to remain mobile off-road, three attributes were identified. The ability to travel on vertical and horizontal slopes and the amount of ground clearance are the largest factors in a vehicle's off-road capability. Speed and power were considered, but not included. Power is included in the slope attributes by requiring the vehicle to negotiate slopes without losing vehicle control while still maintaining forward progress. Speed was not included because off-road missions are not about how fast, but how rough of terrain can the vehicle negotiate.

b. On-Road

Conversely, missions on improved roads do consider how fast the vehicle can travel as well as how far it can travel without having to stop for fuel. Thus, the two main attributes used to represent on-road capabilities are speed and range.

3. Transportability

The U.S. has not fought a war on U.S. soil since the Mexican-American war. There are no indications that this will change soon, so the Marine Corps must be prepared to transport all equipment needed to a contested location. The degree to which the vehicles can be loaded into or on another vehicle and moved determines transportability. However, because the transport vehicles do not deliver at the same rate the throughput of these transport vehicles must be taken into consideration. Those transport vehicles operate in two milieus: air and sea. Therefore, air and sea transport will be the means objectives that make up the overall objective of transportability.

a. Sea

The sea objective consists of both amphibious class shipping and landing craft throughput. Amphibious class shipping refers to the standard MEU; comprised of an LHD, LHA, and LPD; from which the Marine Corps projects power into foreign objectives. While there are other modes of sea transport including commercial shipping and maritime prepositioning ships (MPS), the MEU ships are often the first called upon to deliver Marine equipment with smaller stowage compartments.

b. Air

The air objective consists of fixed wing and rotary wing aircraft attributes. The fixed wing assets capable of moving the tactical vehicles are the C130, C17, and C5. The C130 is included as measure of a vehicle's air transportability because these aircraft are owned and operated by the Marine Corps. The C17 is used to represent the U.S. Transportation Command assets for global repositioning.

4. Protection

When applied to vehicles, this objective is most heavily influenced by the most likely enemy to be encountered in the region and their weapons of choice. The protection levels associated with each vehicle are measured across five categories addressing specific threats to the survivability of the vehicle or its occupants. The attributes that provide a complete and exhaustive representation of protection are direct fire, indirect fire, mine/IED, reactive armor, and fire suppression.

B. VALUE FUNCTIONS

The value functions for the model's objectives and attributes, Appendix A. Model Values, were developed using a variety of techniques. Attribute values like speed and range were measurable through direct means and along a continuous scale. Landing craft throughput values and others were only measurable through a constructed scale. Other values were either binary like CH-53 transportability or step-wise like the STANAG protection levels. All attributes regardless of measurement technique or valuation process have a minimum, below which differences in the value of this attribute are not meaningful, and a maximum value, above which higher levels of the attribute do not add substantial value, creating a relevant range. All threshold values and below will be assigned a value of zero, while all maximum values and above will be assigned a value of one. Within the relevant range for those attributes with scales other than binary a mid-point on the attribute scale is identified for which a vehicle is assigned a value of 0.5. Mid-point values for some attributes are set at points which coincide with current capabilities of like equipment or common doctrinal values. Appendix A. Model Values explains in detail how these values are measured, the critical values, justification for the measures, and the calculations to develop the scales of measure.

1. Mobility

The mobility definition says that for mobility to be achieved the force must remain together to fulfill their primary mission. For that reason, the threshold and objective values for each factor are based on the current combat vehicles in the Marine Inventory: M1A1 Abrams Tank, Amphibious Assault Vehicle (AAV), and the Light Armored Vehicle 25 (LAV-25) (Jane's by IHS Markit, 2018a, 2018e, 2018f). The objective values resulting from the largest value of the three combat vehicles and the threshold value being half of the objective value or that of the smallest value of the combat vehicles whichever is greater. The tactical vehicles evaluated in this study must be able to maintain speed with these combat vehicles on roads and traverse similar terrain off-road during an assault to be effective as tactical or support vehicles.

a. Speed

Overall travel speed is measured on improved surface roads, which include all-weather dirt roads, in miles per hour (MPH). As shown in Figure 6, the relevant range of speeds will be 30 MPH to 60 MPH measured on a continuous scale. The midvalue is set at 35 MPH because that is the established speed at which the range of a vehicle is determined and a common speed at which convoys travel.

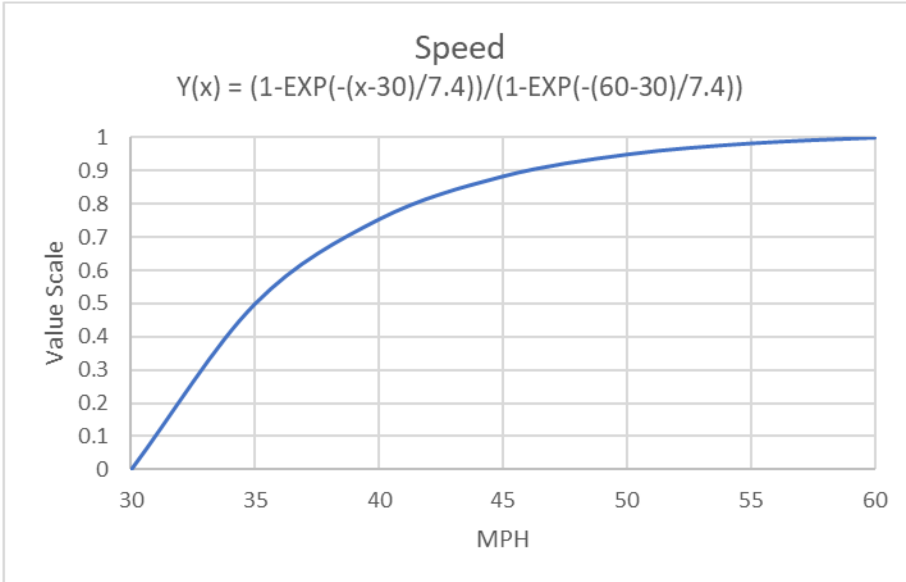


Figure 6. Value Graph of Speed

b. Range

Range is the distance a vehicle can travel on an improved road on one full fuel tank. Only internal fuel tanks are used for this measurement. External spare fuel cans are not included in the calculation. Shown in Figure 7, the threshold range is 260 miles with an objective range of 400 miles measured on a continuous scale. Midvalue for this scale is 300 miles because that is the common range assumption used during operational planning.

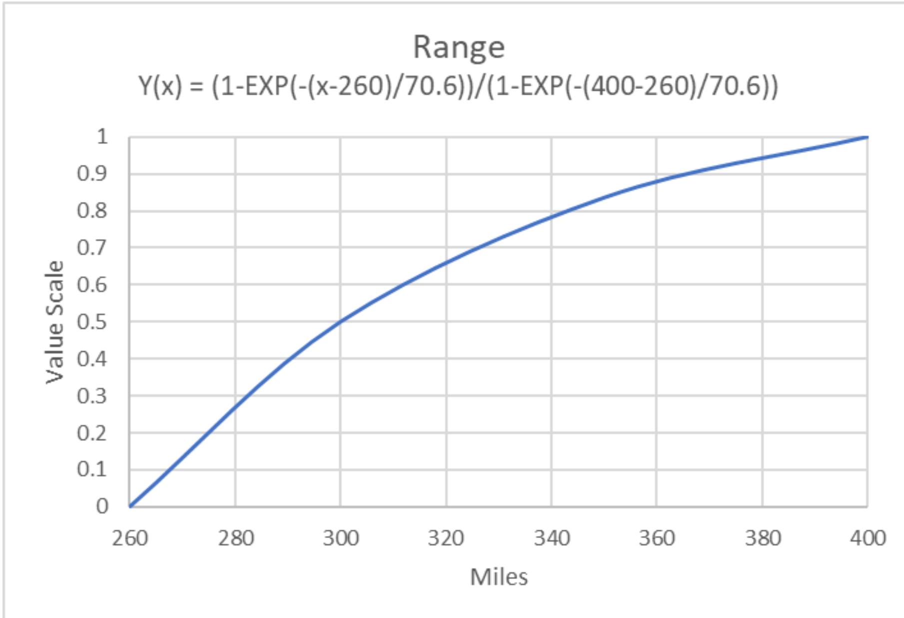


Figure 7. Value Graph of Range

c. Slope

The agility of the vehicle to traverse a horizontal slope, shown in Figure 8, and forward vertical slope, shown in Figure 9, is a classic indicator of mobility. Each test requires the vehicle to maintain forward momentum without rollover. The side slope scale is from 20% to 40%. The vertical slope scale is from 30% to 60%. Both scales are assigned values along a linear function with the threshold value assigned 0 while the maximum and above will be assigned a 1.

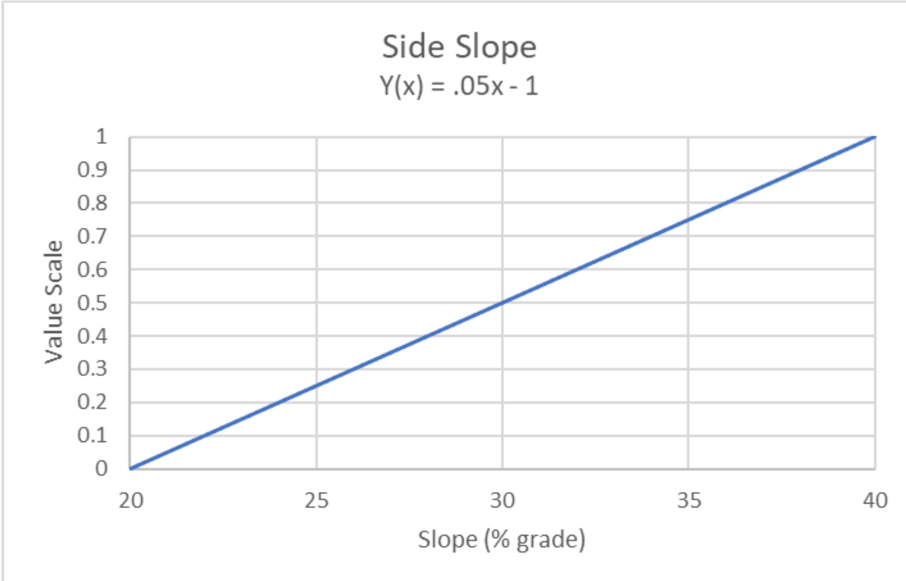


Figure 8. Value Graph of Side Slope

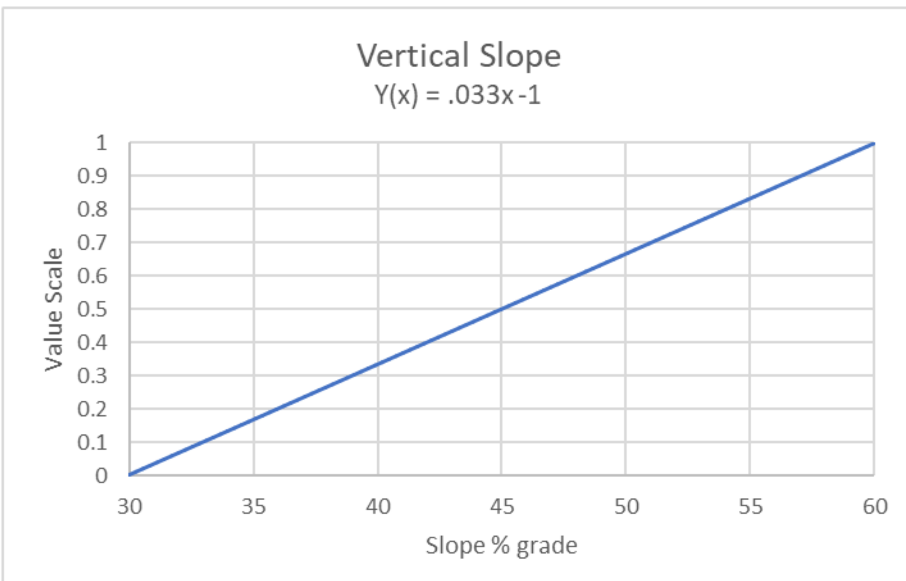


Figure 9. Value Graph of Vertical Slope

d. Clearance

The ground clearance of a vehicle is directly related to the range of mobility in off-road conditions that it may traverse. Ground clearance is measured from the surface on which all the vehicles tires/tracks sit flat to the lowest point on the hull for tracked vehicles or the lowest point of the vehicle on wheeled vehicles (Jane's by IHS Markit, 2018d). The ground clearance range is from 9 inches to 19 inches, as shown in Figure 10. The midvalue is 16 inches, equal to two of the three combat vehicles.

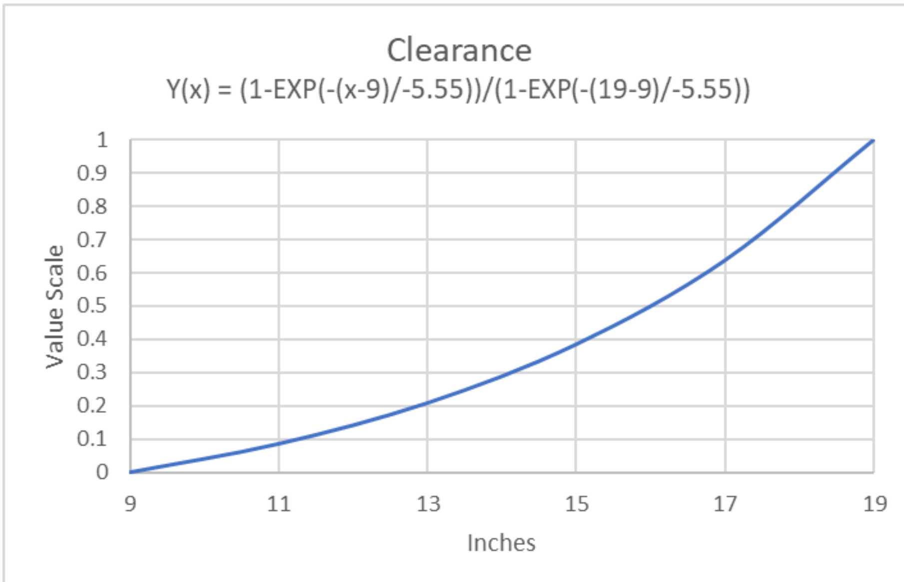


Figure 10. Value Graph of Ground Clearance

2. Transportability

Transportability is a necessary ends objective because the tactical employment of the vehicles occurs all across the world and there is often a time constraint associated with the mission. Because the vehicles cannot always drive themselves either because of water obstacles or due to temporal requirements, movement of the vehicles by other means is required. Other means in the case of tactical vehicles is through the air or over the sea. The vehicles' capacity for being moved by these other means directly impacts its efficacy in supporting missions in the various environments against the expected enemies.

a. Amphibious Shipping Stowage

The MOC has reaffirmed the principle of maneuver warfare as the Marine Corps' concept of employment. It has further identified that maneuver warfare includes using the sea as maneuver space and the integration of the Marine Corps into Navy shipping is critical (Neller, 2016). There are three types of amphibious ships that transport Marine equipment: the LPD, LHA, and LHD. Each ship has a vehicle hold that is limited in height or access and each has multiple decks of vehicle holds. Amphibious stowage is evaluated using a standard MEU/ARG that consists of an LHA, LPD, and an LHD with the attribute scale as a percentage of stowage space that is accessible and usable by the vehicle. Figure 11 shows the relevant range is 50% of the stowage space up to 100% of the stowage space must be accessible and usable by the vehicle. The mid-point value is set a 66.67% to represent 2 out of 3 of the ships capable of stowing the vehicle.

