



Calhoun: The NPS Institutional Archive
DSpace Repository

Theses and Dissertations

1. Thesis and Dissertation Collection, all items

2019-12

**APPLICATION OF EXPEDIENT
LEADER-FOLLOWER TECHNOLOGY TO AN
INFANTRY BRIGADE COMBAT TEAM**

Bobzin, Lauren B.; Leichty, Benjamin; Winkler, Austin J.

Monterey, CA; Naval Postgraduate School

<https://hdl.handle.net/10945/64106>

This publication is a work of the U.S. Government as defined in Title 17, United States Code, Section 101. Copyright protection is not available for this work in the United States.

Downloaded from NPS Archive: Calhoun



Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

<http://www.nps.edu/library>



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

MBA PROFESSIONAL PROJECT

APPLICATION OF EXPEDIENT LEADER-FOLLOWER TECHNOLOGY TO AN INFANTRY BRIGADE COMBAT TEAM

December 2019

By: Lauren B. Bobzin
Benjamin Leichty
Austin J. Winkler

Advisor: Daniel Reich
Co-Advisor: Ira A. Lewis

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE December 2019	3. REPORT TYPE AND DATES COVERED MBA Professional Project	
4. TITLE AND SUBTITLE APPLICATION OF EXPEDIENT LEADER-FOLLOWER TECHNOLOGY TO AN INFANTRY BRIGADE COMBAT TEAM			5. FUNDING NUMBERS
6. AUTHOR(S) Lauren B. Bobzin, Benjamin Leichthy, and Austin J. Winkler			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Acquisition Research Program, Monterey, CA 93943			10. SPONSORING / MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			12b. DISTRIBUTION CODE A
13. ABSTRACT (maximum 200 words) Autonomous ground resupply (AGR) possesses significant potential to address the growing military transportation gap and alter the future of combat sustainment. An Army Infantry Brigade Combat Team can organically transport only 58% of assigned assets. To address this shortfall, among other capability gaps, the U.S. Army Combat Capability Development Center began researching and testing Expedient Leader Follower (ExLF) AGR technology during fiscal year (FY) 2016 and will begin field testing within two Army transportation companies beginning in the fourth quarter of FY2019. ExLF technology provides the capability to conduct a three- to ten-vehicle convoy with one manned vehicle leading the ExLF vehicles in trace. Some key priorities outlined by U.S. Army Combined Arms Support Command include (1) performing convoy operations autonomously and (2) assessing legacy equipment against ExLF equipped convoys. The ExLF technology must provide tangible results across these stated objectives in order to justify the investment across all ground forces, including the Marine Corps.			
14. SUBJECT TERMS Expedient Leader Follower, ExLF, autonomous ground resupply, AGR, Infantry Brigade Combat Team, IBCT, optimization			15. NUMBER OF PAGES 85
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

**APPLICATION OF EXPEDIENT LEADER-FOLLOWER TECHNOLOGY TO
AN INFANTRY BRIGADE COMBAT TEAM**

Lauren B. Bobzin, Captain, United States Marine Corps
Benjamin Leichty, Captain, United States Marine Corps
Austin J. Winkler, Captain, United States Army

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF BUSINESS ADMINISTRATION

from the

**NAVAL POSTGRADUATE SCHOOL
December 2019**

Approved by: Daniel Reich
Advisor

Ira A. Lewis
Co-Advisor

Eddine Dahel
Academic Associate, Graduate School of Defense Management

THIS PAGE INTENTIONALLY LEFT BLANK

APPLICATION OF EXPEDIENT LEADER-FOLLOWER TECHNOLOGY TO AN INFANTRY BRIGADE COMBAT TEAM

ABSTRACT

Autonomous ground resupply (AGR) possesses significant potential to address the growing military transportation gap and alter the future of combat sustainment. An Army Infantry Brigade Combat Team can organically transport only 58% of assigned assets. To address this shortfall, among other capability gaps, the U.S. Army Combat Capability Development Center began researching and testing Expedient Leader Follower (ExLF) AGR technology during fiscal year (FY) 2016 and will begin field testing within two Army transportation companies beginning in the fourth quarter of FY2019. ExLF technology provides the capability to conduct a three- to ten-vehicle convoy with one manned vehicle leading the ExLF vehicles in trace. Some key priorities outlined by U.S. Army Combined Arms Support Command include (1) performing convoy operations autonomously and (2) assessing legacy equipment against ExLF equipped convoys. The ExLF technology must provide tangible results across these stated objectives in order to justify the investment across all ground forces, including the Marine Corps.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
II.	BACKGROUND	5
	A. DEFINING AUTONOMY	5
	B. CURRENT STATE OF THE ExLF PROGRAM.....	6
	C. BRIGADE COMBAT TEAMS.....	8
	D. SUSTAINMENT WITHIN A BRIGADE COMBAT TEAM.....	9
	E. PALLETIZED LOAD SYSTEM.....	10
	F. ARMY CAPABILITY GAPS	11
III.	METHODOLOGY	13
	A. BACKGROUND.....	13
	1. Supported Units Characteristics	14
	2. BSB Transportation Capacity	18
	3. Additional Assumptions	23
	B. SIMULATION AND MODEL.....	24
	1. Flow of Supplies	24
	2. Simulating Consumption.....	25
	3. Distribution Plan.....	26
IV.	RESULTS AND ANALYSIS	33
	A. RESULTS	33
	B. ANALYSIS	34
	1. The Impact of ExLF.....	35
	2. HEMTT Fueler Shortfall	35
	3. Limitations.....	35
V.	CONCLUSIONS AND RECOMMENDATIONS.....	37
	A. BATTLEFIELD APPLICATION	37
	B. MAINTENANCE IMPLICATIONS.....	37
	1. Negative Considerations.....	37
	2. Positive Considerations	38
	C. SURVIVABILITY	39
	D. PERSONNEL CONSIDERATIONS	39
	E. FORMS AND LEVELS OF IMPLEMENTATION OF ExLF	40
	1. Status Quo Capacity with Less Personnel and Equipment.....	40
	2. Small Capacity Increase with Less Personnel	41

3.	Large Capacity Increase with More Equipment.....	41
4.	Alternative Options for Displaced Personnel	42
F.	MARINE CORPS ExLF APPLICATION	43
G.	FUTURE RESEARCH	45
1.	Enemy Action Incorporation	45
2.	Personnel Survivability Considerations.....	45
3.	Mechanical Failure Considerations.....	46
4.	Simulation Scope.....	46
5.	Prioritization Points Significance	46
6.	Organic Lift Gap.....	47
7.	Other AGR Systems.....	47
H.	CONCLUSION	47
	APPENDIX A. INFANTRY 1—SIMULATED CONSUMPTION	49
	APPENDIX B. INFANTRY 2—SIMULATED CONSUMPTION	51
	APPENDIX C. INFANTRY 3—SIMULATED CONSUMPTION	53
	APPENDIX D. FIELD ARTILLERY—SIMULATED CONSUMPTION	55
	APPENDIX E. CAVALRY—SIMULATED CONSUMPTION.....	57
	APPENDIX F. ENGINEER—SIMULATED CONSUMPTION	59
	APPENDIX G. SIMULATED TRUCK AVAILABILITY	61
	APPENDIX H. PRIORITIZATION POINTS TABLE.....	63
	LIST OF REFERENCES	65
	INITIAL DISTRIBUTION LIST	67

LIST OF FIGURES

Figure 1.	Human-Machine Command and Control Relationship. Adapted from Ivanova, Gallasch, and Jordans (2016).	6
Figure 2.	Infantry Brigade Combat Team Organizational Chart. Source: U.S. Army (2015, Figure 1-1).	9
Figure 3.	Palletized Load System. Source: Oshkosh Defense (2019).	11
Figure 4.	Load Handling System.....	19
Figure 5.	M1076 PLS Trailer	20
Figure 6.	Compatible Water Tank Rack.....	20
Figure 7.	M978 HEMTT Fueler	21
Figure 8.	Modular Fuel System.....	22
Figure 9.	Logistics Process Flow	24

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1.	Classes of Supply. Source: U.S. Army (2008b).....	15
Table 2.	Conversion: 1 DOS for Supported Units in Simulation	17
Table 3.	Simulation Brigade Support Battalion Distribution Assets	18
Table 4.	Platform Configurations.....	22
Table 5.	IBCT Status Quo 21-Day Simulation	33
Table 6.	IBCT with ExLF 21-Day Simulation.....	34