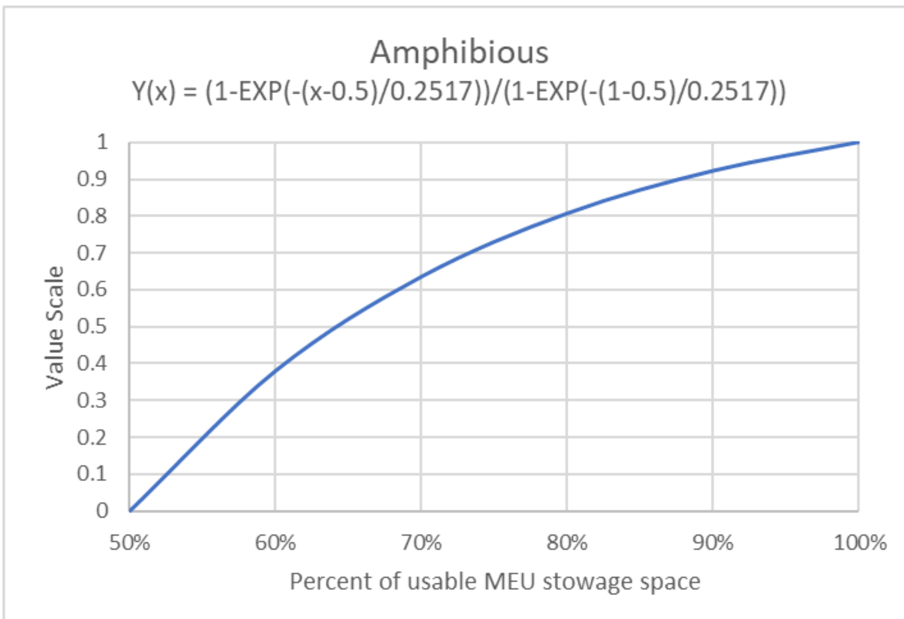


Figure 11. Value Graph of Usable Amphibious Stowage

b. Landing Craft Throughput

Part of using the sea as maneuver space is getting the force ashore. Across the surface, this is done via landing craft. Two landing craft that are used to accomplish this are the Landing Craft Air Cushioned (LCAC) and the Landing Craft Utility (LCU). A standard MEU/ARG contains five LCACs and two LCU landing craft. These landing craft move at significantly different speeds when delivering cargo. Throughput calculations will be completed using Equation 4. The number of landing craft (I_i) are multiplied by the number of vehicles of the given type it can transport (X_i) multiplied by the number deliveries the craft can make (T_i) from 25 miles offshore within a 6-hour period. The measure is reported in the number of companies delivered in 6-hours with 30 vehicles representing a completely motorized company, as shown in Figure 12.

$$Throughput = T_a I_a X_a + T_u I_u X_u \quad (4)$$

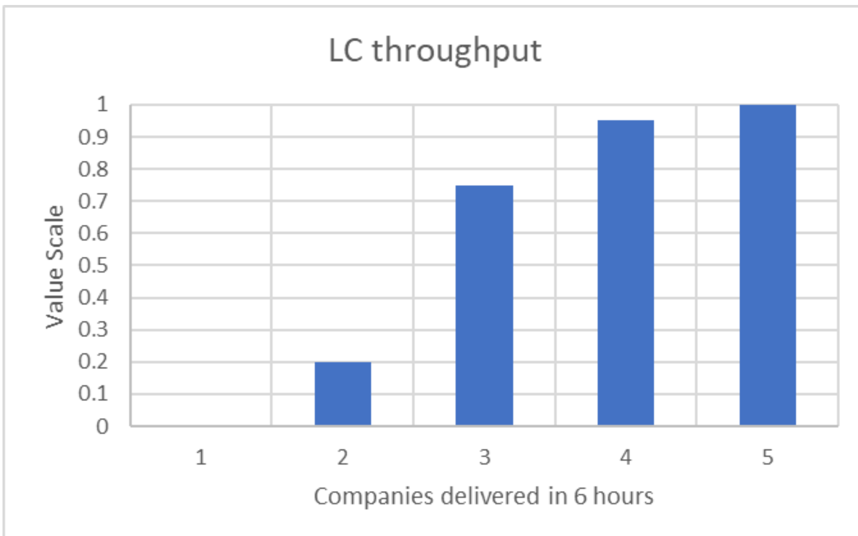


Figure 12. Value Graph of Landing Craft Throughput

c. *Fixed-wing Airlift*

Movement of vehicles and forces worldwide is sometimes required faster than shipping can support or movement from one land-based location to another with no need to move across the water. An alternative is movement by aircraft where the options are the Marine Corps operated C-130 or the Air Force operated C-17 cargo plane. The measurement scale is how many vehicles may be transported in each aircraft as shown in Figure 13 and Figure 14. These values are necessarily step-wise along the number of vehicles within the relevant range.

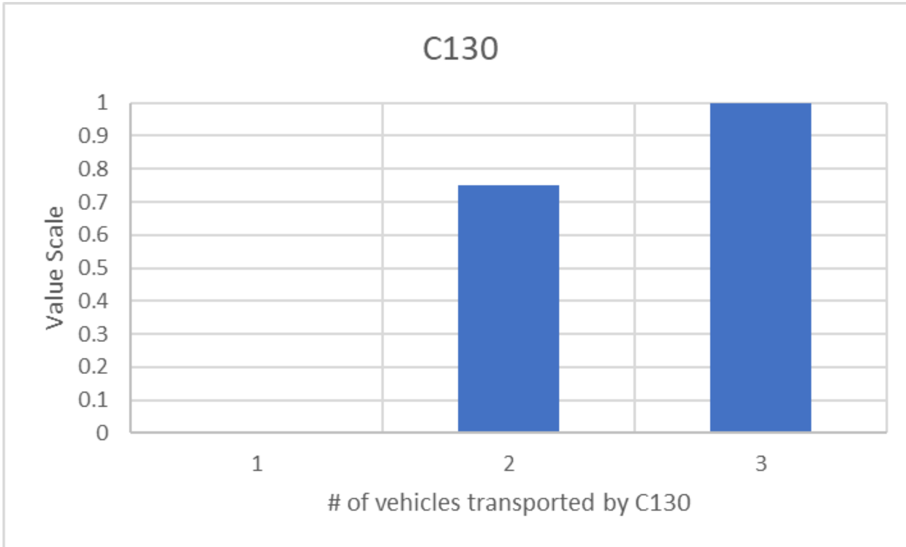


Figure 13. Value Graph of C130 Compatibility

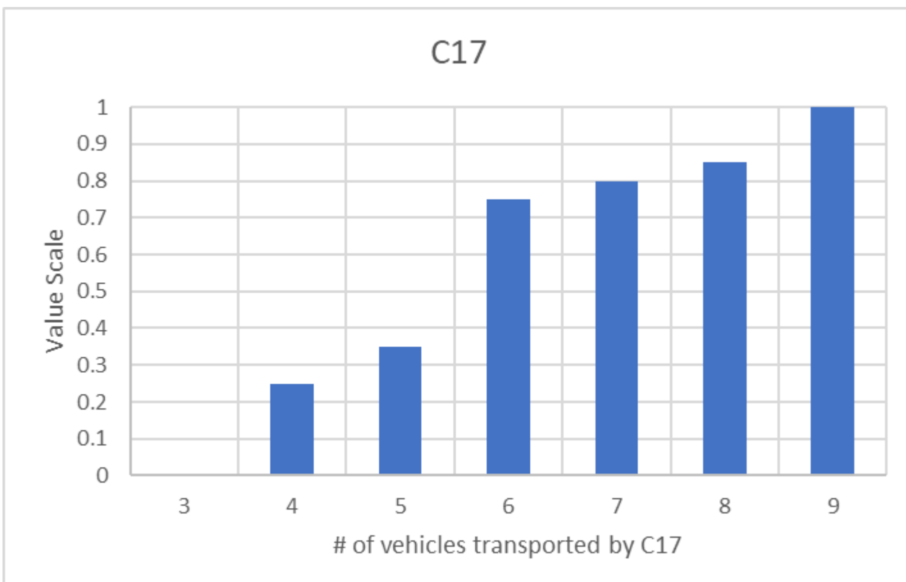


Figure 14. Value Graph of C17 Compatibility

d. Rotary-wing Air Lift

Rotary wing options are both Marine operated CH-53 heavy lift helicopter or the tilt rotor MV-22 Osprey. Resupply and recovery operations are often carried out by helicopters and that includes movement of vehicles. Each vehicle is assigned a binary value depending on its ability to be transported by a CH-53E Sea Stallion or the MV-22 Osprey.

3. Protection

The internationally accepted standard for armored vehicle protection levels is STANAG 4569. This internationally recognized and accepted standard also provides detailed instructions as to how to conduct the testing and under what environmental conditions (NATO, 2012). To protect trade secrets and classified military capabilities minimum average protection levels were used and compared to desired threshold protection level using information gained through open sources and public knowledge. All attributes of protection are assigned step-wise values coinciding with the appropriate STANAG level within the relevant range as shown in Figure 15.

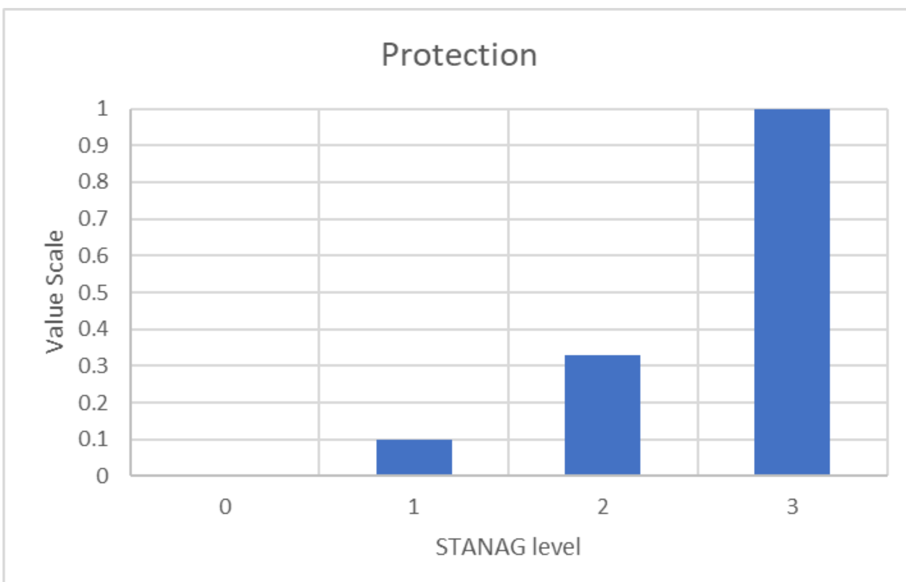


Figure 15. Value Graph of Protection Level

a. Direct Fire

Protection against direct fire weapons is measured by the caliber of the projectile at a specified distance to the target vehicle. These protection levels range from small caliber pistol ammunition to large caliber automatic cannons. The direct-fire category measures the vehicle's ability to withstand penetration at single point of impact. The objective level for direct fire weapons is STANAG K3.[2]

b. Indirect Fire

Protection against indirect fire weapons is measured by the caliber of the projectile and the proximity to the burst. This protection is required to hold from all angles except from below the vehicle and measures the resistance to both blast pressure and the kinetic energy of irregularly-shaped fragments from the projectiles casing. The protection from below the vehicle is measured via a separate scale. The objective level for indirect fire is STANAG K3.[3]

c. Mine/IED

Protection against Mine/IED strikes is measured by the explosive mass and the location of the blast with respect to the centerline of the vehicle. This category measures the resistance to blast pressure from below the chassis. The STANAG scale separates each explosive mass category into underbelly shots and shots initiated under any wheel or track location. The objective level for mine blasts is STANAG M3a/3b.[4]

d. Reactive Armor

Reactive armor are panels along the vehicle in which there is some reactive technology installed to counter rocket propelled grenades and other explosively formed penetrating rounds. The value is binary with one being assigned if the vehicle employs any reactive armor, zero otherwise.

[2] STANAG K3 for direct fire weapons requires minimum protection against 7.62mm armor -piercing rounds from machine gun and sniper rifles at a range of 30 meters from all angles.

[3] STANAG K3 for indirect fire weapons requires minimum protection against a 155mm artillery burst from 60 meters at up to 30 degrees elevation around the entire vehicle.

[4] STANAG M3a/3b requires minimum protection against mine explosions under any wheel or underbelly attacks from an 8kg blast AT mine.

e. Fire Suppression

Fire can be the cause of casualties in vehicles of all types. To account for the protection of service members from vehicle fires, a fire suppression system is included in the force protection evaluation criteria. The threshold is binary with one being assigned if the vehicle contains a suppression system, zero otherwise.

C. OBJECTIVE AND ATTRIBUTE WEIGHTS

Weights assigned to the ends objectives are determined using specific environmental characteristics and the expected enemy to develop the preferences illustrated in Table 4. The weights listed were generated using swing weighting and multilinear functions.

Table 4. Baseline Weighting of MOE Criteria per Region

	Mobility	Transportability	Protection
Indo-Pac	0.19	0.5	0.31
Europe	0.5	0.33	0.17
Mid East	0.3	0.1	0.6

Weighting of the attributes represents the desirability of those attributes in line with the priorities of the decision-makers. For this model, weights were assumed based on doctrinal documents and common tendencies in decision-making. The weights account for the regional characteristics and the enemy's doctrine most likely to be faced in the region.

1. Mobility

Mobility is the second highest weighted objective in the Middle East being assessed as three times as important as a unit difference in transportability, yet only half as important with a unit difference in mobility as a unit difference in protection. While there are road networks in the major cities and high-speed roadways connecting most major cities, the majority of the region is not developed and requires movement over unimproved roads or across open land. A weight of 0.3 was calculated for mobility in the Middle East using the swing weight technique. Europe on the other hand, has a vast road network and the anticipated conflict in the region will require much greater mobility to execute a conventional maneuver warfare strategy. As such, mobility is the highest weighted objective in Europe with a weighting of 0.5. The terrain dictates a severe constriction of mobility in the Indo-Pacific resulting in the smallest weighting for the region at 0.06.

The mean objectives, sea and air, are weighted based on the region's terrain and infrastructure as well as the current level of access and global pre-positioning of forces and equipment. In the Middle East transport by sea is minimally effective because of those countries with coastlines almost half are unfriendly toward the United States limiting access to surrounding countries. Additionally, ground transport across the Middle East is fraught with danger as supply convoys and the like are often harassed or halted due to enemy action or terrain restrictions. Air is therefore a more desirable mode of transport and is weighted 3:1 for the region. Europe does not pose the same level of risk via sea transport with the majority of European nations friendly to the United States with a mature road network infrastructure to support transport by the sea. As such, sea and air are closely weighted with a slight edge given to sea at a ratio of 5:4 due to the volume possible through transport by sea. The Indo-Pacific region requires the use of sea transport at an even greater rate than Europe. More than 80% of the countries in the region including the two expected threat nations have coastline access. And among these countries, the road network, while not as robust as Europe, is still effective enough to support movement from coastal cities inland; thus, the weighting ratio is 2:1.

The weights of the on-road and off-road objectives was supported by the calculated road density of each region in contrast to the published Marine Corps mission profile by Walsh (2017) in the MOC of 70% of missions occurring off-road and 30% on-road. Road density is calculated as the total amount of road network in kilometers divided by the total area of the region. The calculation results in a measure of kilometers per square kilometer. These measures were collected from the CIA World Fact Book website (CIA, 2018). The weights are limited to 90% in either direction because regardless of availability of road networks a small percentage of operating time will always be needed in both settings. In Europe, the road density is 1.36 km/km^2 so a weight of 0.9 will be assigned to on-road.

The Middle East has a density of 0.18 km/km^2 so a corresponding weight of 0.18 will be assigned. The Indo-Pacific region has a calculated road density of 0.66 km/km^2 resulting in a weight of 0.66. For each region, the off-road weight is 1 minus the on-road weight.

2. Transportability

Transportability objective is weighted relatively low in the Middle East with a weight of 0.19. In the Middle East, most conflicts will be supplied by overland supply routes or commercial movement of equipment as has been seen during the conflicts in Iraq, Syria and Afghanistan. Transportability in Europe is weighted 0.31 because when employing maneuver warfare on a large scale, movement of forces in relation to the enemy is required, and as was seen in World War II the sea can be a very effective maneuver space. Since Europe is surrounded by the Mediterranean Sea, Atlantic Ocean and the North Sea, transportability is weighted over force protection. For a very similar reason transportability in the Indo-Pacific is the highest weighted objective in the region at 0.5.

3. Protection

Protection in the Middle East region is the highest weighted objective of the three ends-objectives. Underbelly strikes from Mines and IEDs as well as direct fire attacks from RPG and medium machine guns pose the greatest threat to mission accomplishment. This extreme threat is reflected in the 0.6 weighting. Conversely, in Europe protection is valued lowest at 0.17, not because it is unimportant, but because it is not a requirement to execute the expected tactical employment strategy. Protection in the Indo-Pacific is linked with mobility. A large majority of the areas in which potential conflict may arise is constricted with respect to off-road travel. Because the vehicles are restricted to roads, this produces a target rich environment for the use of mines and ambushes necessitating the weighting of protection as the second highest objective in the Indo-Pacific region with a weight of 0.31.

V. RESULTS

A. BASELINE SCENARIO

The input values represented in Table 5 were evaluated using the multi-criteria model in Figure 5 as described in Chapter IV. Each vehicle's input values were applied to all three regions resulting in nine MOEs shown in Table 6.

Table 5. Vehicle Input Data. Adapted from Jane's by IHS Markit (2018c, 2018d, 2018g).

Mobility

	Speed (MPH)	Range (miles)	Vert Slope (% grade)	Horz Slope (% grade)	Clearance (inches)
HMMWV	45	250	60	40	15.5
MATV	65	320	60	30	16
JLTV	70	350	60	40	18

Transportability

	Land Craft (Company throughput)	Amphibious (% MEU)	C130 (# per A/C)	C17 (# per A/C)	Lift by CH-53 (Y/N)	Lift by MV-22 (Y/N)
HMMWV	6.524	100%	3	10	Yes	Yes
MATV	2.304	67%	2	4	Yes	Yes
JLTV	4.453	100%	2	8	Yes	Yes

Protection

	Direct Fire (STANAG)	Indirect Fire (STANAG)	Mine/IED (STANAG)	Reactive armor (Y/N)	Fire suppression (Y/N)
HMMWV	3	2	1	Yes	No
MATV	3	3	3	No	Yes
JLTV	3	3	3	Yes	Yes

Figure 16 illustrates the weighted contributions of each of the 16 attributes to each vehicle in each region and can be compared to the perfect score noted in the column marked "Base."

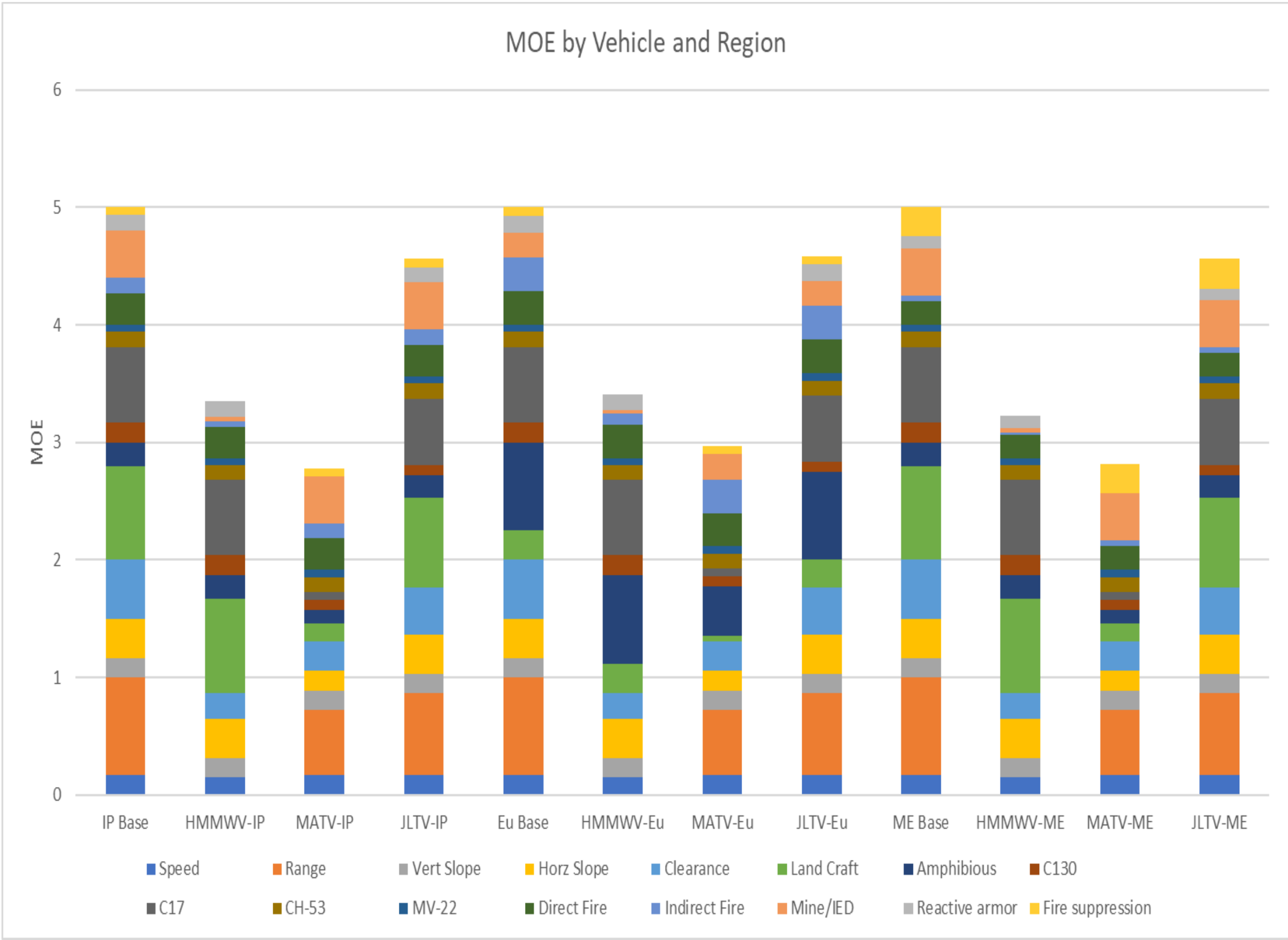


Figure 16. MOE Broken Down by Attribute Contributionsfor Base Scenarios by Vehicle and Region

The attribute values in Table 5 were then applied to the means and ends-objective weighting resulting in the MOEs in Table 6. The MOEs are color coded to display the rankings within each region with green being the most effective vehicle while red is the least for that region. The scores were generated independently of other vehicles in the region and independent of the same vehicles' score in other regions as can be seen by the separate tables and charts in Appendix B and Appendix C. The JLTV is the most effective vehicle for all regions with a high MOE of 0.95 and a low of 0.77. The result is not unexpected as the criteria that shaped this model were derived from the MOC which was published well after the HMMWV and MRAP were fielded. Yet, the JLTV's were still being crafted and adjusted to the service needs. Newer equipment, including vehicles, are expected to perform better than the previous models.

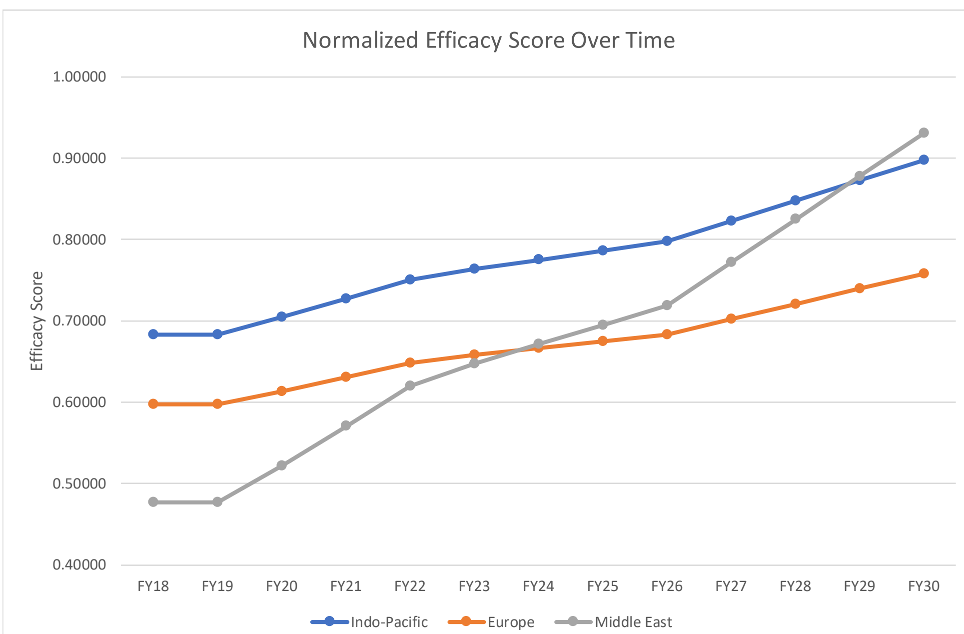
Table 6. Baseline MOEs

	Indo-Pacific	Europe	Middle East
HMMWV	0.714	0.525	0.499
MATV	0.544	0.558	0.755
JLTV	0.936	0.771	0.950

Beyond which vehicle is the best or worst is a more telling statistic; the range of efficacy across regions is an interesting measure to note. The difference between the most and least effective vehicles in the Indo-Pacific is 0.438 and the Middle East shows a difference of 0.507. However, Europe only shows a difference of 0.179. The disparity can be explained by the weighting of the objectives for each region and how the size of the vehicle and level of armor protection factored in the calculation. In the Indo-Pacific the size of the vehicle was critical in determining transportability as 63% of the MOE. Likewise, in the Middle East the level of protection was 60% of the MOE. In Europe both protection and transportability are muted with both categories combined only impacting 50% of the MOE.

The current vehicle fielding plan was evaluated using the MOEs from Table 6 and multiplying them by the number of vehicles projected to be in the inventory through FY30.

This overall score was then normalized by dividing by the total number of vehicles in the inventory. These normalized regional efficacy scores are located in the table at the bottom of Figure 17. All these calculations were made independently from other years and independently from other regions in the same year. The three regional scores for each fiscal year can then be summed to create a annual efficacy score for that year's projected portfolio mix. The annual efficacy scores can then be summed across time to create the tactical wheeled vehicle strategic efficacy score. This score will show the strategy's effectiveness over time as the inventory levels change as projected. It will also be a useful metric when comparing to other strategies or during sensitivity analysis. The most obvious trend to note is that the overall vehicle efficacy score for all regions increases over time as HMMWVs are reduced and replaced with the more effective JLTV. The graph in Figure 17 provides a clear visual representation of this trend. It shows the annual efficacy scores in the Middle East improve so much comparatively as to move the Middle East region from the least effective region for the vehicle inventory to the most effective.



	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
Indo-Pacific	0.6835	0.6835	0.7046	0.7274	0.7506	0.7636	0.7749	0.7862	0.7975	0.8224	0.8474	0.8724	0.8973
Europe	0.5977	0.5977	0.6136	0.6307	0.6481	0.6578	0.6663	0.6747	0.6832	0.7019	0.7207	0.7394	0.7581
Middle East	0.4774	0.4774	0.5221	0.5705	0.6197	0.6472	0.6711	0.6950	0.7189	0.7719	0.8248	0.8777	0.9306

Figure 17. Normalized Regional Baseline Efficacy Scores with Graph

The normalized scores can also be used to calculate the marginal efficacy of a vehicle for each region. Marginal efficacy can be determined using Equation 5 for each region. The marginal efficacy of the JLTV is .00001254 in Indo-Pacific, .00000940 in Europe, and .00002657 in the Middle East. Conversely, the marginal efficacies for the HMMWV is the negative of those for the JLTV, because the HMMWV inventory is changing in the opposite direction by the same magnitude. The M-ATV does not have a marginal efficacy because the inventory levels do not change in the baseline scenario. These results suggest the JLTV should be applied to the Middle East first because it provides the greatest overall impact to the probability of mission success.

$$(\Delta EfficacyScore) / (\Delta Inventory) \tag{5}$$

Finally, to account for the likelihood that conflict will occur in specific regions, weights for each region were developed using the assessment of security experts. A report by the RAND corporation and an interview with former CIA director John Brennan estimates military conflict with China over the next 20 years as unlikely, but a conflict with North Korea in the next year at 25 – 30% (Dobbins et al., 2011; Woolf, 2017). Conflict with Russia is thought to be considerably higher by experts; George Beebe, Michael Kofman, and Paul Saunders; at the Center for The National Interest (Majumdar, 2018). They place estimates at 50% that conflict with Russia will occur in the near future. John Alterman of the Center for Strategic and International Studies believes there is a 30% chance of conflict with Iran (Hendin, 2018). However, in the Middle East there is currently military conflict involving the use of tactical vehicles in Iraq, Afghanistan, and Syria therefore a 100% chance of tactical use in the region. These estimates can be used to create the ratio of 1:2:4 with the Indo-Pacific being the base case at a 25% chance followed by Europe that is twice as likely at 50% and finally the Middle East is twice as likely again at 100%.

Results of these regional probability weights are shown in Figure 18. The blue line shows the effect of evenly weighted regions. The orange line shows the weighting as estimated by the security experts with the 1:2:4 ratio. This demonstrates that when accounting for probability of conflicts within regions the total growth over time increases.

The weighted efficacy score starts at 54.9% of desired capability compared to the even distribution starting at 60.4% with the weighted scenario ending at 87.6% while the even distribution ends at 86.1%. This increase of 32.7 percentage points for the probabilistic scenario is much greater than the 25.7 percentage point increase of the evenly weighted scenario. The additional growth over time is due to weighting more heavily a region for which the JLTV has a higher marginal efficacy.

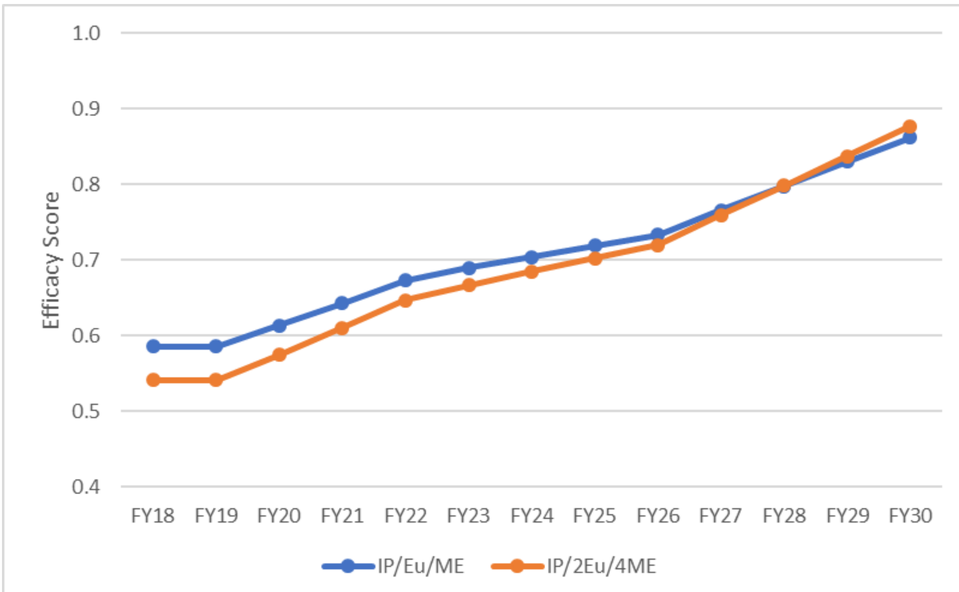


Figure 18. Scenario Weighting Annual Efficacy Scores

B. EXCURSIONS

Chapter V, Section A provides the baseline analysis from which adjustments can be made to some of the subjective inputs to the model. This is useful in showing decision-makers how the model reacts and the direction the outputs move with specific adjustments.