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

A2AD	Anti-Access/Area Denial
AGR	Autonomous Ground Resupply
AI	Artificial Intelligence
BCT	Brigade Combat Team
BSB	Brigade Support Battalion
C2	Command and Control
DoD	Department of Defense
DR	Directed Requirement
DSB	Defense Science Board
ExLF	Expedient Leader-Follower
FLOT	Forward Line of Troops
FSC	Forward Support Company
GAO	Government Accountability Office
HE	Heavy Equipment
HEMTT	Heavy Expanded Mobility Tactical Truck
IBCT	Infantry Brigade Combat Team
JLTV	Joint Light Tactical Vehicle
JtLE	Joint Logistics Enterprise
LHS	Load Handling System
LVSR	Logistics Vehicle System Replacement
MOSA	Modular Open-Source Approach
PLS	Palletized Load System
R&D	Research and Development
TWV	Tactical Wheeled Vehicle

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

Immense thanks are owed to our two excellent MBA project advisors, Dr. Daniel Reich and Dr. Ira Lewis, without whose influence and talents we would still be flailing at an outline. Additionally, the guidance of Jochele Benson and Karey Shaffer of the NPS Acquisition Research Program greatly aided in keeping this project on the rails.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

Ground transportation represents the foundation for all logistics and sustainment support of military operations in theater, but the Department of Defense (DoD) currently has a growing “transportation problem that threatens the nation’s ability to [effectively] project power abroad” (Van Howe, 2019). The United States Army places such a significant demand on tactical ground transportation capacity that an Infantry Brigade Combat Team (IBCT) has the capability of moving only 58% of its organic assets and personnel in a single movement. Budget constraints and DoD personnel caps remove any consequential solution that involves the scale of increases necessary to bridge such a large transportation capability gap. Therefore, the need for a revolutionary, yet cost effective, solution manifests. Autonomous ground resupply (AGR) technology represents one viable solution, specifically the ongoing Expedient Leader-Follower (ExLF) program. This technology is particularly relevant as the United States shifts focus to preparing for a total war conflict where this significant transportation capability gap presents an untenable liability.

In 2017, U.S. defense strategy pivoted toward preparing for large-scale combat against a near-peer adversary. After prolonged conflicts in Iraq and Afghanistan, where the United States faced enemies with a limited ability to disrupt sustainment efforts, the prospect of conventional war with a global power has refocused military leaders on the preparedness of the military logistics enterprise to operate within an increasingly contested environment (Government Accountability Office [GAO], 2019). In 2018, The Defense Science Board’s (DSB) *Task Force on Survivable Logistics* described “significant shortfalls” in its evaluation of logistics readiness:

Since the end of the Cold War, the United States has not fought an adversary capable of the catastrophic disruption of military supply chains and deployment of personnel and materiel. As a result, the Joint Logistics Enterprise (JtLE) has suffered neglect and chronic underfunding relative to other DoD priorities. Simultaneously, the ability of strategic competitors to threaten the JtLE has increased as they invest in anti-access/area denial (A2AD) capabilities and gray zone tactics. (Defense Science Board [DSB], 2018, p. 2)

The DSB report specified several key vulnerabilities within logistics operations that will present substantial challenges in future warfare, especially against a near-peer adversary. Critical shortages and readiness issues currently plaguing transportation assets threaten the ability of our military forces to effectively project power in a future full-scale conflict. The over-reliance on contractor support in recent conflicts provides additional evidence of a fundamental lack in organic lift capability, especially regarding a sufficient logistics capacity to support full-scale operations (Hunter & McCormick, 2017; Van Howe, 2019). At the same time, the increasing range of precision-guided weapons will require an extended reach, as well as new strategies to protect assets, supply stocks, and forward lines of communication (DSB, 2018). With the expectation of contested domains, the emerging paradigm for future operations is that of a more efficient and technologically advanced combat force supported by a smaller and increasingly disaggregated logistics footprint, which will only intensify the need for a robust and responsive ground logistics transportation capability.

One promising solution to these challenges envisions the rapid expansion of unmanned systems to perform warfighting and logistics functions previously conducted exclusively by human operators. AGR technology provides seamless integration of manned and unmanned systems, which will enable power projection in contested domains by increasing both speed and capacity while simultaneously mitigating risk exposure for military personnel (Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics [OUSD(AT&L)], 2018). The DoD has largely directed its investment in unmanned systems with a preference toward aerial over ground platforms. In the realm of ground transportation, and consistent with developing a more agile combat force, investment has centered on ultra-light vehicles rather than the medium and heavy-lift platforms required to provide the bulk of sustainment support in theatre (Gordon et al., 2015; Van Howe, 2019). Furthermore, while the DoD continues to value agility, Van Howe (2019) notes that the Army's ability to carry out "mass sustainment" is still critical to achieving decisive action against an evenly matched adversary. Continuing underinvestment in these all-important AGR platforms will make it more difficult to sustain combat forces in a prolonged, large-scale conflict, especially against a near-peer

adversary. Overall, balanced investment in unmanned systems across all domains will better diversify operational risk and ensure sufficient logistics capacity needed to win a total war conflict.

The ExLF program represents an AGR technology that currently holds promise for bridging the ground transportation capability gap. As a limited autonomous control system, ExLF installs into existing military vehicle platforms, allowing them to effectively maneuver in a convoy without a human operator behind the wheel. At approximately one-fourth the cost of a new Joint Light Tactical Vehicle (JLTV), ExLF provides “potentially paradigm-shifting [and cost effective] capability into maneuver formations” (Van Howe, 2019). The United States would overcome its transportation problem and be better prepared for total war against a near-peer adversary if ExLF technology could provide significant improvements to logistics and sustainment support capacity.

THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND

Before moving into the details of methodology and outcomes, it is important to establish a foundation of terms, Army structure, and the current state of the ExLF program. An overview of the functions of a Brigade Combat Team and utilization of ground transportation assets is critical to understanding the results of this research.

A. DEFINING AUTONOMY

Understanding the opportunities and challenges presented by autonomy necessitates a common understanding of what *autonomy* means. Defined simply, autonomy is technology that enables robots to execute functions traditionally performed by humans. Autonomy generally includes the ability to sense and react to the environment through a sequence known as the perception-cognition-action information-processing loop (Cummings, 2017). Machine autonomy relies on artificial intelligence (AI) to perform tasks such as visual perception, voice recognition, or decision-making.

Appreciating the advanced nature of an autonomous system requires distinguishing *how much* autonomy a system possesses relative to other autonomous systems. However, attempting to define levels of autonomy along a singular scale has only created confusion (NATO, 2015). Instead, the DSB recommends focusing on how autonomy supports specific capabilities within an autonomous system (DSB, 2016). Applying similar logic, a recent NATO report (2015) proposed a framework for classifying autonomous technologies in terms of three key attributes:

1. The human-machine command and control (C2) relationship
2. The type of decision being automated
3. The sophistication of the machine decision-making

A report from Australia's Department of Defence neatly summarizes this NATO framework, which we adapted to create Figure 1.

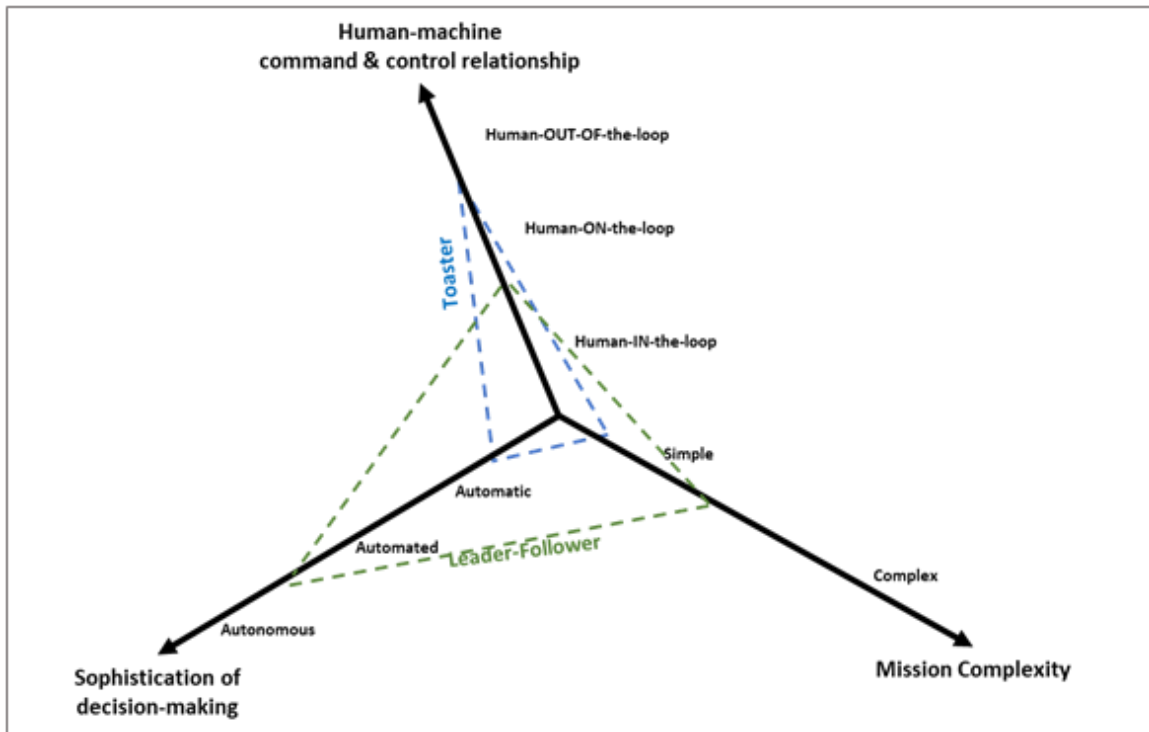


Figure 1. Human-Machine Command and Control Relationship. Adapted from Ivanova, Gallasch, and Jordans (2016).