1. Weighting Adjustments

Ends objectives' weighting is among the most subjective inputs of the model. The weights and their justification for their values were explained in Chapter III, Section C. To determine how sensitive the model is to changes in these parameters the values were moved to a more equal weighting while preserving the ordering from most valued (highest weight) to least valued (lowest weight), followed by more extreme weightings, still preserving the order. The results can be found in Appendix D. The model outputs of regional vehicle efficacy scores will be compared with these baseline scores located in Table 6. Additionally, the total efficacy will be evaluated after each adjustment to see whether the changes carry through to the final output.

To begin the analysis, all weights in Table 4 will be centralized by adjusting toward the equal weight of 0.33 by 50% as shown in Table 7. In the case of transportability in Indo-Pacific, the current weight is 0.5 so 50% of the difference to 0.33 is 0.085. Therefore, the new weight of transportability will be 0.5 minus 0.085 to bring the weight closer to 0.33 for a new weight of 0.415. This method allows evaluation of the portfolio with a much more conservative estimate of relative importance of the ends objectives yet maintains the relative ranking of the value of the ends objectives.

Table 7. Centralized Weighting

	Mobility	Transportability	Protection
Indo-Pac	0.26	0.415	0.32
Europe	0.415	0.33	0.25
Mid East	0.315	0.215	0.465

After constructing the centralized weighting scale an extremized weighting scale will be developed to observe the model if more exaggerated weights are used. The weights in Table 4 will be adjusted, only this time it will be adjusted out toward the end points of the measurement scale. All numbers below 0.33 will be moved by 50% toward zero, while all weights above 0.33 will be moved toward one by 50%, resulting in the extremized weights in Table 8.

Table 8. Extremized Weighting

	Mobility	Transportability	Protection
Indo-Pac	0.095	0.75	0.155
Europe	0.585	0.33	0.085
Mid East	0.15	0.05	0.8

With the new weighting, the model was run again for each set of weights and generated Table 9 and Table 10. In each table, an additional column has been added next to each region. This column labeled "Δbase" shows both the direction and magnitude of change from the original weighting scenario.

Table 9. Efficacy Scores Using Centralized Weights

	Indo-Pacific	Δbase	Europe	Δbase	Middle East	Δbase
HMMWV	0.6570	-0.0566	0.5511	0.0261	0.5752	0.0761
MATV	0.5751	0.0309	0.5669	0.0085	0.6793	-0.0753
JLTV	0.9290	-0.0068	0.7768	0.0063	0.9223	-0.0277

Table 10. Efficacy Scores Using Extremized Weights

	Indo-Pacific	Δbase	Europe	Δbase	Middle East	Δbase
HMMWV	0.8568	0.1432	0.4961	-0.0288	0.4278	-0.0713
MATV	0.4193	-0.1249	0.5455	-0.0128	0.8273	0.0727
JLTV	0.9273	-0.0085	0.7592	-0.0113	0.9750	0.0250

The results for the weighting adjustments were as expected. The extremized weights created a larger spread of efficacy scores across a region while centralizing the weights brought the regional efficacy scores closer. Because the relative position of the weights did not change, the ranking of vehicles across regions did not change. This can be accounted for in the magnification of the positive and negative attributes of a vehicle canceling the other in a similar manner across all vehicles and regions.

A more unexpected result was the strategic efficacy scores for each adjustment. When summing all the baseline scenario annual efficacy scores across time the resulting strategic efficacy score is 27.5 as seen in Table 11. Yet when adjusted towards more centralized weighting the score increased by only 0.1 to 27.6 and when adjusted outward toward more extremized weighting the score only moved 0.22 to 27.7, in each case preserving the baseline assumption of equal probability by region. These are fairly insignificant changes over 12 fiscal years. These results suggest that weights themselves don't matter nearly as much as the relative relationship between them.

Table 11. Annual Efficacy Scores by Weighting Adjustment with Strategic Efficacy Score

Annual Efficacy Scores

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	Strategic Efficacy Score
Baseline	1.750	1.750	1.831	1.919	2.008	2.058	2.102	2.145	2.188	2.284	2.380	2.476	2.572	27.47
Centralized	1.787	1.787	1.862	1.943	2.025	2.071	2.110	2.150	2.190	2.278	2.367	2.455	2.543	27.57
Extremized	1.782	1.782	1.860	1.944	2.029	2.077	2.119	2.160	2.202	2.294	2.386	2.478	2.570	27.68
Randomized	1.877	1.877	1.941	2.011	2.081	2.121	2.155	2.190	2.224	2.300	2.376	2.452	2.528	28.13

To confirm that relative position among weights is more significant than the weights themselves, nine random numbers between 0 and 1 were generated and used as the weights as shown in Table 12. The strategic efficacy score using these random numbers was calculated as 28.1. The relative position of the weights among the vehicles and regions were significantly different than those of the baseline scenario. Starting with a random number baseline efficacy score of 28.1 the weights were centralized, and the efficacy score was recalculated at 27.9. The weights were adjusted outward toward the extremes resulting in an efficacy score of 27.9, with a calculated difference of 0.04 not representing a meaningful difference in this model. Nearly all calculated differences of these treatments occurred at the hundredths or thousandths position very similar to the differences noted in Table 9 and Table 10. The fact that regardless of what weights are assigned the strategic efficacy score remains very similar as long as the relative position of the the regional weights remains constant. Sampling more than two dozen random weighting scenarios that created a variety of relative weighting positions resulted in a spread of efficacy scores as low as 25 and as high as 31.

The consistency of the scores following the weighting treatments and the variety of scores following the relative position adjustments suggests that decision-makers and analysts should be much more concerned with the relative position of the ends objective weights within the regions than with the actual weights themselves.

Table 12. Randomly Generated Weights.

	Mobility	Transportability	Protection
Indo-Pac	0.484	0.050	0.466
Europe	0.025	0.414	0.561
Mid East	0.601	0.315	0.084

2. Policy Adjustments

Observing the marginal efficacy of the JLTV and the baseline MOEs in Table 6, a proposed policy change is to remove HMMWVs from tactical mission support in the Middle East. Additionally, replacing M-ATVs with the first JLTVs is part of the scenario analysis. Replacing M-ATVs seems counterintuitive; however, given the efficacy of the JLTV in the Middle East, this is where the greatest potential impact to the vehicle portfolio occurs after removing HMMWVs from the Middle East.

To begin this scenario analysis, the strategic efficacy score will be recalculated with each individual policy change and then again with all policy changes. It will be examined in its raw form and will not be discounted for regional conflict likelihood. Using this step approach will help to determine how the proposed policy change will impact the efficacy score at each step and finally with full implementation. The results of these changes are documented in Appendix E. Scenario Analysis Charts and a summary found in Figure 19.

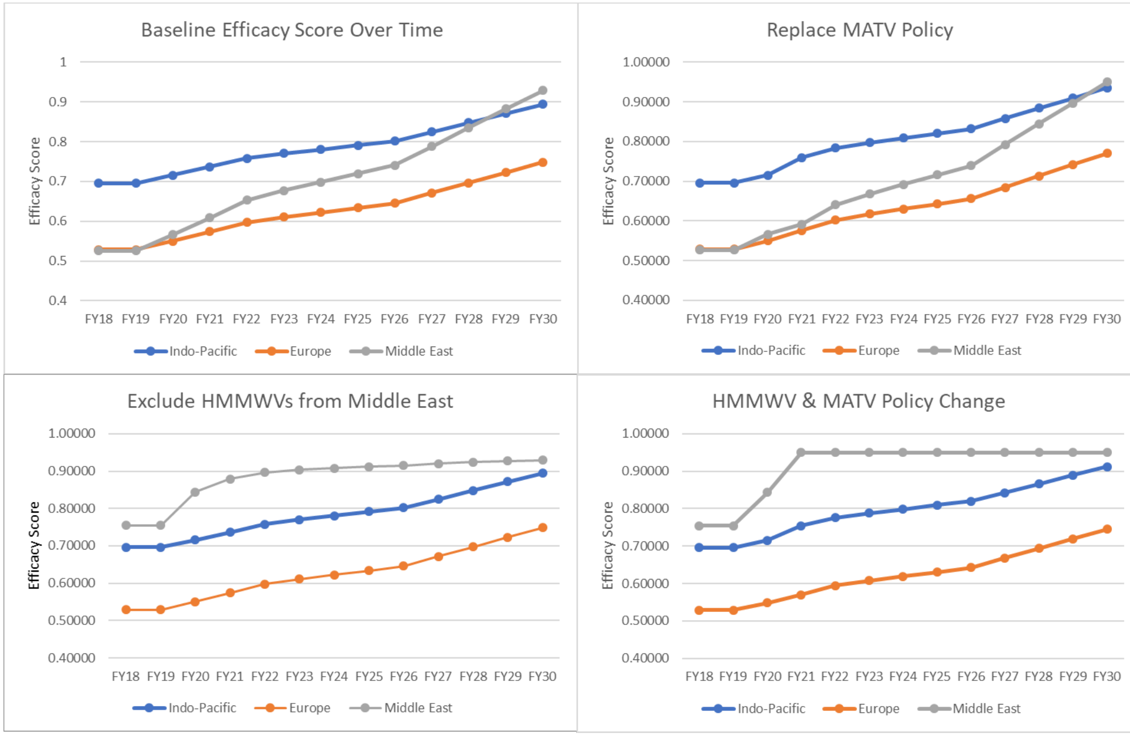


Figure 19. Efficacy Scores of Scenario Analysis

The first policy adjustment is to replace all M-ATVs with the JLTV when enough have been delivered for complete replacement. Because the JLTV and M-ATV are very similar in capabilities, maintaining two systems is not cost-effective in a resource-constrained environment. An optimization tool was used to identify at which point M-ATVs should be removed from the inventory. For the optimization the M-ATV inventory levels were set as the decision variables with the strategic efficacy score as the objective function to be maximized. Unconstrained, the optimal point was immediately; however, this would not be a feasible solution so that point in time was adjusted to the second year of fielding of JLTVs at which time there were enough JLTVs to replace the 2,007 M-ATVs. This resulted in a slightly lower efficacy score by 0.3 points over the 12-year fielding period. The result is the graph in the upper right quadrant of Figure 19. The change results in a total efficacy score of 27.8; an increase of 0.279 over the baseline scenario during the relevant range of FY18 through FY30. This is not a significant increase and the overall shape of the graph remains similar to the baseline evaluation. However, the fact that the adjustment does result in a positive change, regardless of magnitude, suggests that if a cost savings can be realized this policy change should be adopted. This policy change does result in a reduced inventory capacity by the 2,007 M-ATVs that are removed and this inventory shortage will be addressed in adjustment three of this scenario analysis.

The second adjustment to be made is a strategic employment decision based on the efficacy of HMMWVs in the Middle East. The HMMWV efficacy score of 0.49 is the lowest among all the scores generated and as such is lowering the total portfolio efficacy score. Additionally, protection is the highest weighted objective in the Middle East region and HMMWVs only provide one-third of the desired protection level with an efficacy score of 0.21 out of a possible 0.6. Therefore, HMMWVs were removed from the calculations for the Middle East representing a policy of not employing HMMWVs as tactical vehicles in the region. The result of this adjustment is shown in the lower left quadrant of Figure 19. There is a significant change in the Middle East trend line in both starting position and shape. This policy change shifts the starting efficacy score of the Middle East from 0.526 up to 0.754. From this new starting position in FY18 the trend line then begins increasing and approaches 0.93 by FY30. Over the relevant range this policy change increases the total strategic efficacy score to 29.8; a total increase of 2.176 points.

The final adjustment made for the scenario analysis is to combine these policies. Additionally, to account for the loss of inventory capacity after removing M-ATVs, HMMWVs were increased by the number of M-ATVs removed to maintain the total vehicle inventory at 19,063. There exists a one-for-one exchange because the M-ATVs and HMMWVs have the same passenger capacity for tactical missions. In execution this would be accomplished by delaying the disposal of 2,007 HMMWVs across the sunset plan through FY30. The results are shown in the lower right quadrant of Figure 19. The Middle East trendline displays a similar shape as that of the change to HMMWV employment policy with one exception; the line accelerates much faster and reaches 0.95, the regional efficacy of the JLTV, by FY21. The overall efficacy total of 30.4 increased from the baseline by 2.792. This increase is greater than the sum of the two separate policies suggesting a positive correlation between the two policy changes.

VI. CONCLUSION AND RECOMMENDATIONS

A. OVERVIEW

This thesis examines the Marine Corps' tactical wheeled vehicle portfolio in the context of the future threat environment. Vehicles within this portfolio have received criticism and there has been much controversy surrounding the continued use of some of the vehicles.

The portfolio was evaluated using a multi-criteria effectiveness model that generated a comparable metric. The model is designed to be flexible and allow decision-makers to apply the most current threat assessment and risk acceptance levels. These inputs can be used to evaluate current strategic policy decisions or forecast the effects of future decisions.

B. RESEARCH QUESTIONS ANSWERED

1. Primary Research Question

- *Given the current Ground Combat Tactical Vehicle Strategy and the Marine Operating Concept, what is the proper portfolio mix to be most effective in the anticipated threat environment?*

To answer this question a multi-criteria decision model was developed and input data gathered from Jane's by IHS Markit was used to calculate MOEs for each vehicle across the three main areas of strategic concern. The ideal portfolio mix would be a 100% JLTV inventory. However, given the constraints of vehicle availability Table 13 shows the identified inventory numbers that provide the greatest efficacy in the future threat environment.

Table 13. Recommended Vehicle Inventory Levels

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
HMMWV	17056	17056	17056	15558	13708	12672	11772	10872	9972	7981	5990	3999	2007
MATV	2007	2007	2007	0	0	0	0	0	0	0	0	0	0
JLTV	0	0	1685	3505	5355	6391	7291	8191	9091	11082	13073	15064	17056

2. Secondary Research Question

- *Is there a point in time at which the M-ATV or HMMWV will no longer be required as a tactical vehicle? If so, when?*

Table 13 displays the inventory levels of all three tactical wheeled vehicles across time through FY30. With the implementation of a strategic employment policy of not using HMMWVs for tactical missions in the Middle East, the tactical wheeled vehicle portfolio achieves the greatest efficacy by divesting from the M-ATVs in FY21 and following the current fielding and sunset plans for the JLTV and HMMWV respectively.

C. OTHER ISSUES

The largest obstacle to this thesis was the obtainment of official data. Because the model includes protection capabilities only open source material were used to estimate the levels of protection afforded by each vehicle.

The objectives have been documented throughout the thesis and where possible factual objective measures were used to develop the objectives weighting in the model. However, some weights were required to be estimated using prior knowledge and experience as well as inferring from the source documents these values even though they were not explicitly stated. Only the actual decision-makers responsible for the Marine Corps' tactical wheeled vehicle fleet can accurately assess the true weights.

D. RECOMMENDATIONS

The model evaluated the current plan and two policy changes which produced nearly a 10% increase in efficacy through FY30. This significant improvement in the use of the limited vehicle fleet leads to two recommendations:

1. HMMWV Exclusion

The HMMWV has long been bemoaned as underequipped for use in the Middle East. Local commanders have made decisions at the small unit level to not employ HMMWVs "outside the wire." It is recommended that this be adopted by the Marine Corps as a strategic employment constraint and disallow the use of the HMMWV of any variant on a tactical combat mission. This is not to say that HMMWVs should not be in the Middle East as they can conduct any number of missions on airfields and bases. In fact, the more of these non-tactical missions they conduct the more JLTVs and M-ATVs are available for use on the combat missions.