B. CURRENT STATE OF THE ExLF PROGRAM

The recent development of a semi-autonomous capability under the AGR umbrella, known as Expedient Leader-Follower (ExLF), enables a convoy to operate with one manned “leader” vehicle leading a line of three to nine unmanned “follower” vehicles. Given the significant number of casualties suffered during ground resupply operations, the potential of ExLF technology to limit personnel exposure to hostile environments, while simultaneously expanding throughput capacity, offers a compelling reason to develop the technology.

In 2017, proponents of ExLF presented a seven-year acquisition strategy to secure the funding necessary to integrate ExLF technology in heavy-lift tactical wheeled vehicle (TWV) platforms. Instead, the Army Chief of Staff rejected their plan and challenged the program team to get a “good enough, fast enough, cheap enough” ExLF capability into the hands of soldiers within 36 months (Hatfield, 2018, p. 14). To meet this intent, the ExLF development team proposed issuing systems based on the appliqué autonomy kit solutions

developed through AGR. The ExLF Directed Requirement (DR) was signed May 4, 2017, releasing the funding necessary to design and build prototype systems. In December 2019, the Army will equip the palletized load system (PLS) vehicles of two transportation companies with the ExLF capability in order to conduct a year-long operational evaluation of the technology.

The ExLF program represents a significant advance in the development of autonomous technology and the way in which that technology is acquired. Innovative in both concept and design, ExLF capability has the potential to address key sustainment challenges, shape new concepts of support, and inform future modernization efforts. A summary of the strategic significance of ExLF follows.

Advanced Technology: ExLF represents a key technological advancement in unmanned systems with the integration of a truly autonomous capability into military operations versus previous remote-controlled technology (drones or explosive ordinance disposal robots).

Crucial Capability: By advancing the goals of the AGR program, ExLF has the potential to address key logistics challenges in ground mobility. Integrating autonomous capabilities with ground transportation will generate efficiencies throughout the distribution system. Fewer manned systems also lead to fewer soldiers in harm's way.

Key Diversifier: The investment in ExLF technology occupies a historically neglected niche of DoD investment as an unmanned ground vehicle technology, applied to a medium-lift mobility platform. Defense research and development (R&D) spending to develop autonomous capabilities has fallen far short of commercial investment (Cummings, 2017), as well as DoD investment in unmanned aerial and ultra-light robotic systems (Gordon et al., 2015).

Flexible, Adaptable, and Scalable Design: Designed as an appliqué solution, ExLF delivers autonomous capability through the integration of modular hardware kits that can be adapted to multiple platforms for one-tenth of what it would cost to develop an entirely new vehicle (Gordon et al., 2015). The ExLF capability also applies a scalable open architecture that will underpin much of the planned portfolio of future unmanned systems.

Known as “MOSA,” this *modular*, open-source approach is consistent with the theme of interoperability, reflecting the DoD’s long-term vision for manned/unmanned teaming.

Rapid Acquisition: The ExLF program reflects a concerted effort to bridge the historically long gap between the development and fielding of a critical technology. The relative success or failure of the ExLF program will inform not only the ExLF technology, but also the acquisition strategies used to accelerate its development (Hatfield, 2018; Goure, 2018).

Current application and study of the ExLF system have been focused on autonomous ground resupply that occurs significantly behind the forward line of troops. The future of any autonomous ground technology will eventually hinge on the successful implementation within units that represent the “tip of the spear.” In the Army, that means Brigade Combat Teams.

C. BRIGADE COMBAT TEAMS

Brigade Combat Teams (BCT) represent the Army’s primary unit for building and implementing combat power. Prior to 2004, the Army was division-centric, relying on large 15,000 soldier formations to serve as the lowest level unit capable of deploying and sustaining without outside assistance. General Peter Schoomaker, the Army’s Chief of Staff from 2003 to 2007, led the transformation to create brigades of approximately 3,000 soldiers that were self-sufficient and thus allowed the Army to deploy more appropriately sized formations based on the conflict at hand (Garamone, 2004). These brigades are standardized across the Army, based on the function they are expected to perform. The currently existing BCT formations include Infantry, Armored, and Stryker. An Infantry Brigade Combat Team (IBCT) serves as the basis of our analysis and is depicted in Figure 2. Other brigade types that were created during this period of reorganization include combat aviation, fires, sustainment, battlefield surveillance, and maneuver enhancement (U.S. Army, 2015).¹

¹ Information on how BCTs are organized and function can be found in *Army Field Manual 3-96: Brigade Combat Team* (U.S. Army, 2015).

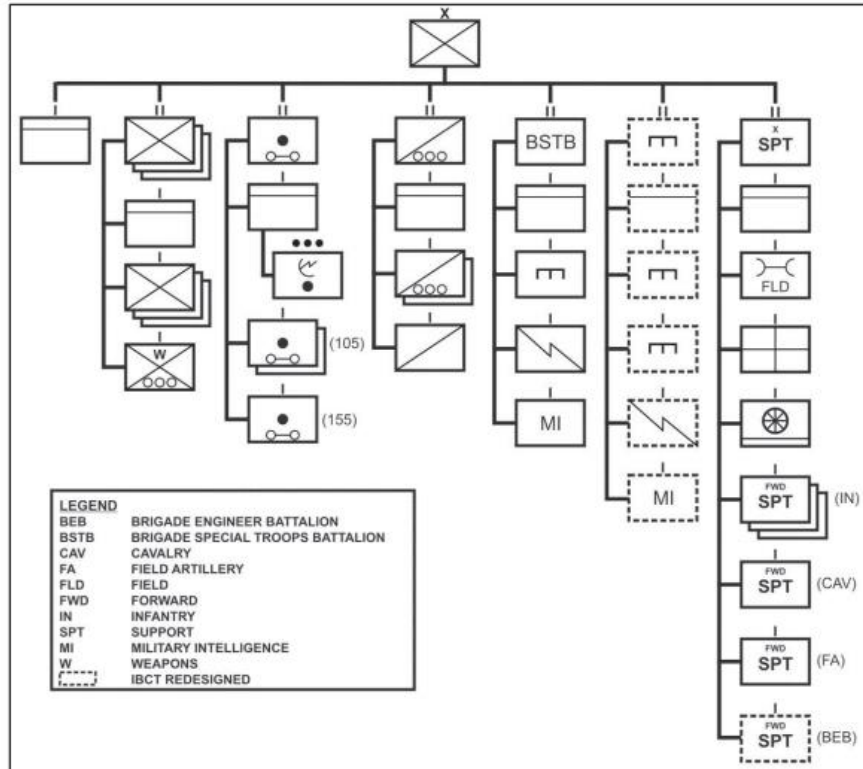


Figure 2. Infantry Brigade Combat Team Organizational Chart.
Source: U.S. Army (2015, Figure 1-1).

D. SUSTAINMENT WITHIN A BRIGADE COMBAT TEAM

A BCT is designed to organically carry at least three days of supply on hand. The Brigade Support Battalion (BSB),² which is often co-located with the Brigade Headquarters, operates as the primary source of resupply for other battalions within the brigade. The BSB will deploy a vehicle resupply convoy and deliver the needed materiel when a battalion requires resupply. As with the brigade, battalions are also designed to maintain three days of supply³ on hand. In an ideal scenario, the supported battalion will consume one day of supply and immediately be resupplied with a day of supply from the

² Battalions are the unit type immediately subordinate to a brigade. They generally have between 300 and 800 soldiers and perform a specific function within the brigade. Some battalion specialties include support, infantry, cavalry, field artillery, and engineer.

³ A day of supply represents everything the unit needs to sustain itself for a 24-hour period. These needs may fluctuate based on the unit's size and current mission.

BSB. This system translates to a goal of constantly having between two and three days of supply on hand at every level of the organization.

Every BSB is equipped based on the type of BCT it supports. As an example, a BSB that supports an IBCT will have fewer fuel tankers than a BSB that supports an Armored BCT. A BSB consists of four directly managed companies⁴ as well as a number of companies delegated to directly support the other battalions in the BCT. These delegated companies, known as a Forward Support Company (FSC), essentially represent a smaller-scale version of the BSB. The FSC sustains the subordinate units of the battalion to which it is assigned. All maneuver battalions in a BCT have their own FSC. The Heavy Expanded Mobility Tactical Truck (HEMTT) represents the most common dedicated sustainment vehicle organic to all BSBs and FSCs, in various quantities and variants depending on the mission of that particular BCT.

E. PALLETIZED LOAD SYSTEM

The Palletized Load System (PLS), depicted in Figure 3, is a variant of Oshkosh Defense LLC's HEMTT platform. HEMTT variants serve as one of the primary resupply distribution vehicles utilized in the Army. They are capable of delivering materiel in bulk quantities over rough terrain. A "pallet position" is the primary unit of measure for goods transported with the PLS. Each PLS has eight pallet positions and is capable of towing a trailer with an additional eight positions.

⁴ An Army company is the unit type immediately subordinate to a battalion.



Figure 3. Palletized Load System. Source: Oshkosh Defense (2019).

F. ARMY CAPABILITY GAPS

The Army has identified 14 capability sets that require creation or improvement if it hopes to contribute to the Joint Force (Training and Doctrine Command, 2018). We refer to these lacking capabilities as “gaps.” ExLF has the potential to address Gap 5 and Gap 10, which include:

(5) Establishing precision logistics that provides a reliable, agile, and responsive sustainment capability necessary to support rapid power projection, Multi-Domain Operations, and independent maneuver from the Strategic Support Area to the Deep Maneuver Area. (Supported by Army Materiel Modernization Priorities: Future Vertical Lift, Army Network). (Training and Doctrine Command [2018, p. xi])

(10) Providing to the Joint Force Commander multi-domain formations and systems that can converge capabilities to attack specific vulnerabilities in Chinese and Russian multi-layered, mutually reinforcing military forces and systems. This means creating commanders and staffs who have the means and ability to access and employ capabilities that reside across the Joint Force. (Supported by Army Materiel Modernization Priorities: Long-Range Precision Fires, Next Generation Combat Vehicles, Future Vertical Lift, Soldier Lethality). (Training and Doctrine Command [2018, p. xii])

THIS PAGE INTENTIONALLY LEFT BLANK

III. METHODOLOGY

The Army has directed the manning and equipping of BSBs to fulfill the sustainment needs of the brigade and has identified a transportation shortfall of approximately 42%. The purpose of this simulation is to explore the potential of ExLF to address this shortfall reflected in Gaps 5 and 10 by effectively expanding transportation capacity through personnel efficiency. To do so, we built a scenario reflecting the steady resupply of an IBCT over 21 days and compared the logistics impact of BSB support with ExLF technology to a base case without ExLF. While our scenario is limited in complexity, the simulation and model provide a framework and starting point for more advanced applications and analysis.

A. BACKGROUND

An IBCT consists of seven battalions: three infantry battalions, one cavalry (reconnaissance) battalion, one field artillery battalion, one engineer battalion, and one brigade support battalion. The BSB is relied upon to support the mobility and endurance of the six other units engaged in combat operations by conducting regular resupply of needed supplies. Our scenario analyzes four categories of supplies: Class I (water), Class III (fuel), Class V (ammunition),⁵ and a catch-all category known as “all other” which includes Classes II, IV, VI, VII, VIII, and IX. We assume each supported unit is capable of holding three days of supply on hand and located at an equal, fixed distance away from the BSB. Each day supplies are consumed by the using unit, and the BSB must allocate its distribution assets to support the highest priority needs across the supported battalions. We chose to assume IBCT consumption rates that are reflective of major combat operations.

In this simplified scenario, demand and supply are the two primary factors affecting sustainment operations. Demand refers to the rate at which each supported unit

⁵ Class V is measured as a part of the “all other” category for all units with the exception of the Field Artillery Battalion. Field Artillery’s Class V transportation requirements were significant while the other units’ Class V requirements were negligible and had no material effect in the simulation.

is consuming water, fuel, ammunition, or other materials. Supply refers to the BSB's distribution capacity, or the finite amount of transportation resources, personnel, and equipment available to resupply supported units in a timely fashion. While time and space are other important logistics considerations, our scenario holds these factors constant. Finally, combat operations are highly dynamic and often unpredictable. There are countless factors that can affect both the consumption of military supplies and the overall sustainment effort. Throughout our analysis, we make a number of key assumptions in order to limit the complexity of our scenario towards a manageable framework for comparative analysis.

1. Supported Units Characteristics

The supported units in our scenario are three infantry battalions, one cavalry (reconnaissance) battalion, one field artillery battalion, and one engineer battalion. Our scenario evaluates how well the BSB performs in resupplying these units with needed supplies.

a. Categories of Supplies

At the tactical level, military supplies affect a unit's readiness and the commander's options to accomplish the mission.

The U.S. Armed Forces divide all military supplies into 10 "Classes of Supply," shown in Table 1.

Table 1. Classes of Supply. Source: U.S. Army (2008b).

Table 1-1 Classes of supply	
Classes of supply	References
Class 1 – Subsistence, including free health and welfare items.	AR 30-22
Class 2 – Clothing, individual equipment, tentage, tool sets and tool kits, hand-tools, administrative, and housekeeping supplies and equipment (including maps). This includes items of equipment, other than major items, prescribed in authorization/allowance tables and items of supply (not including repair parts.	AR 700-84, CTA 50-900, CTA 50-970
Class 3 – POL, petroleum and solid fuels, including bulk and packaged fuels, lubricating oils and lubricants, petroleum specialty products; solid fuels, coal, and related products.	AR 11-27, AR 700-36, AR 710-2, FM 10-13, FM 10-18, FM 10-68, FM 10-69, FM 10-71, SB 710-2, TM 5-675
Class 4 – Construction materials, to include installed equipment, and all fortification/barrier materials	AR 420-17
Class 5 – Ammunition, of all types (including chemical, radiological, and special weapons), bombs, explosives, mines, fuses, detonators, pyrotechnics, missiles, rockets, propellants, and other associated items.	AR 190-59, AR 190-11, AR 190-13, AR 190-51, AR 700-19, AR 710-2, SB 700-2, SB 708-3, FM 9-38, TM 9-1300-206
Class 6 – Personal demand items (nonmilitary sales items).	AR 700-23
Class 7 – Major items: A final combination of end products which is ready for its intended use: (principal item) for example, launchers, tanks, mobile machine shops, vehicles.	AR 710-1, FM 704-28, SB 700-20, Appropriate authorization documents.
Class 8 – Medical material, including medical peculiar repair parts.	AR 40-61, CTA 8-100
Class 9 – Repair parts and components, including kits, assemblies and subassemblies, reparable and nonreparable, required for maintenance support of all equipment.	AR 710-2, AR 710-1, Appropriate TMs
Class 10 – Material to support nonmilitary programs; such as, agricultural and economic development, not included in classes 1 through 9.	CTA 50-909

The characteristics of the force, the operational environment, and the mission objectives dictate the flow and importance of each class of supply. We focused on three primary classes of supply that are most relevant to major combat operations, Class I, Class III, and Class V. Estimating the demand of these supplies is often a tactical focus of logistics planners as their consumption is both continuous and essential to the conduct of battle. However, things such as repair parts and construction materials can also be critical to force sustainment and may have a substantial lift requirement. We chose to incorporate the other classes of supply (Classes II, IV, VI, VII, VIII, IX) by including a fourth, catch-all category of supply in our model called “All Other.”

b. Measurement in Days of Supply

Our primary method for measuring supported unit supply inventories is days of supply. *Days of supply* translates a store of supplies into the number of days that a given

quantity of supplies will sustain a supported unit under specific conditions. What physically constitutes a day of supply (DOS) is linked to the unit size, type, and mission. One DOS of food for a 500-soldier infantry battalion will be higher than one DOS of food needed to sustain a 300-soldier engineer battalion. However, what represents one DOS of fuel will be much higher for the engineers. DOS gives the commander a common unit to understand the supply readiness of his subordinate units. It allows for the quick understanding of the current status of a given unit, without requiring in-depth knowledge of what 100 gallons of fuel means for readiness to one battalion versus another. Unless specified for a mission, units deploy with three DOS on hand and expect to be resupplied with one DOS every subsequent day. This provides a cushion for variability of consumption as well as for the times when resupply is infeasible for one or two days.

c. Demand Planning Factors

Supply planning factors can be grouped into two general categories based on the underlying factors that drive consumption: population or equipment. Ammunition consumption rates depend on the number and type of weapons coupled with an estimated level of use. Similarly, fuel consumption depends on the number of fuel-consuming assets, the rate at which each asset consumes fuel, and how frequently or steadily these assets operate. Taking this underlying equipment information into account, and assuming a level of activity consistent with major combat operations, the CASCOM planning tools generate an estimate for one day of supply of Class III and Class V for all six of our supported units.