2. M-ATV Divestiture

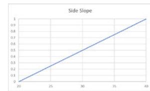
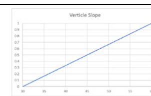
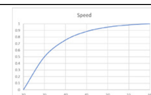
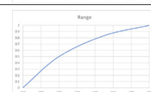
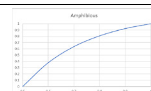
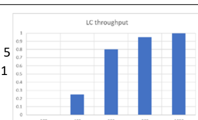
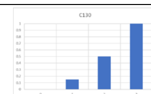
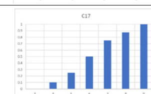
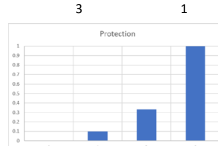
In a resource constrained environment having multiple pieces of equipment to execute the same mission is untenable. The public and Congress have already made their concerns known through news articles and congressional testimonies. The model has shown that the JLTV is far more effective than the M-ATV in every environment. With the knowledge that the mission will not be negatively impacted by the replacement of the M-ATV with the JLTV the only question remaining was when. This was calculated by finding the optimal point in the output analysis when the M-ATV inventory could be reduced to zero while maximizing the efficacy score of the tactical wheeled vehicles. This point was discovered to be in FY21. FY21 should have an authorized inventory of zero M-ATVs, 3,505 JLTVs, and 15,558 HMMWVs.

E. POTENTIAL FOR FUTURE RESEARCH

While this model was able to evaluate efficacy of the vehicle strategy using objective data and some priority assumptions, it did not incorporate cost. Any future implementation of this model should endeavor to add a layer of cost to complete a full cost-effectiveness analysis. With that added constraint decision-makers could better balance the procurement of the expensive optimal solution with that of a sub-optimal less expensive one. As an example, this model could be applied to the numerous classes of unmanned aerial vehicles in which there are multiple models performing nearly the same functions. Likewise, this could be applied to any number of communications, weapon, or defensive systems across the DoD in which there are a set of known mission criteria that can be effectively represented by system capabilities and attributes.

To further this model a layer of vehicle operating costs could be added to determine the cost-effectiveness ratio for the tactical wheeled vehicles. This future research could use the efficacy scores generated from this thesis and the associated operating costs for the tactical wheeled vehicles to rank and prioritize the vehicles employment by region. That solution could then be evaluated against the Marine Corps' financial limitations and responsibilities to confirm or amend the recommendations of this thesis.

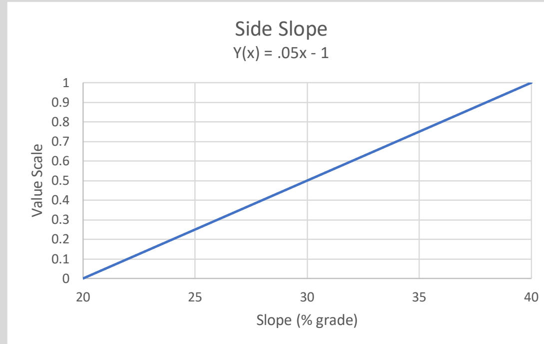
APPENDIX A. MODEL VALUES

Objective		Attribute	How its measured	Critical values	Justification
Mobility	Off-road	side slope	The vehicle's performance will be measured in % slope . It must travel on a dry hard surface perpendicular to a side slope with no degradation in vehicle control	High: 40% Low: 20% ρ: ∞ 	A common specification cited for all tactical vehicles and included as a requirement in critical design reviews. CVs are developed using the minimum and maximum values achieved by the three combat vehicles M1A2 tank, LAV, AAV
		vertical slope	The vehicle's performance will be measured in % slope . It must travel on a dry hard surface perpendicular to a side slope with no degradation in vehicle control	High: 60% Low: 30% ρ: ∞ 	A common specification cited for all tactical vehicles and included as a requirement in critical design reviews. CVs are developed using the minimum and maximum values achieved by the three combat vehicles M1A2 tank, LAV, AAV
		clearance	The distance measured, in inches, from the gound to the lowest point on a vehicles underbelly.	High: 19" Low: 9" ρ: -5.55 	A common specification cited for all tactical vehicles and included as a requirement in critical design reviews. CVs are developed using the minimum and maximum values achieved by the three combat vehicles M1A2 tank, LAV, AAV
	On-road	speed	The maximum speed, in average miles per hour, attainable on a paved road.	High: 60mph Low: 30mph ρ: 7.4 	A common specification cited for all tactical vehicles and included as a requirement in critical design reviews. CVs are developed using the minimum and maximum values achieved by the three combat vehicles M1A2 tank, LAV, AAV
		range	Maximum distance, measured in miles, achieved on a single tank of JP-8 fuel at a sustained speed of 35 mph on a paved road.	High: 400mi Low: 260mi ρ: 70.6 	A common specification cited for all tactical vehicles and included as a requirement in critical design reviews. CVs are developed using the minimum and maximum values achieved by the three combat vehicles M1A2 tank, LAV, AAV
Transportability	Sea	Amphibious ship stowage	The percentage of hold space in an ARG/MEU consisting of an LHD, LHA, LPD that the vehicle can use.	High: 100% Low: 50% ρ: .2517 	The MOC/GCTVS directs the use of the sea as maneuver space and as a way of delivering forces in support of integrating with Naval Forces. (GCTVS pp. 4, MOC pp. 10) ICODES determines the ability to fit in various hold spaces
		Landing Craft throughput	Throughput, reported in the number of companies, is the sum of the total inventory (I) of two landing craft, LCAC (a) and LCU (u), per MEU/ARG multiplied by the trips per unit time (T) and number of vehicles it can hold (X) respectively. Where the trips/time is measured using a 25 mile swim over a 6 hour total period. The formula: Throughput = $T_a I_a X_a + T_u I_u X_u$	High: 5 Low: 1 	The MOC/GCTVS directs the use of the sea as maneuver space and as a way of delivering forces in support of integrating with Naval Forces. (GCTVS pp. 4, MOC pp. 10) ICODES determines the ability to fit in various hold spaces.
	Air	C130 throughput	Vehicle specifications and aircraft capabilities are used to determine the number of vehicles that can be transported per flight	High: 3 Low: 1 	The GCTVS specifies that vehicles must support strategic deployment via transport aircraft (pp. 7)
		C17 throughput	Vehicle specifications and aircraft capabilities are used to determine the number of vehicles that can be transported per flight	High: 9 Low: 3 	The GCTVS specifies that vehicles must support strategic deployment via transport aircraft (pp. 7)
		CH-53	Binary, assign 1 if the vehicle can be transported by the aircraft. Zero otherwise.		GCTVS states all new vehicles need to be transportable by CH-53 or MV-22 (pp. 6-7)
		MV-22	Binary, assign 1 if the vehicle can be transported by the aircraft. Zero otherwise.		GCTVS states all new vehicles need to be transportable by CH-53 or MV-23 (pp. 6-7)
Protection	direct fire		the vehicle must resist penetration by a prescribed round at a calculated angle of attack with a 90% statistical confidence level measured in STANAG levels K 1-6	STANAG Lvl (K or M) / v(x): 0 / 0 1 / .1 2 / .33 3 / 1	AEP-55 Volume 1-5 specify the procedures to test direct fire protection meeting the requirements listed in the NATO STANAG 4569
	indirect fire		the vehicle must resist penetration by a prescribed round at a calculated angle of attack with a 90% statistical confidence level measured in STANAG levels K 1-6		AEP-55 Volume 1-5 specify the procedures to test for indrect fire protection meeting the requirements listed in the NATO STANAG 4569
	mine/IED		The vehicle must resist penetration by a prescribed underbelly attack at a calculated net explosive weight with a 90% statistical confidence level measured in STANAG levels M 1-4		AEP-55 Volume 2 and 3 specify the procedures to test for mine/IED protection meeting the requirements listed in the NATO STANAG 4569
	reactive armor		Binary, assign 1 if the vehicle's armor plan uses reactive armor. Zero otherwise		Reactive armor combats EFP rounds commonly found in armor piercing artillery and RPGs as well as tank rounds.
	fire suppression		Binary, assign 1 if the vehicle has a passive fire suppression system installed. Zero otherwise		A common specification cited for all tactical vehicles and included as a requirement in critical design reviews

Y(x) = .05x - 1

X	Y
20	0
25	0.25
30	0.5
35	0.75
40	1

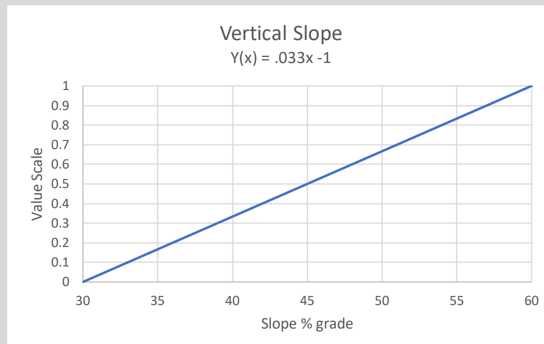
Midvalue equals the mathematical average so values are distributed linearly



Y(x) = .033x -1

X	Y
30	0
35	0.166667
40	0.333333
45	0.5
50	0.666667
55	0.833333
60	1

Midvalue equals the mathematical average so values are distributed linearly

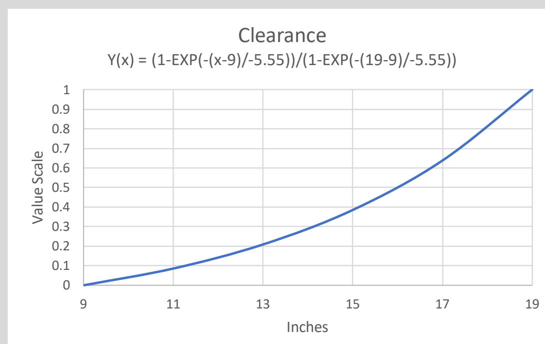


Y(x) = (1-EXP(-(x-9)/-5.55))/(1-EXP(-(19-9)/-5.55))

X	17
midvalue	16
High	19
Low	9
Norm Mvalue	0.7
Rho	-5.55
R	-0.555
Z	
v increasing	0.637634105
v decreasing	-0.433842474

X	Y
9	0
11	0.085731
13	0.208656
15	0.384911
17	0.637634
19	1

Midvalue is equal to two of the three combat vehicles at 16 inches

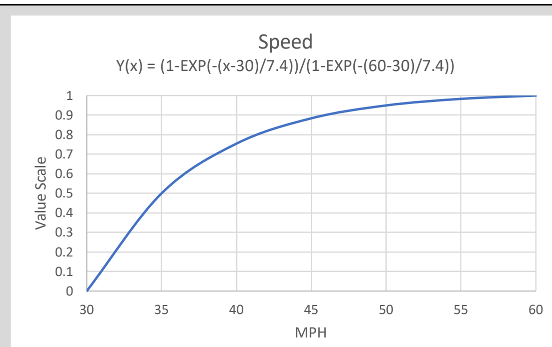


Y(x) = (1-EXP(-(x-30)/7.4))/(1-EXP(-(60-30)/7.4))

X	35
midvalue	35
High	60
Low	30
Norm Mvalue	0.166666667
Rho	7.4
R	0.246666667
v increasing	0.499861019
v decreasing	0.965897288
High R	0.252
Low R	0.236
High z	0.17
Low z	0.16

X	Y
30	0
35	0.5
40	0.7541
45	0.88361
50	0.94945
55	0.98295
60	1

Midvalue is equal to the average speed used in the range evaluation at 35 mph

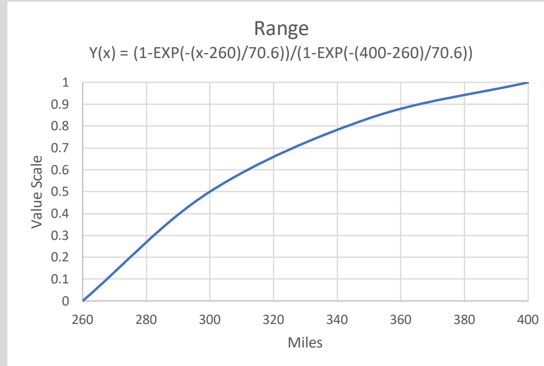


Y(x) = (1-EXP(-(x-260)/70.6))/(1-EXP(-(400-260)/70.6))

X	300
midvalue	300
High	400
Low	260
Norm Mvalue	0.285714286
Rho	70.6
R	0.504285714
Z	
v increasing	0.501577535
v decreasing	0.757421666
High R	0.522
Low R	0.491
High z	0.28
Low z	0.29

X	Y
260	0
300	0.5
350	0.835524
400	1

Midvalue is set at the common planning factor for military operations at 300 miles

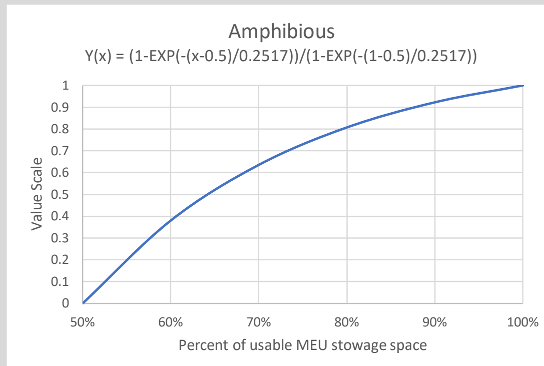


Y(x) = (1-EXP(-(x-0.5)/0.2517))/(1-EXP(-(1-0.5)/0.2517))

X	0.9
midvalue	0.667
High	1
Low	0.5
Norm Mvalue	0.334
Rho	0.2517
R	0.5034
Z	
v increasing	0.922447315
v decreasing	-0.232572942
High R	0.522
Low R	0.491
High z	0.34
Low z	0.33

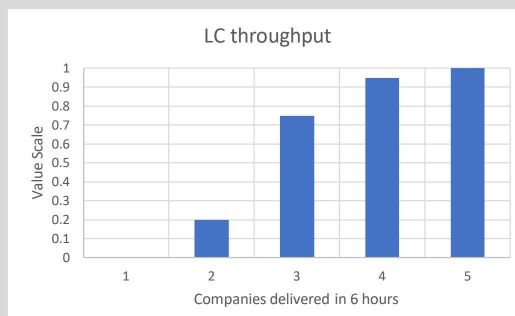
X	Y
0.5	0
0.6	0.379992
0.7	0.635398
0.8	0.807064
0.9	0.922447
1	1

Midvalue is .667 representing 2 out of 3 ships capable of supporting the vehicle



LCAC	**HMMWV**	**MATV**	**JLTV**
Trips	2.875	2.875	2.875
inventory	5	5	5
capacity	12	4	8
LCU			
trips	1.161290323	1.16129	1.16129
inventory	2	2	2
capacity	10	5	8
Throughput	196	69	134
	Total Capacity		
Marines	782.9032258	276.4516	534.3226
Co	6.524193548	2.303763	4.452688
Bn	1.957258065	0.691129	1.335806
Reg	0.55921659	0.197465	0.381659

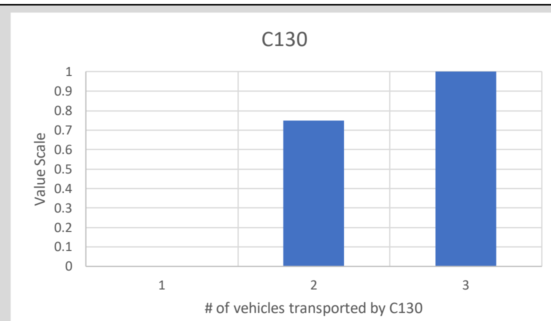
X(Co)	Y
1	0
2	0.2
3	0.75
4	0.95
5	1



3 companies provide 75% of the capability of a 5-company battalion. The last company worth of Marines are non-essential support Marines that provide a small percentage of the battalion's combat capability