Class I consumption is population-based and is typically measured in gallons per person per day. Class I consumption will also vary with the level of activity and environment. Logistics planners often use “minimum” and “sustaining” planning factors across different climate environments to capture this variation. We chose to utilize the “minimum” planning factor to reflect an austere environment and took the average consumption rate, 4.27 gallons per person per day, across all climates. We then multiplied this consumption rate by the population of our unit to determine their water requirement. We chose to estimate demand for potable water only, as non-potable water could be considered less essential to life support (U.S. Army, 2008a).

To estimate consumption and transportation parameters related to our other classes of supply, we utilized data tools obtained from the U.S. Army Combined Arms Support Command (CASCOM). CASCOM is a major subordinate command of the Training and Doctrine Command (TRADOC) and is charged with the development of concepts, doctrine, and training in support of the Army’s sustainment mission. The Planning and Data Branch (PDB) of CASCOM is responsible for “collecting, developing, maintaining, and validating logistics planning data” (U.S. Army, Combined Arms Support Command, 2019). As part of this mission, the PDB has developed a number of online tools and calculators used to aid logistics planners. One of these tools, the “Quick Logistics Estimation Tool” (QLET), is an Excel-based and lighter version of the Army’s OPLOG Planner. It provides minimum and maximum consumption estimates across a range of operations. We used data consistent with “major combat operations” to determine requirements for Class III, V, and “All Other” categories of supplies. While the QLET can be used to determine transportation requirements to support multiple units for a specific duration of time, another tool, the “Platform Calculator” estimates how many pallets and specific vehicle types are needed to carry a given quantity of supplies.

Using the previously mentioned resources, we created a conversion table depicting one DOS for each category of supply for our supported units (see Table 2). Converting DOS into a physical quantity of supply allows us to determine the transportation requirement.

Table 2. Conversion: 1 DOS for Supported Units in Simulation

1 DOS in UNITS					
UNIT	Class I Bulk Water gallons	Class III Fuel gallons	Class V Ammo pounds	OTHER Pallets	
INF1	2,066	1,104	145	1	17
INF2	2,066	1,104	145	1	17
INF3	2,066	1,104	145	1	17
FA	2,502	2,728	7,914	5.33	17
CAV	1,544	1,262	80	1	14
ENG	2,399	4,970	68	1	20

While we tried to rely on Army planning factors and tools as much as possible to anchor our methods, the conversion factors we calculated are specific to our simulation. We relied on our expertise as logistics officers to interpret the outputs from the Army tools to generate reasonable, average estimates for consumption in our simplified scenario. In practice, these calculations of DOS might differ greatly for similar units, by more precisely reflecting all the specific circumstances of the operating environment and mission.

2. BSB Transportation Capacity

Resupply operations require transportation assets and personnel trained to use this equipment. Distribution or “lift” capacity is used to describe the amount of supplies a given logistics support unit can move with all available assets and personnel. Our simulation assumes that the BSB has the transportation assets shown in Table 3.

Table 3. Simulation Brigade Support Battalion Distribution Assets

Simulation BSB Distribution Assets	
Assets	Number
HEMTT Fuelers	5
LHSs	28
Trailers	33
Hippos	10
Fuel Racks (MFS)	5

Unit equipment, in some cases, may be adjusted as required to meet mission requirements. In our scenario, we assumed that the equipment set was static over the course of the 21-day simulation. Maintenance requirements, discussed later, was the only factor affecting equipment availability.

a. Description of Transportation Assets for Supply Classes

The Load Handling System (LHS) is the primary logistics resupply vehicle used in our scenario (see Figure 4). While ExLF is currently being tested on the Palletized Load System, IBCTs are generally equipped with LHS vehicles in lieu of PLS vehicles. The LHS is an identical platform to the PLS, apart from having one fewer rear axle (three on a PLS, two on a LHS). This translates to the LHS having a smaller load capacity in regards to weight, but an identical capacity for volume.



Source: <https://oshkoshdefense.com/vehicles/m1120a4-lhs/#overview>

Figure 4. Load Handling System

The PLS Trailer (M1076) is a trailer designed to be pulled by any HEMTT variant but would be transported by an LHS (see Figure 5). A trailer can transport the equivalent of eight single stacked pallets.



Source: <https://oshkoshdefense.com/vehicles/pls-m1076-trailer/>

Figure 5. M1076 PLS Trailer

The LHS Compatible Water Tank Rack (AKA “Hippo”) attaches to the back of a PLS, LHS, or M1076 trailer (see Figure 6). The Hippo has a capacity of 2000 gallons of water and requires the complete volume capacity of the transportation platform.



Source: <https://asc.army.mil/web/portfolio-item/cs-css-load-handling-system-compatible-water-tank-rack-hippo/>

Figure 6. Compatible Water Tank Rack

The M978 HEMTT Fueler is the Army's prime mover for Class III (see Figure 7). It has a capacity of 2,500 gallons and is also able to tow a trailer with additional fuel capacity provided by a Modular Fuel System (MFS).



Source: https://www.armyrecognition.com/hemtt_a4_trucks_variants_oshkosh_defense_uk/m978_a4_hemtt_oshkosh_military_fuel_servicing_truck_tanker_data_sheet_information_specifications_uk.html

Figure 7. M978 HEMTT Fueler

The Modular Fuel System (MFS) attaches to an M1075 trailer or HEMTT LHS/PLS and can transport 2,500 gallons of fuel (see Figure 8). It is usually paired with a HEMTT refueler to provide a total fuel capacity of 5,000 gallons in one platform.



Source: https://www.leonardodrs.com/media/6278/mfs_datasheet.pdf

Figure 8. Modular Fuel System

b. Platform Configurations

These distribution assets can be arranged in different configurations to meet a specific support requirement—usually to transport a particular class of supply. For our analysis, we assume that the four most typical platform configurations are the only ones that can be used to resupply supported units. We refer to these four configurations by the category of supply they would transport (see Table 4).

Table 4. Platform Configurations

PLATFORM CONFIGURATION		LHS's	HEMTT's	Class I MRE's (Pallets)	Water Capacity (Gallons)	Fuel Capacity (Gallons)	Class V Capacity (Pallets)	Other Classes (Pallets)
CLASS I	LHS + Traller + (1) Hippo	1	-	8 pallets	2000 gal	-	-	-
CLASS III	HEMTT Fueler + MFS on Traller	1	-	-	-	5000 gal	-	-
CLASS V	LHS + Traller (Class V)	-	1	-	-	-	16 pallets	-
ALL OTHER	LHS + Traller (No Class V)	1	-	-	-	-	-	16 pallets

Class I is transported by an LHS with a trailer and a Hippo (2,000-gallon water tank) loaded either on the LHS or the trailer. We chose to assume that the additional bed space available would be used exclusively for transporting other Class I material (food) and not heavier items from our other categories of supply or an additional water tank.

Knowing that demand for meals-ready-to-eat (MRE) would never exceed the eight pallet positions reserved on the Class I platform, we can assume that the entire Class I resupply schedule is driven by a unit's need for water. The Class III platform includes a HEMTT fueler as the prime mover, which is paired with the MFS to move a total capacity of 5,000 gallons of fuel.⁶ The platform for both Class V and "All Other" categories is an LHS with a trailer. Safe handling of ammunition requires that certain types of ammunition cannot be transported with other materials. In order to keep our model simple, we chose to assume that Class V never shares bed space with any other class of supply, but that all types of Class V can be transported together. In practice, this constraint would be entirely dependent on the type of ammunition being transported. While some types of small arms ammunition can be transported with other materials (making our assumption overly conservative), other types of munitions must be segregated completely, and cannot even share space with other Class V material. Because we chose not to analyze specific ammunition types, our simulation does not incorporate these constraints.

c. Personnel Requirement

The standard requirement for vehicle operation is the use of two soldiers. One serves as the driver, while the second is a passenger and takes the role of "truck commander." It would be exceedingly unusual for a single soldier to operate a vehicle, and such a step is generally taken only in emergency scenarios.

3. Additional Assumptions

We chose to make several additional assumptions in order to limit the complexity of our analysis. First, we assume that each battalion is only responsible for sustaining itself and will not share supplies or assets with adjacent units. We also assume that any casualties experienced (personnel or equipment) are immediately replaced and thus maintain a consistent average demand for the full duration of the simulation. In order to isolate our simulation to one part of the supply chain, we assume that the BSB has an infinite store of

⁶ We assume that petroleum supply specialists operate the HEMTT Fuelers and require special certifications to transport hazardous materials such as Class III. Other platforms and personnel are assumed to lack these certifications and were not used to transport Class III within our simulation.

supplies and therefore is only constrained by available transportation capacity to deliver the various classes of supplies to the supported battalions organic to the IBCT.