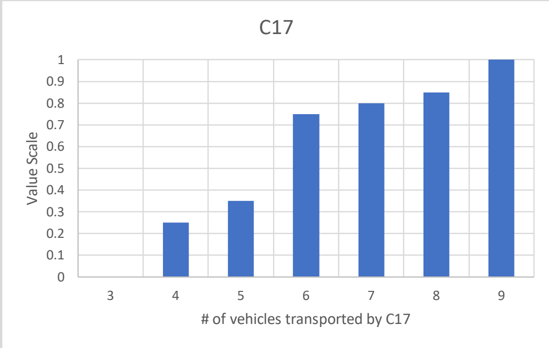
X	Y
1	0
2	0.75
3	1

2 vehicles together provide the bulk of a squad's capabilities while the third can complete a squad and offer more tactical options



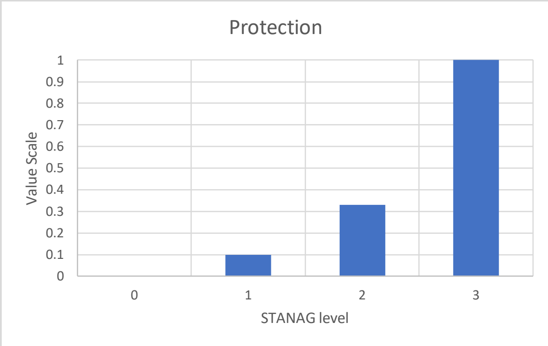
X	Y
3	0
4	0.25
5	0.35
6	0.75
7	0.8
8	0.85
9	1

2 of 3 squads provide the bulk of the platoon's capability and adding the final mounted squad completes the platoon and opens up all tactical options



STANAG Lvl	v(x)
0	0
1	0.1
2	0.33
3	1

Stanag level 3 is the target level of protection.
Each previous level is less desired at a 3:1 ratio



APPENDIX B. BASELINE RESULTS

Attribute Data - HMMWV

Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
45	250	60	40	15.5	6.5241935	1	3	10	Yes	Yes	3	2	1	Yes	No

Indo-Pacific

	Mobility					**Transportability**						**Protection**				
	0.19					0.5						0.31				
	On-road	**Off-road**				**Sea**		**Air**								
	0.67	0.33				0.67		0.33								
	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
Weights	0.17	0.833	0.167	0.334	0.499	0.8	0.2	0.17	0.64	0.13	0.06	0.27	0.13	0.40	0.13	0.07
Attribute values	0.88	0	1	1	0.43983	1	1	1	1	1	1	1	0.33	0.1	1	0
	0.15	0	0.167	0.334	0.21947	0.8	0.2	0.17	0.64	0.13	0.06	0.266	0.04389	0.04	0.133	0

Effectiveness	Mobility	Transportability	Protection
0.7137	0.0640	0.5000	0.1497

Europe

	Mobility					**Transportability**						**Protection**				
	0.5					0.33						0.17				
	On-road	**Off-road**				**Sea**		**Air**								
	0.9	0.1				0.55		0.45								
	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
Weights	0.17	0.833	0.167	0.334	0.499	0.25	0.75	0.17	0.64	0.13	0.06	0.29	0.29	0.21	0.14	0.07
Attribute values	0.88	0	1	1	0.43983	1	1	1	1	1	1	1	0.33	0.1	1	0
	0.15	0	0.167	0.334	0.21947	0.25	0.75	0.17	0.64	0.13	0.06	0.2857	0.094281	0.02142	0.1428	0

Effectiveness	Mobility	Transportability	Protection
0.5249	0.1024	0.3300	0.0925

Middle East

	Mobility					**Transportability**						**Protection**				
	0.3					0.1						0.6				
	On-road	**Off-road**				**Sea**		**Air**								
	0.18	0.82				0.25		0.75								
	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
Weights	0.17	0.833	0.167	0.334	0.499	0.8	0.2	0.17	0.64	0.13	0.06	0.2	0.05	0.4	0.1	0.25
Attribute values	0.88	0	1	1	0.43983	1	1	1	1	1	1	1	0.33	0.1	1	0
	0.15	0	0.167	0.334	0.21947	0.8	0.2	0.17	0.64	0.13	0.06	0.2	0.0165	0.04	0.1	0

Effectiveness	Mobility	Transportability	Protection
0.4991	0.1852	0.1000	0.2139

Attribute Data - MATV

Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
65	320	60	30	16	2.3037634	0.667	2	4	Yes	Yes	3	3	3	No	Yes

Indo-Pacific

	Mobility					Transportability							Protection				
	0.19					0.5							0.31				
	On-road		Off-road			Sea		Air									
	0.67		0.33			0.67		0.33									
	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
Weights	0.17	0.833	0.167	0.334	0.499	0.8	0.2	0.17	0.64	0.13	0.06	0.27	0.13	0.40	0.13	0.07
Attribute values	1	0.664	1	0.5	0.49992	0.2	0.5620478	0.5	0.1	1	1	1	1	1	0	1
	0.17	0.553	0.167	0.167	0.24946	0.16	0.1124096	0.09	0.06	0.13	0.06	0.266	0.133	0.4	0	0.068
	Mobility					Transportability							Protection				
	0.1282					0.1472							0.2688				

Effectiveness
0.5442

Europe

	Mobility					Transportability							Protection				
	0.5					0.33							0.17				
	On-road		Off-road			Sea		Air									
	0.9		0.1			0.55		0.45									
	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
Weights	0.17	0.833	0.167	0.334	0.499	0.25	0.75	0.17	0.64	0.13	0.06	0.29	0.29	0.21	0.14	0.07
Attribute values	1	0.664	1	0.5	0.49992	0.2	0.5620478	0.5	0.1	1	1	1	1	1	0	1
	0.17	0.553	0.167	0.167	0.24946	0.05	0.4215359	0.09	0.06	0.13	0.06	0.2857	0.2857	0.2142	0	0.0716
	Mobility					Transportability							Protection				
	0.3532					0.0594							0.1457				

Effectiveness
0.5583

Middle East

	Mobility					Transportability							Protection				
	0.3					0.1							0.6				
	On-road		Off-road			Sea		Air									
	0.18		0.82			0.25		0.75									
	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
Weights	0.17	0.833	0.167	0.334	0.499	0.8	0.2	0.17	0.64	0.13	0.06	0.2	0.05	0.4	0.1	0.25
Attribute values	1	0.664	1	0.5	0.49992	0.2	0.5620478	0.5	0.1	1	1	1	1	1	0	1
	0.17	0.553	0.167	0.167	0.24946	0.16	0.1124096	0.09	0.06	0.13	0.06	0.2	0.05	0.4	0	0.25
	Mobility					Transportability							Protection				
	0.1824					0.0322							0.5400				

Effectiveness
0.7546

Attribute Data - JLTV

Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
70	350	60	40	18	4.4526882	1	2	8	Yes	Yes	3	3	3	Yes	Yes

Indo-Pacific

	Mobility					Transportability						Protection				
	0.19					0.5						0.31				
	On-road		Off-road			Sea		Air								
	0.67		0.33			0.67		0.33								
	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
Weights	0.17	0.833	0.167	0.334	0.499	0.8	0.2	0.17	0.64	0.13	0.06	0.27	0.13	0.40	0.13	0.07
Attribute values	1	0.836	1	1	0.80254	0.95	1	0.5	0.88	1	1	1	1	1	1	1
	0.17	0.696	0.167	0.334	0.40047	0.76	0.2	0.09	0.56	0.13	0.06	0.266	0.133	0.4	0.133	0.068

Effectiveness	Mobility	Transportability	Protection
0.9358	0.1664	0.4594	0.3100

Europe

	Mobility					Transportability						Protection				
	0.5					0.33						0.17				
	On-road		Off-road			Sea		Air								
	0.9		0.1			0.55		0.45								
	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
Weights	0.17	0.833	0.167	0.334	0.499	0.25	0.75	0.17	0.64	0.13	0.06	0.29	0.29	0.21	0.14	0.07
Attribute values	1	0.836	1	1	0.80254	0.95	1	0.5	0.88	1	1	1	1	1	1	1
	0.17	0.696	0.167	0.334	0.40047	0.2375	0.75	0.09	0.56	0.13	0.06	0.2857	0.2857	0.2142	0.1428	0.0716

Effectiveness	Mobility	Transportability	Protection
0.7705	0.4334	0.1671	0.1700

Middle East

	Mobility					Transportability						Protection				
	0.3					0.1						0.6				
	On-road		Off-road			Sea		Air								
	0.18		0.82			0.25		0.75								
	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
Weights	0.17	0.833	0.167	0.334	0.499	0.8	0.2	0.17	0.64	0.13	0.06	0.2	0.05	0.4	0.1	0.25
Attribute values	1	0.836	1	1	0.80254	0.95	1	0.5	0.88	1	1	1	1	1	1	1
	0.17	0.696	0.167	0.334	0.40047	0.76	0.2	0.09	0.56	0.13	0.06	0.2	0.05	0.4	0.1	0.25

Effectiveness	Mobility	Transportability	Protection
0.9500	0.2684	0.0816	0.6000

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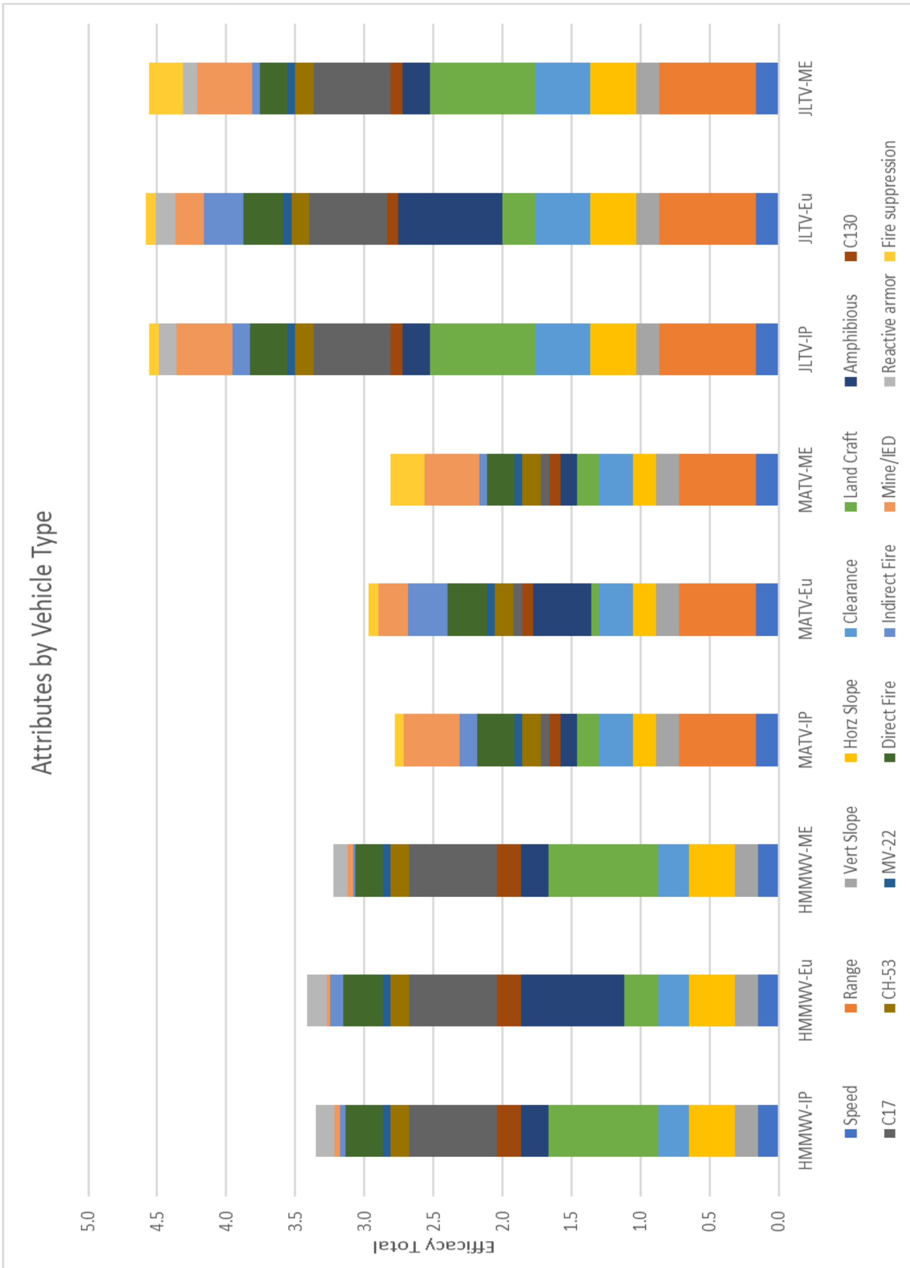
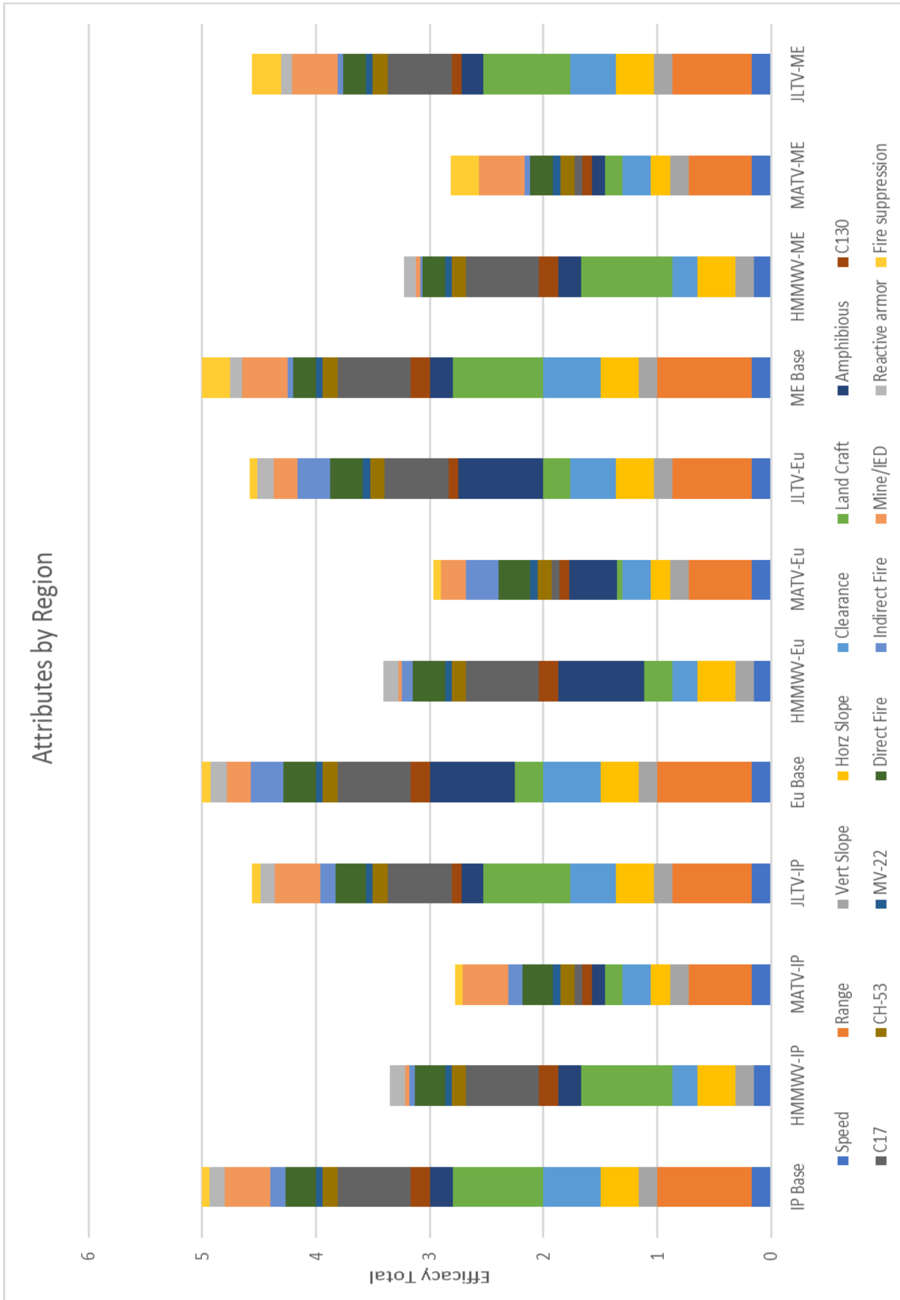
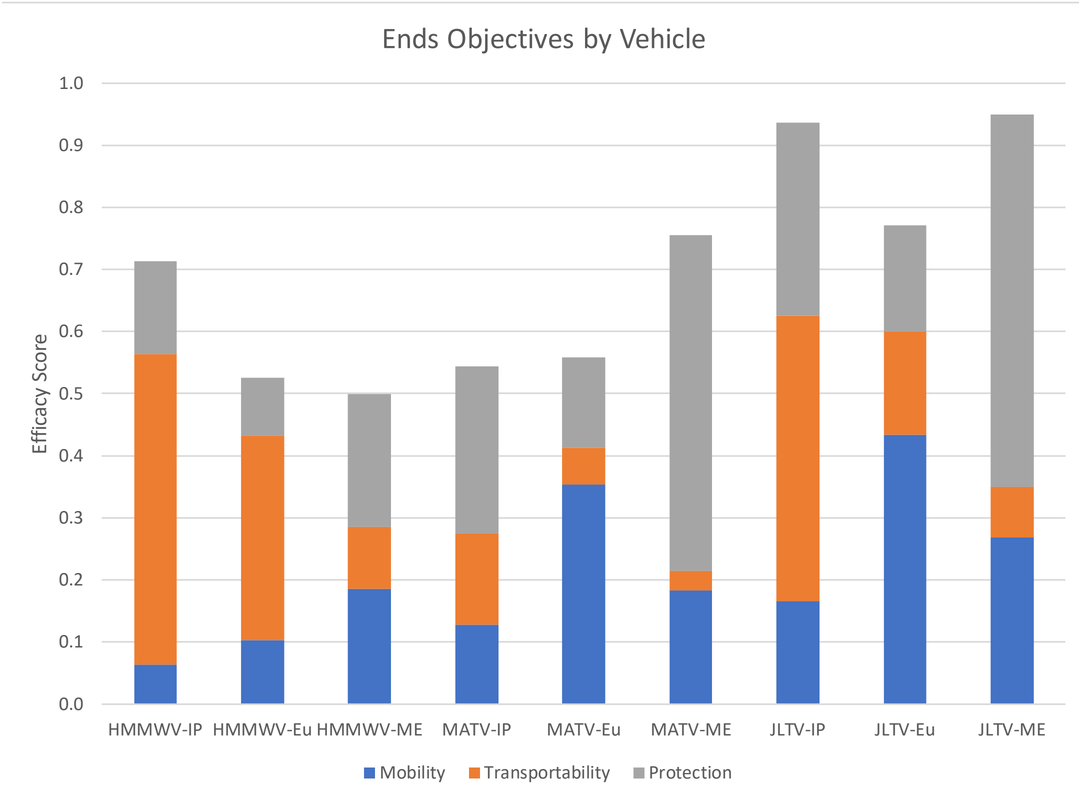
APPENDIX C. ATTRIBUTE AND OBJECTIVE GRAPHS