Finally, sustainment vehicles like the PLS and LHS participate in sustainment convoys. These convoys are accompanied by security elements using other vehicle types that are not represented in our model. Security vehicles can carry small amounts of supplies, but these amounts are minimal and would have no material impact on the results of our simulation.

B. SIMULATION AND MODEL

The overall framework for our quantitative analysis is a running “balance sheet” of inventory levels of each of our four supply categories at each of our six units.

1. Flow of Supplies

Our Excel model is organized from left to right to reflect our defined sequence of logistics process events. This flow is outlined in Figure 9.

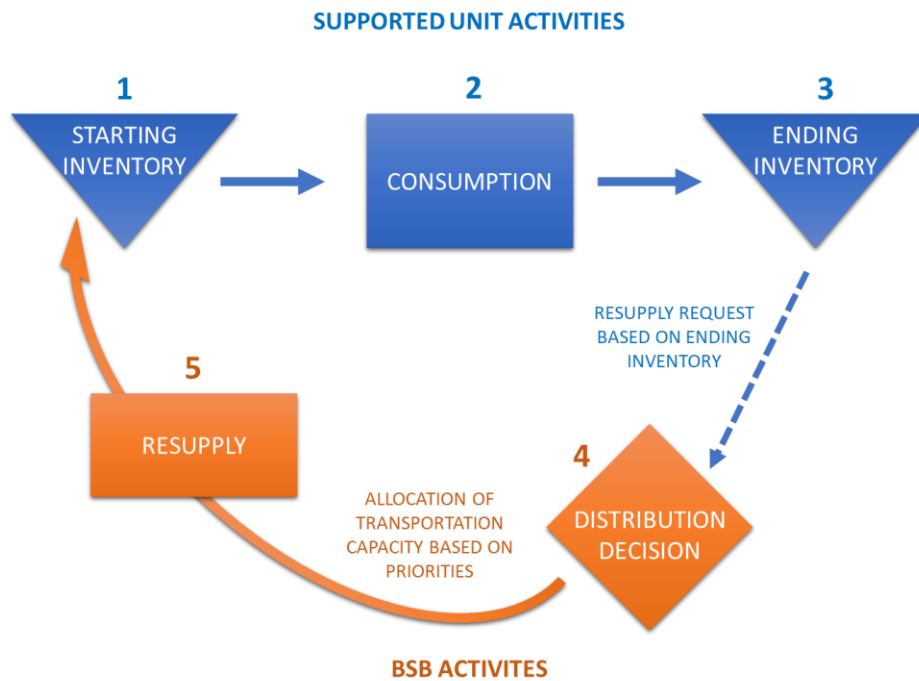


Figure 9. Logistics Process Flow

1. Starting balance: The measurement in DOS of each category of supply at each supported unit.
2. Consumption: The simulated consumption in DOS of each category of supply at each supported unit.
3. Ending Inventory: The measurement in DOS of each category of supply at each supported unit after consumption has occurred. A supported unit communicates ending inventory back to the BSB generating logistics requirements.
4. Distribution Plan: The BSB aggregates and weighs the logistics requirements of all units based on their ending inventory. Based on that, the BSB decides how to best allocate transportation assets in order to resupply supported units.
5. Resupply: Supported units are replenished based on the BSB's distribution plan, and a new beginning balance of supplies at each unit is calculated to begin the following day.

We assume that each unit can only hold three days of supply on hand, so the beginning balance of any category of supply cannot exceed three DOS. Three DOS is also, therefore, the “target” amount of supplies a using unit could and would want to carry on hand. The amount that current inventory is below three DOS reflects the *shortage* of a particular supply for a given unit. We also chose to assume that a resupply occurs early enough in the day that those supplies are available to support consumption that day and are therefore included in the day's beginning balance.

2. Simulating Consumption

The planning factors provided by CASCOM offer us a minimum, maximum, and average level of consumption for each category of supply. Given these parameters, we chose to use triangular distributions to simulate 21 days of consumption for Class I, III, V, and “All Other” categories of supply through Crystal Ball software.

3. Distribution Plan

The central aspect of our simulation is the decision the BSB must make on how best to utilize its distribution assets in order to resupply supported units. We chose to develop a model to resolve this decision in our simulation. Integer programming (IP) is used to determine mathematically, an optimal outcome whose requirements (objectives and constraints) are represented by linear relationships. Our model deals with allocating a finite resource (transportation capacity) to various activities (the replenishment of specific supplies to specific units) in order to best meet operational priorities (indicated by maximizing prioritization points).

a. *Assigning Prioritization Points*

When allocating a limited number of transportation assets across competing shortages, a supporting logistics unit would prioritize resupply efforts according to three main *criticality factors* that describe the urgency of the need:

1. Ending inventory level (or “shortage”): When a unit’s current inventory stores fall below a certain threshold of supply, maneuver options become increasingly constrained.
2. The relative importance of a supply class: While ammunition may be important to the conduct of combat operations, Class I provides basic life-support that supersedes all other supply priorities. Class III is essential to unit mobility and therefore less important than Class I and Class V, which provides for self-defense. While certain parts or materials might be deemed critical, taken together, “All Other” will not be more important than Class, I, III, or V.
3. The relative importance of the unit: In the scenario we have developed, the actions of the infantry units through regular resupply will likely be most important to the overall mission. Therefore, enabling them through regular resupply will be a priority. Further, any mission order will designate one unit the “main effort” in a particular phase of an operation, indicating that

the actions of this unit among all others are essential to the accomplishment of the mission. Our main effort is “Inf 1,” whose actions are only slightly more important than the other two infantry battalions. Next, the field artillery and cavalry units are more likely to provide essential support to the infantry battalions and, therefore, the combat mission overall. Of the six units, we consider the engineer battalion the lowest priority during large-scale combat operations. While the importance of a unit to the overall mission varies greatly with circumstance—and would likely change over the course of an entire operation—we chose to hold these relative priorities constant for the duration of our 21-day simulation. This is reasonable to assume in practice over a relatively short period of time.

We developed a table of prioritization points in order to quantitatively relate these three factors and provide an overall “criticality score” for a specific resupply requirement. The entire table is provided in Appendix H. Assigning quantitative values to the replenishment of specific supplies for specific units allows us to utilize a linear programming tool to optimize the allocation of distribution assets in order to best support the overall mission.

b. Distribution Model Formulation

Indices & Sets

- $i \in I$ Class of supply (1, 3, 5, AO)
- $j \in J$ Supported Unit (INF1, INF2, INF3, FA, CAV, ENG)

Input Parameters

- C Overall transportation Capacity of BSB (number of prime movers)
- C_1 Bulk water distribution capacity
- C_3 Bulk fuel distribution capacity
- C_5 Platform space available for the transport of ammunition
- C_{AO} Platform space available for the transport of “All Other” supplies

Calculated Parameters

- E_{ij} Ending inventory of class $i \in I$ at unit $j \in J$ (measured in DOS)
- W_{ij} Conversion factor for number of vehicles per DOS, for $i \in I, j \in J$

- S_{ij} Shortage of class $i \in I$ at unit $j \in J$ (measured in trucks)
- P_{ij} Prioritization points for level of supply E_{ij} for $i \in I, j \in J$

Integer Decision Variables

- X_{ij} Number of trucks of supply $i \in I$ shipped to unit $j \in J$

Objective Function

- (1) Maximize $\sum_{i \in I} \sum_{j \in J} X_{ij} P_{ij}$

Constraints

- (2) $\sum_{i \in I} \sum_{j \in J} X_{ij} \leq C$ (total shipping capacity)
- (3) $\sum_{j \in J} X_{ij} \leq C_i \forall i \in I$ (shipping capacity by class)
- (4) $X_{ij} \leq \lceil S_{ij} \rceil, \forall i \in I, j \in J$ (shipping limit)
- (5) $X_{ij} \in \{0, 1, 2, \dots\} \forall i \in I, j \in J$

(1) Explanation of Objective Function and Constraints

Our objective function (1) prioritizes shipments based on the current level of supply, by class of supply and unit, seeking to maximize aggregate value. The model allocates transportation capacity subject to four main constraint types. Constraint (2) represents overall transportation capacity—the availability of 33 prime movers (28 LHS vehicles and five HEMTT fuelers) to move all supplies. Constraint (3) ensures that the amount of water, fuel, ammunition, and “all other” supplies transported does not exceed the transportation capacity available to move these supplies. Constraint (4) ensures that no more than the amount of trucks required to meet demand may be shipped. Constraint (5) ensures that our decision variables are integers, since distribution assets cannot be divided, due to the specialized shipping requirements of each class of goods.