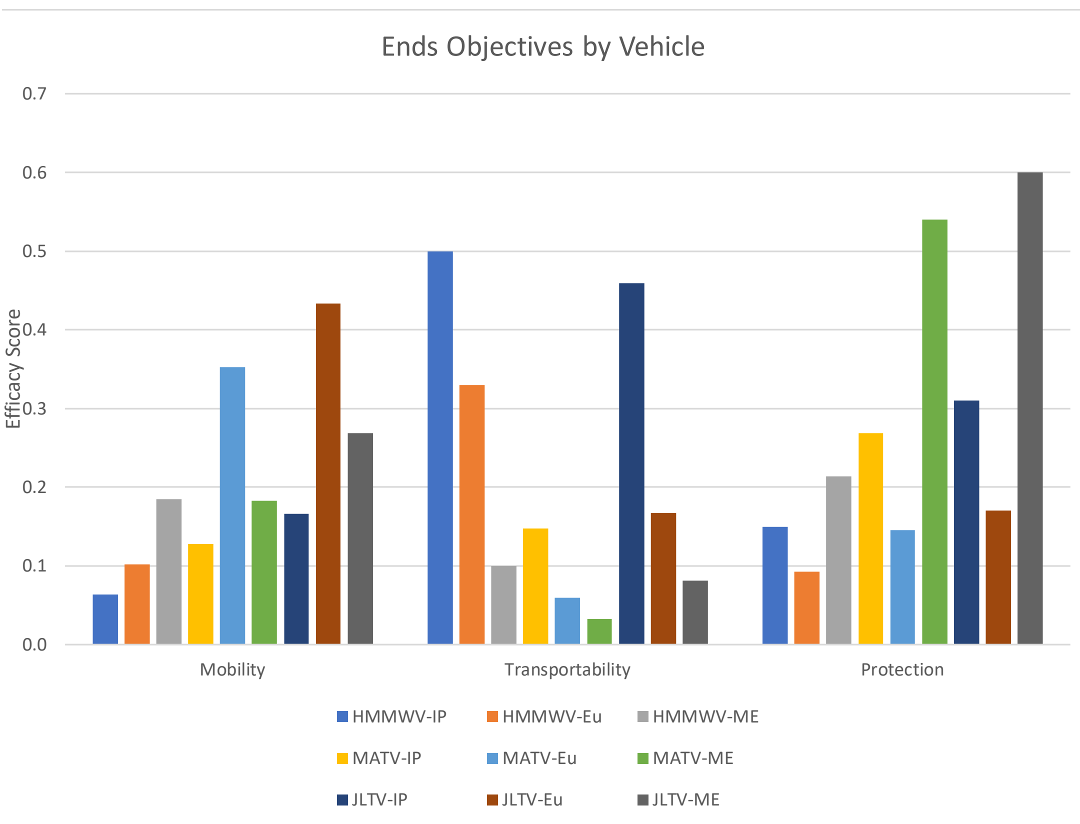


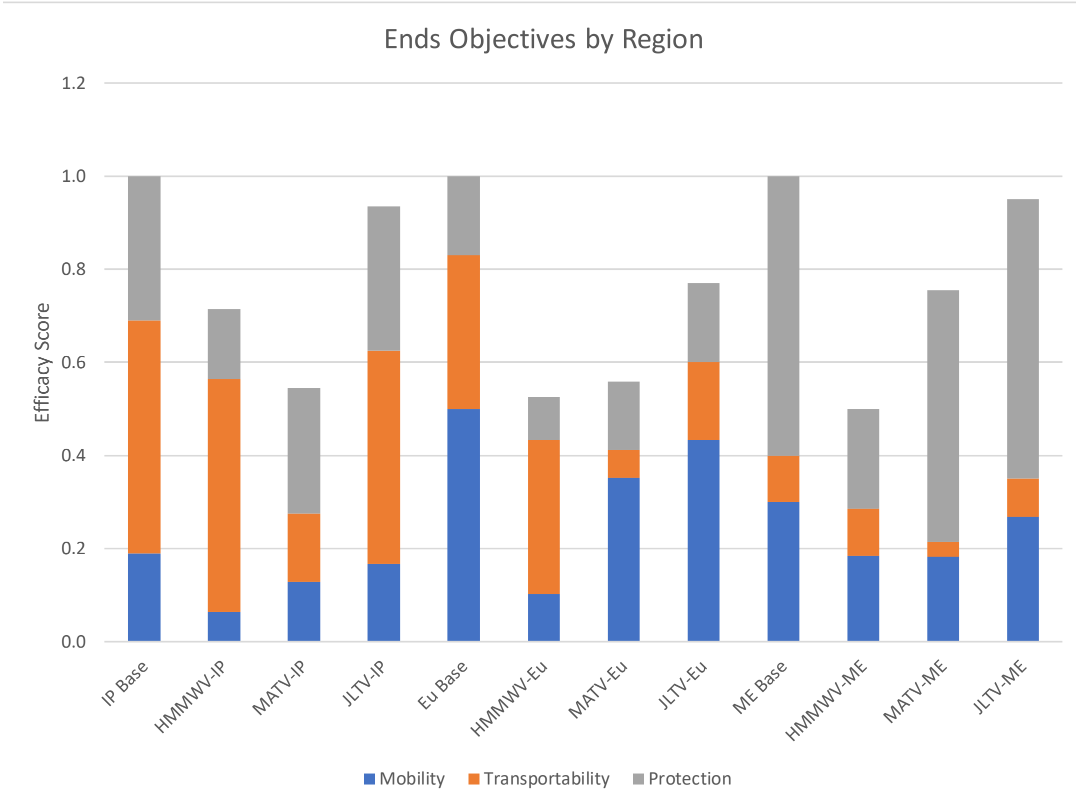
	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
HMMWV-IP	0.1476	0.0000	0.1670	0.3340	0.2195	0.8000	0.2000	0.1700	0.6400	0.1300	0.0600	0.2660	0.0439	0.0400	0.133	0
HMMWV-Eu	0.1476	0.0000	0.1670	0.3340	0.2195	0.2500	0.7500	0.1700	0.6400	0.1300	0.0600	0.2857	0.0943	0.0214	0.1428	0
HMMWV-ME	0.1476	0.0000	0.1670	0.3340	0.2195	0.8000	0.2000	0.1700	0.6400	0.1300	0.0600	0.2000	0.0165	0.0400	0.1	0
MATV-IP	0.1670	0.5530	0.1670	0.1670	0.2495	0.1600	0.1124	0.0850	0.0640	0.1300	0.0600	0.2660	0.1330	0.4000	0	0.0680
MATV-Eu	0.1670	0.5530	0.1670	0.1670	0.2495	0.0500	0.4215	0.0850	0.0640	0.1300	0.0600	0.2857	0.2857	0.2142	0	0.0716
MATV-ME	0.1670	0.5530	0.1670	0.1670	0.2495	0.1600	0.1124	0.0850	0.0640	0.1300	0.0600	0.2000	0.0500	0.4000	0	0.2500
JLTV-IP	0.1670	0.6960	0.1670	0.3340	0.4005	0.7600	0.2000	0.0850	0.5600	0.1300	0.0600	0.2660	0.1330	0.4000	0.1330	0.0680
JLTV-Eu	0.1670	0.6960	0.1670	0.3340	0.4005	0.2375	0.7500	0.0850	0.5600	0.1300	0.0600	0.2857	0.2857	0.2142	0.1428	0.0716
JLTV-ME	0.1670	0.6960	0.1670	0.3340	0.4005	0.7600	0.2000	0.0850	0.5600	0.1300	0.0600	0.2000	0.0500	0.4000	0.1000	0.2500



	Speed	Range	Vert Slope	Horz Slope	Clearance	Land Craft	Amphibious	C130	C17	CH-53	MV-22	Direct Fire	Indirect Fire	Mine/IED	Reactive armor	Fire suppression
IP Base	0.1670	0.8330	0.1670	0.3340	0.4990	0.8000	0.2000	0.1700	0.6400	0.1300	0.0600	0.2660	0.1330	0.4000	0.1330	0.0680
HMMWV-IP	0.1476	0.0000	0.1670	0.3340	0.2195	0.8000	0.2000	0.1700	0.6400	0.1300	0.0600	0.2660	0.0439	0.0400	0	0
MATV-IP	0.1670	0.5530	0.1670	0.1670	0.2495	0.1600	0.1124	0.0850	0.0640	0.1300	0.0600	0.2660	0.1330	0.4000	0	0.0680
JLTV-IP	0.1670	0.6960	0.1670	0.3340	0.4005	0.7600	0.2000	0.0850	0.5600	0.1300	0.0600	0.2660	0.1330	0.4000	0.1330	0.0680
Eu Base	0.1670	0.8330	0.1670	0.3340	0.4990	0.2500	0.7500	0.1700	0.6400	0.1300	0.0600	0.2857	0.2857	0.2142	0.1428	0.0716
HMMWV-Eu	0.1476	0.0000	0.1670	0.3340	0.2195	0.2500	0.7500	0.1700	0.6400	0.1300	0.0600	0.2857	0.0943	0.0214	0	0
MATV-Eu	0.1670	0.5530	0.1670	0.1670	0.2495	0.0500	0.4215	0.0850	0.0640	0.1300	0.0600	0.2857	0.2857	0.2142	0	0.0716
JLTV-Eu	0.1670	0.6960	0.1670	0.3340	0.4005	0.2375	0.7500	0.0850	0.5600	0.1300	0.0600	0.2857	0.2857	0.2142	0.1428	0.0716
ME Base	0.1670	0.8330	0.1670	0.3340	0.4990	0.8000	0.2000	0.1700	0.6400	0.1300	0.0600	0.2000	0.0500	0.4000	0.1000	0.2500
HMMWV-ME	0.1476	0.0000	0.1670	0.3340	0.2195	0.8000	0.2000	0.1700	0.6400	0.1300	0.0600	0.2000	0.0165	0.0400	0	0
MATV-ME	0.1670	0.5530	0.1670	0.1670	0.2495	0.1600	0.1124	0.0850	0.0640	0.1300	0.0600	0.2000	0.0500	0.4000	0	0.2500
JLTV-ME	0.1670	0.6960	0.1670	0.3340	0.4005	0.7600	0.2000	0.0850	0.5600	0.1300	0.0600	0.2000	0.0500	0.4000	0.1000	0.2500


Ends Objectives by Vehicle
Efficacy Score
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
HMMWV-IP
HMMWV-Eu
HMMWV-ME
MATV-IP
MATV-Eu
MATV-ME
JLTV-IP
JLTV-Eu
JLTV-ME
Mobility
Transportability
Protection


Ends Objectives by Vehicle
Efficacy Score
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Mobility
Transportability
Protection
HMMWV-IP
HMMWV-Eu
HMMWV-ME
MATV-IP
MATV-Eu
MATV-ME
JLTV-IP
JLTV-Eu
JLTV-ME


Ends Objectives by Region
Efficacy Score
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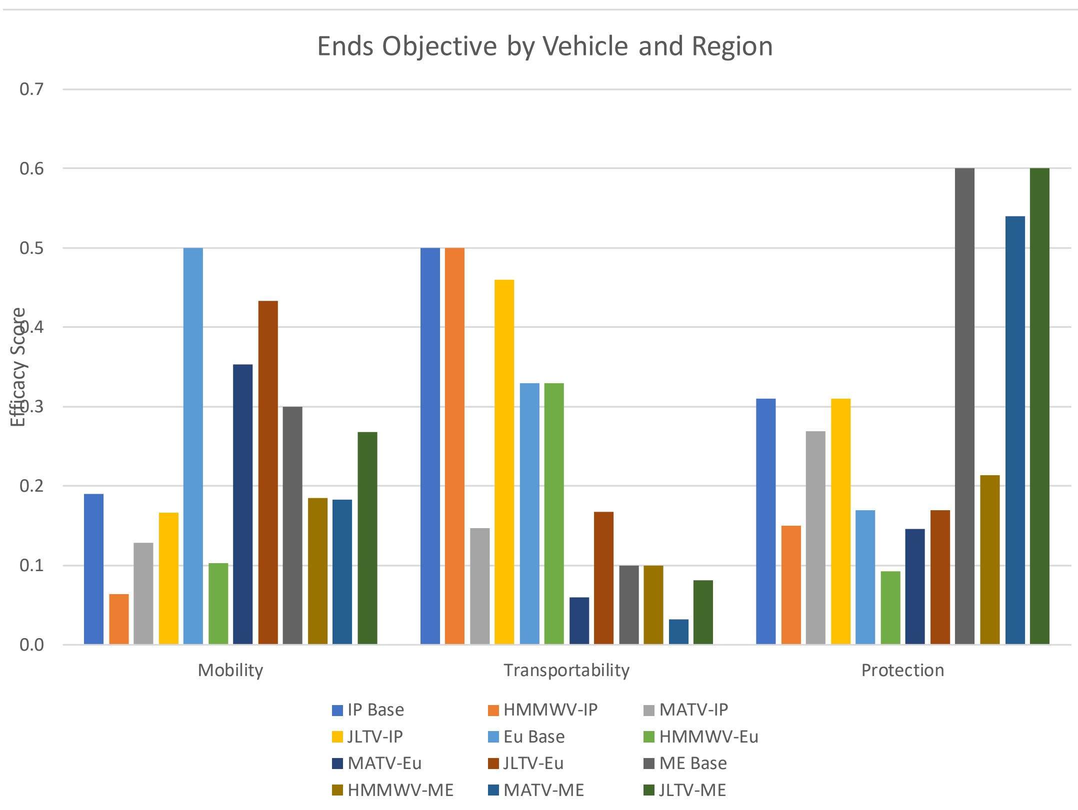
1.0
0.8
0.6
0.4
0.2
0.0
IP Base
HMMWV-IP
MATV-IP
JLTV-IP
Eu Base
HMMWV-Eu
MATV-Eu
JLTV-Eu
ME Base
HMMWV-ME
MATV-ME
JLTV-ME
Mobility
Transportability
Protection