(2) Adjusting Capacity to Reflect Variation in Equipment Readiness

Realistically, not all equipment a unit has will be available for operational use. Both planned and unplanned maintenance will limit the number of vehicles available at a given time. We chose to assume that the average operational availability of Army vehicles was 85%, with a floor of 70%. Using a triangular distribution in Crystal Ball to simulate the operational readiness of LHS and HEMTT fuelers results in adjusted capacity levels for

both those assets each day. On any given day, there will be a minimum of 19 LHSs available, with an average of 23.8. Similarly, there will be between three and five, but most often four, HEMTT refuelers available for resupply operations each day.

(3) Adjusting for Oversupply with Binary Demand Constraints

Ideally, we would want to *minimize* risk by maximizing the prioritization points reflected in *post-distribution* supply inventories (next day “beginning inventory”) at each supported unit. However, our integer programming model is not ideally suited to account for these non-linear effects directly. Instead, the model uses *pre-distribution* inventories (current day “ending inventory”) in order to assess the urgency of need and allow the BSB to prioritize resupply efforts accordingly. As expected, the key limitation of this approach is that optimizing based on prioritization points determined by pre-distribution inventories encourages over-supply. For example, if the highest priority unit has zero days of the most urgently needed supply, the model would maximize prioritization points by sending all vehicles to that location.

We refined our model to ensure that it does not errantly reward the extra unused capacity in the objective function. To adjust for this issue, we created a mirror set of decision variables and demand constraints, making the decision variables binary and the demand constraints equal to the exact amount of supplies a unit requires. The binary decision variables activate when shipments exceed supply. The model then deducts the proportional value of prioritization points within our objective function. In order to remove the incentive for shipping an underutilized truck for a highly prioritized supply class and unit, we introduce a new set of parameters and binary decision variables:

Binary Decision Variables

$Y_{ij} = \{ 1 \text{ if a truck is shipped to cover a partial truckload of demand, } 0 \text{ otherwise} \}$

We can now reformulate our model as:

Objective Function

$$(6) \text{ Maximize } \sum_{i \in I} \sum_{j \in J} (X_{ij} - Y_{ij}([S_{ij}] - S_{ij})) P_{ij}$$

Constraints

- (7) $\sum_{i \in I} \sum_{j \in J} X_{ij} \leq C$ (total shipping capacity)
- (8) $\sum_{j \in J} X_{ij} \leq C_i \forall i \in I$ (shipping capacity by class)
- (9) $X_{ij} \leq \lfloor S_{ij} \rfloor, \forall i \in I, j \in J$ (shipping limit)
- (10) $X_{ij} - Y_{ij} \leq \lfloor S_{ij} \rfloor, \forall i \in I, j \in J$ (linking constraint)
- (11) $X_{ij} \in \{0, 1, 2, \dots\} \forall i \in I, j \in J$
- (12) $Y_{ij} \in \{0, 1\} \forall i \in I, j \in J$

The updated objective (6) now caps the incentive to ship at the prorated amount of any partial shipment required to fully meet demand. For example, if a unit's shortage was 2,100 gallons of water, the BSB would not send more than two Class I platforms (carrying 2,000 gallons of water each) to fulfill this need. Allocating any more resources would be a wasted use of capacity, no matter how great the initial urgency of the shortage. Whereas objective (1) awarded prioritization points for up to 4,000 gallons shipped, objective (6) now only awards prioritization points for the first 2,100 gallons shipped.

In order to ensure the binary variables are activated when partial-truck demand utilizes full-trucks for shipments, constraints (10) act as a linking constraint, by rounding down the shortage amount measured in vehicles to less the actual shortage amount allowed in constraints (9). When the shortage is already an integer value, constraints (9) and (10) become redundant.

Constraints (7) to (9) and (11) remain the same as in the original model. The binary constraints are introduced in (12).

(4) Simulation with ExLF

Using this distribution model within our simulation allows us to optimize the distribution of transportation assets each day. Ultimately, our simulation generates the ending inventory of each category of supply at each supported unit over a 21-day period. This allows us to see how adjustments in transportation capacity affect the logistics response and timely resupply of each supported unit.

Creating transportation capacity requires both equipment and personnel. Vehicles and their distribution assets require drivers to conduct resupply operations, and obviously drivers would be no use without vehicles to drive. Most units, including our simulated

BSB, are manned with two drivers per vehicle. While vehicles can theoretically operate for 24 hours per day, per most safety policies, all drivers must receive eight hours of rest during the same 24-hour day. Therefore, while 33 vehicles operating for 24 hours theoretically represents the maximum transportation capacity of the BSB, available drivers can only operate 33 vehicles for 16 hours per day.

By allowing for unmanned follower vehicles, ExLF technology decreases the amount of personnel required to operate the BSB's vehicles, thereby removing this personnel constraint present in the base case and allowing capacity to expand back towards the theoretical maximum of 33 vehicles operating 24 hours per day. Instead of expressing transportation capacity in terms of a longer operating day, an equivalent way to understand the expansion of transportation capacity with ExLF technology is 50% more vehicles operating for the same length operating day. Therefore, to capture the impact of ExLF in our second 21-day simulation, we increased the number of vehicle platforms (after adjusting for maintenance effects) by 50%. For example, if our simulation on a given day resulted in 24 available LHS vehicles (four down for maintenance), under ExLF we represented this expanded capacity by adjusting our constraint 50% higher to 36 HEMTT vehicles. This reflects the idea that 24 vehicles incorporating ExLF technology and enjoying greater personnel efficiency can achieve the same theoretical logistics throughput as 36 vehicles operating without ExLF technology.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. RESULTS AND ANALYSIS

As previously stated, an IBCT’s logistics support system aims to ensure supported units constantly have between two and three days of supply on hand. Therefore, scenarios where classes of supply resulted in less than 2 DOS at the end of any given day represented an increased level of risk for that unit. These scenarios provide the basis through which the simulation results are compared and analyzed between two 21-day simulations; the status quo IBCT and an IBCT with ExLF-enabled transportation. All other variables were held constant in order to isolate the effect of ExLF implementation.

A. RESULTS

The first simulation, the status quo IBCT, resulted in a total of 37 occurrences where a unit’s level of supply dipped below the 2 DOS level threshold. The data table from the result of the simulation is provided in Table 5.

Table 5. IBCT Status Quo 21-Day Simulation

	INFANTRY 1				INFANTRY 2				INFANTRY 3				FIELD ARTILLERY				CAVALRY				ENGINEER			
	I	III	V	AO	I	III	V	AO	I	III	V	AO	I	III	V	AO	I	III	V	AO	I	III	V	AO
1	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
2	3.00	2.10	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.98	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.02	3.00	3.00	3.00	2.93	3.00	3.00
3	3.00	3.00	3.00	3.00	3.00	1.91	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.91	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.86	3.00	3.00
4	3.00	2.05	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.07	3.00	3.00	3.00	2.56	3.00	3.00	3.00	1.68	3.00	3.00	3.00	2.79	3.00	3.00
5	3.00	3.00	3.00	3.00	3.00	1.95	3.00	3.00	3.00	1.07	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.83	3.00	3.00
6	3.00	2.01	3.00	3.00	3.00	0.85	3.00	3.00	3.00	3.00	3.00	2.96	3.00	1.92	3.00	3.00	3.00	1.89	3.00	3.00	3.00	2.82	3.00	3.00
7	3.00	1.01	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.87	3.00	3.00	3.00	2.54	3.00	2.99	3.00	3.00	3.00	3.00	3.00	1.87	3.00	3.00
8	2.98	3.00	3.00	3.00	2.99	1.97	3.00	3.00	3.00	1.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.43	3.00	3.00	3.00	2.79	3.00	3.00
9	3.00	1.84	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.98	3.00	2.08	3.00	3.00	3.00	2.87	3.00	3.00	3.00	2.75	3.00	3.00
10	3.00	3.00	3.00	3.00	3.00	1.86	3.00	3.00	3.00	1.94	3.00	3.00	3.00	2.66	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.67	3.00	3.00
11	3.00	3.00	3.00	3.00	3.00	1.82	3.00	3.00	3.00	1.93	3.00	3.00	3.00	2.62	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.73	3.00	3.00
12	3.00	2.10	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.95	3.00	3.00	3.00	2.86	3.00	1.88	3.00	3.00	3.00	2.74	3.00	3.00
13	2.99	3.00	3.00	3.00	3.00	2.06	3.00	2.95	3.00	1.93	3.00	3.00	3.00	2.02	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.71	3.00	3.00
14	3.00	2.10	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.58	3.00	3.00	3.00	1.82	3.00	3.00	3.00	2.73	3.00	3.00
15	3.00	3.00	3.00	3.00	3.00	1.88	3.00	3.00	3.00	1.91	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.66	3.00	3.00
16	3.00	2.01	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.38	3.00	3.00	3.00	2.68	3.00	3.00
17	3.00	3.00	3.00	3.00	3.00	1.82	3.00	3.00	3.00	1.87	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.64	3.00	3.00
18	3.00	2.05	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.89	3.00	3.00	3.00	2.19	3.00	3.00	3.00	2.61	3.00	3.00
19	3.00	3.00	3.00	3.00	3.00	1.91	3.00	3.00	3.00	2.05	3.00	3.00	3.00	2.35	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.57	3.00	3.00
20	3.00	2.13	3.00	3.00	3.00	0.83	3.00	2.99	3.00	0.96	3.00	3.00	3.00	2.89	3.00	3.00	3.00	1.47	3.00	3.00	3.00	2.52	3.00	3.00
21	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.79	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.52	3.00	3.00
AVG	3.00	2.49	3.00	3.00	3.00	2.33	3.00	3.00	3.00	2.27	3.00	2.99	3.00	2.56	3.00	2.99	3.00	2.51	3.00	3.00	3.00	2.50	3.00	3.00
Days w/DOS < 2 =		37																						