Ends Objective by Vehicle and Region
Efficacy Score
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Mobility
Transportability
Protection
IP Base
HMMWV-IP
MATV-IP
JLTV-IP
Eu Base
HMMWV-Eu
MATV-Eu
JLTV-Eu
ME Base
HMMWV-ME
MATV-ME
JLTV-ME

APPENDIX D. SENSITIVITY ANALYSIS CHARTS

Base weights

	Mobility	Transportability	Protection
Indo-Pac	0.190	0.500	0.310
Europe	0.500	0.330	0.170
Mid East	0.300	0.100	0.600

Base MOEs

	Indo-Pacific	Δbase	Europe	Δbase	Middle East	Δbase	Marginal Efficacy (JLTV)
HMMWV	0.7137	0	0.5249	0	0.4991	0	0.00001165
MATV	0.5442	0	0.5583	0	0.7546	0	0.00001288
JLTV	0.9358	0	0.7705	0	0.9500	0	0.00002365

Total Efficacy 27.46

Central weights

	Mobility	Transportability	Protection
Indo-Pac	0.260	0.415	0.320
Europe	0.415	0.330	0.250
Mid East	0.315	0.215	0.465

Centralized MOEs

	Indo-Pacific	Δbase	Europe	Δbase	Middle East	Δbase	Marginal Efficacy (JLTV)
HMMWV	0.6570	-0.0566	0.5511	0.0261	0.5752	0.0761	0.00001426
MATV	0.5751	0.0309	0.5669	0.0085	0.6793	-0.0753	0.00001184
JLTV	0.9290	-0.0068	0.7768	0.0063	0.9223	-0.0277	0.00001820

Total Efficacy 27.56

Extreme weights

	Mobility	Transportability	Protection
Indo-Pac	0.095	0.750	0.155
Europe	0.585	0.330	0.085
Mid East	0.150	0.050	0.800

Extreme MOEs

	Indo-Pacific	Δbase	Europe	Δbase	Middle East	Δbase	Marginal Efficacy (JLTV)
HMMWV	0.8568	0.1432	0.4961	-0.0288	0.4278	-0.0713	0.00000369
MATV	0.4193	-0.1249	0.5455	-0.0128	0.8273	0.0727	0.00001380
JLTV	0.9273	-0.0085	0.7592	-0.0113	0.9750	0.0250	0.00002870

Total Efficacy 27.68

Random weights

	Mobility	Transportability	Protection
Indo-Pac	0.484	0.050	0.466
Europe	0.025	0.414	0.561
Mid East	0.601	0.315	0.084

Random MOEs

	Indo-Pacific	Δbase	Europe	Δbase	Middle East	Δbase	Marginal Efficacy (JLTV)
HMMWV	0.4282	-0.2855	0.7294	0.2044	0.6830	0.1839	0.00002611
MATV	0.7533	0.2091	0.5712	0.0129	0.5645	-0.1902	0.00000354
JLTV	0.9361	0.0003	0.7911	0.0206	0.8840	-0.0659	0.00000855

Total Efficacy 28.13

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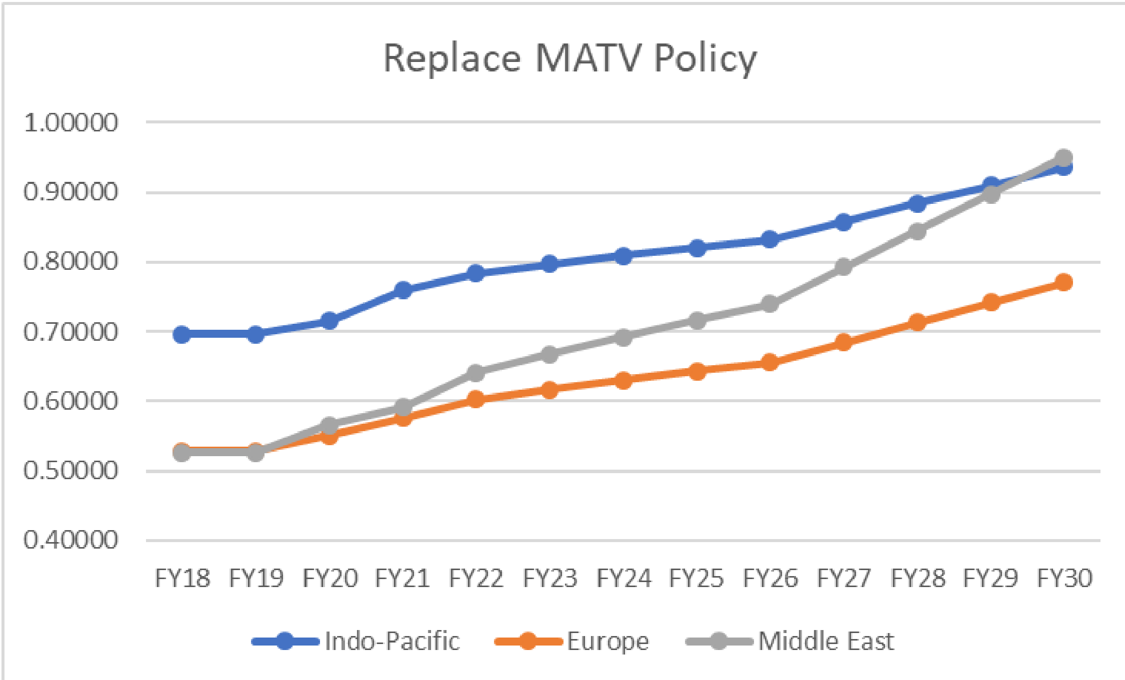
APPENDIX E. SCENARIO ANALYSIS CHARTS



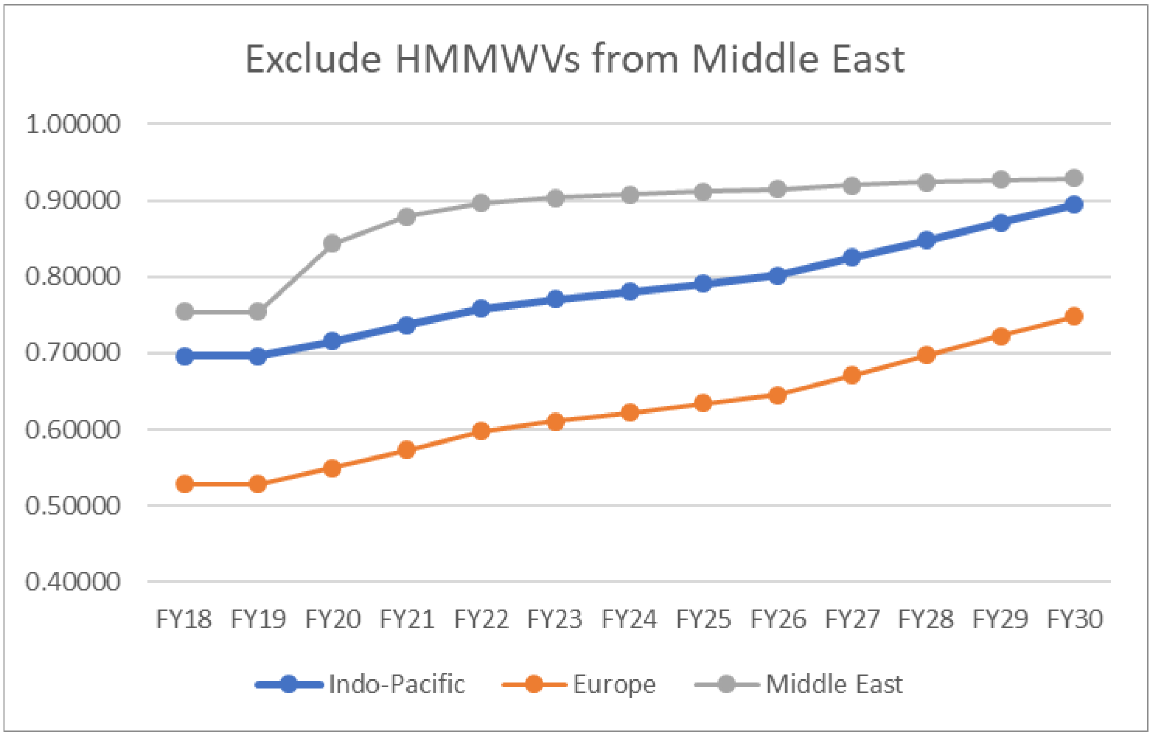
Inventory levels

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
HMMWV	17056	17056	15371	13552	11701	10665	9765	8865	7965	5974	3983	1992	0
MATV	2007	2007	2007	0	0	0	0	0	0	0	0	0	0
JLTV	0	0	1685	3505	5355	6391	7291	8191	9091	11082	13073	15064	17056
	19063	19063	19063	17057	17056	17056	17056	17056	17056	17056	17056	17056	17056

Normalized weighting*

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
Indo-Pacific	0.69581	0.69581	0.71545	0.75929	0.78339	0.79688	0.80860	0.82032	0.83204	0.85796	0.88389	0.90982	0.93576	
Europe	0.52846	0.52846	0.55016	0.57540	0.60205	0.61696	0.62992	0.64288	0.65584	0.68451	0.71317	0.74184	0.77052	
Middle East	0.52601	0.52601	0.56586	0.59176	0.64067	0.66805	0.69185	0.71564	0.73943	0.79206	0.84470	0.89733	0.94999	
Total	1.75028	1.75028	1.83147	1.92645	2.02610	2.08189	2.13036	2.17883	2.22730	2.33453	2.44176	2.54899	2.65627	**27.88452**

*(efficiancy score x inventory level)/USMC vehicle inventory total



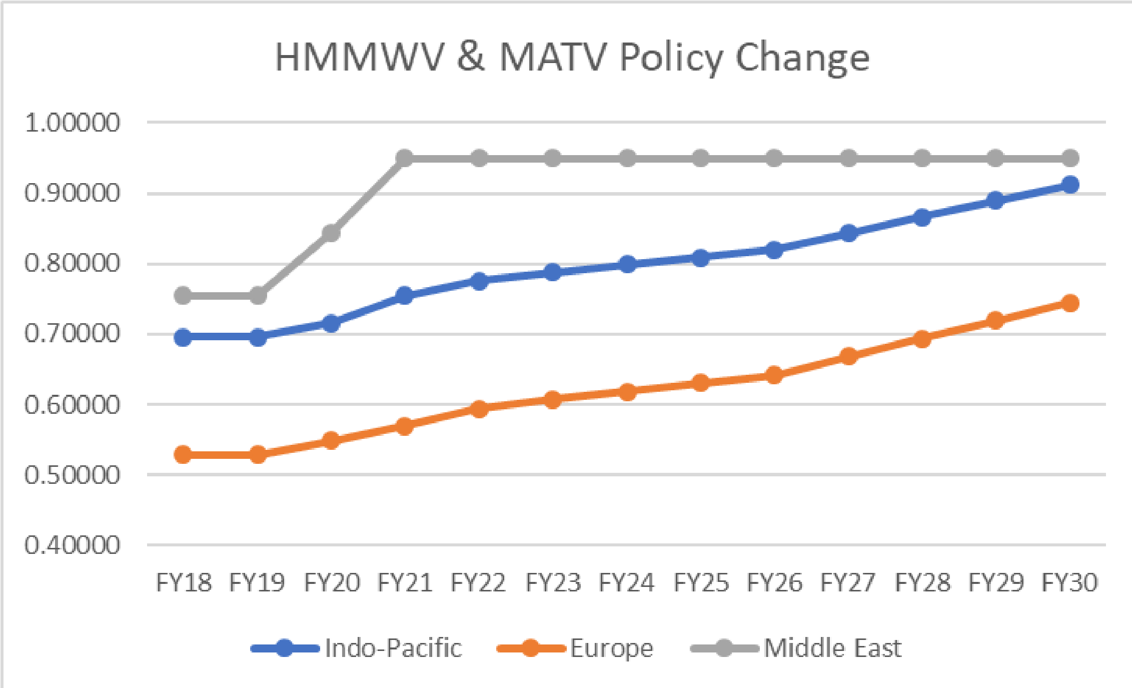
Inventory levels

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
HMMWV	17056	17056	15371	13552	11701	10665	9765	8865	7965	5974	3983	1992	0
MATV	2007	2007	2007	2007	2007	2007	2007	2007	2007	2007	2007	2007	2007
JLTV	0	0	1685	3505	5355	6391	7291	8191	9091	11082	13073	15064	17056
	19063	19063	19063	19064	19063	19063	19063	19063	19063	19063	19063	19063	19063

Normalized weighting*

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
Indo-Pacific	0.69581	0.69581	0.71545	0.73665	0.75821	0.77028	0.78076	0.79125	0.80173	0.82493	0.84813	0.87132	0.89453	
Europe	0.52846	0.52846	0.55016	0.57361	0.59744	0.61079	0.62238	0.63398	0.64557	0.67122	0.69687	0.72252	0.74818	
Middle East	0.75465	0.75465	0.84380	0.87886	0.89673	0.90330	0.90782	0.91154	0.91466	0.92004	0.92399	0.92702	0.92942	
	1.97892	1.97892	2.10941	2.18912	2.25238	2.28437	2.31097	2.33677	2.36197	2.41619	2.46899	2.52087	2.57214	**29.78100**

*(efficiancy score x inventory level)/USMC vehicle inventory total



Inventory levels

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
HMMWV	17056	17056	17056	15558	13708	12672	11772	10872	9972	7981	5990	3999	2007
MATV	2007	2007	2007	0	0	0	0	0	0	0	0	0	0
JLTV	0	0	1685	3505	5355	6391	7291	8191	9091	11082	13073	15064	17056
	19063	19063	20748	19063	19063	19063	19063	19063	19063	19063	19063	19063	19063

Normalized weighting*

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
Indo-Pacific	0.69581	0.69581	0.71530	0.75449	0.77604	0.78812	0.79860	0.80909	0.81957	0.84277	0.86597	0.88916	0.91237	
Europe	0.52846	0.52846	0.54812	0.57009	0.59393	0.60727	0.61887	0.63046	0.64206	0.66771	0.69336	0.71901	0.74467	
Middle East	0.75465	0.75465	0.84380	0.94999	0.94999	0.94999	0.94999	0.94999	0.94999	0.94999	0.94999	0.94999	0.94999	
	1.97892	1.97892	2.10722	2.27457	2.31996	2.34538	2.36746	2.38954	2.41162	2.46046	2.50931	2.55816	2.60703	**30.30853**

*(efficiancy score x inventory level)/USMC vehicle inventory total

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