The second simulation, an IBCT with ExLF, resulted in a total of four occurrences where a unit’s level a supply fell below the 2 DOS level threshold. The data table from the result of the simulation is provided in Table 6.

Table 6. IBCT with ExLF 21-Day Simulation

	INFANTRY 1				INFANTRY 2				INFANTRY 3				FIELD ARTILLERY				CAVALRY				ENGINEER				
	I	III	V	AO	I	III	V	AO	I	III	V	AO	I	III	V	AO	I	III	V	AO	I	III	V	AO	
1	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
2	3.00	2.10	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.93	3.00	
3	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	1.98	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.83	3.00	3.00	
4	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.79	3.00	3.00	
5	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.80	3.00	3.00	
6	3.00	2.01	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.82	3.00	3.00	
7	3.00	3.00	3.00	3.00	3.00	1.99	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.84	3.00	3.00	
8	3.00	3.00	3.00	3.00	2.99	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.79	3.00	3.00	
9	3.00	3.00	3.00	3.00	2.99	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.79	3.00	3.00	
10	3.00	1.97	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
11	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.27	3.00	3.00	3.00	2.96	3.00	3.00	
12	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.97	3.00	3.00	
13	3.00	3.00	3.00	3.00	3.00	2.06	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.94	3.00	3.00	
14	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.96	3.00	3.00	
15	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.89	3.00	3.00	
16	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.91	3.00	3.00	
17	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.87	3.00	3.00	
18	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.19	3.00	3.00	3.00	2.84	3.00	3.00	
19	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.05	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.77	3.00	3.00	
20	3.00	2.13	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.75	3.00	3.00	
21	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.72	3.00	3.00	
AVG	3.00	2.82	3.00	3.00	3.00	2.91	3.00	3.00	3.00	2.86	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.93	3.00	3.00	3.00	2.87	3.00	3.00	
Days w/DOS < 2 =																									4

The figures within the table are rounded up to two decimal places. Therefore, the “2.00” for “INFANTRY 3” on day 5 for class III is actually 1.999564, which just barely breaks the 2 DOS threshold.

B. ANALYSIS

As expected, our simulation incorporating ExLF technology demonstrated that increases in transportation capacity would result in improved logistics performance through more timely resupplies. Overall, Class III was the most strained of our categories under the base scenario and also showed the most improvement with the incorporation of ExLF. This result makes sense given that there were only five total platforms available for transporting fuel, making it the most “constrained” of our transportation assets for this specific category of supply. Also of note, the simulation with ExLF resulted in only four occasions where a supply category fell below 2 DOS, but each of these occasions were just barely below this threshold with a low of 1.975 and an average of 1.985 between all four occasions. Therefore, ExLF provided a nearly complete reduction in risk as measured as any occasion where a supply category falls below 2 DOS.

1. The Impact of ExLF

The status quo for throughput did not place a strain on the supply chain that could be considered catastrophic. While shortfalls well below 2 DOS were experienced, no battalion reached zero DOS in any class of supply. ExLF increases throughput capacity during combat operations, but not to a level that clearly demonstrates a need for adoption of the technology—at least not in the context of this model. The primary consideration where ExLF could be leveraged given the results involves the personnel efficiencies gained from the technology. The ability to increase throughput capacity with fewer operators introduces the option of utilizing these *saved* personnel for alternative purposes.

2. HEMTT Fueler Shortfall

Under the status quo, HEMTT Fueler capacity was unable to meet the full demand of the IBCT for the entirety of the simulation. Even with the increased capacity gained from ExLF, fuel was still constrained for all days simulated. However, the fuel shortfall under ExLF was reduced by 15.7% across all six supported units. While fuel still remained constrained with ExLF, LHS capacity was not fully utilized and may provide an opportunity for the U.S. Army to evaluate the allocation of equipment and personnel assets with respect to Class III. Exchanging LHSs for fuelers and/or motor transport operators for petroleum supply specialists when developing the standard IBCT configuration may solve the identified fuel capacity shortfall.

3. Limitations

There are several limitations in our analysis related to assumptions made to simplify our scenario or made with respect to the application of ExLF technology in order to establish a functioning simulation model to conduct the comparison.

First, we acknowledge that the nature of our scenario does not fully reflect the dynamic nature of combat operations, which can mask the size and nature of the transportation challenge for the Army. For example, we chose to assume steady-state operations ignoring troop movements and the resulting personnel lift requirements. These requirements can be substantial over the course of an operation and particularly during

early stage insertion or major offensives. Similarly, our scenario focuses exclusively on one segment of the supply chain by assuming unlimited supplies at the BSB. This limitation masks strain that might be present throughout the supply chain due to both supply shortages and a lack of lift capacity. To the extent these bottlenecks are related to the lack of available drivers, ExLF has great potential to alleviate this strain with compounding benefits throughout the supply chain. On the other hand, to the extent where bottlenecks are a result of shortages in transportation assets or actual supplies, ExLF would not produce much of an effect at all. A more robust analysis examining a multi-stage supply chain would better parse out the relationships between these bottlenecks and better capture aggregate impacts across the entire supply chain.

Second, the design of our analysis only explores one application of the expanded transportation capacity provided by ExLF technology: increasing throughput in order to provide more frequent resupplies. It is also likely that ExLF would be implemented to decrease the personnel requirement, holding throughput constant, or to resupply units positioned at further distances from the BSB.

Finally, our analysis implicitly assumes that the operational capability of unmanned follower vehicles is the same as manned vehicles. In reality, the ExLF convoys might not possess the same resilience or mobility as fully manned convoys, for example, in the case of adverse weather, rough terrain, navigational challenges, or the performance of complex driving maneuvers (reversing a vehicle with a trailer). Our analysis also does not account for any changes in maintenance patterns due to the implementation of this technology. Our simulation explored the impact of increasing transportation capacity and logistics throughput through personnel efficiency. In reality, incorporating ExLF technology will involve numerous, unknown second and third order effects that must also be considered to provide a more complete evaluation.

V. CONCLUSIONS AND RECOMMENDATIONS

A. BATTLEFIELD APPLICATION

We chose to base our simulation at the Forward Line of Troops (FLOT) in an effort to test ExLF outcomes in the most demanding environment. The Army has identified gaps, as we have previously discussed, in sustainment, and the effects of those gaps are more significantly felt the closer sustainment operations occur to the enemy. That said, our simulation is just an attempt at a proof of concept and is not a recommendation that the Army begin ExLF (or any AGR technology) adoption at the FLOT.

The leaders that will make the decision for adoption of ExLF have extensive professional experience with manned convoy operations. The idea of removing the soldier from the equation may be unpalatable and flies directly in the face of the Army's "boots on ground" mentality. The use of unmanned vehicles in other services (e.g., drones) will soften the perception that operations must be manned, but there will still be a hurdle. Adopting AGR technology in the rear echelons will likely ease potential tensions with the technology and allow programs like ExLF to prove themselves in a lower-threat environment.

Any decision the Army makes on ExLF adoption will factor in many variables. We believe these variables must include considerations in maintenance, survivability, and personnel.

B. MAINTENANCE IMPLICATIONS

Adoption of ExLF will lead to ramifications, both negative and positive, with the maintenance requirements of any vehicle on which the system is applied.

1. Negative Considerations

Additional Maintenance Professionals: ExLF will incorporate technology that is unique to the Army and requires increased investment in maintenance, training, and equipment. This investment must allow for additional allocations of computer/detection system repairers (Military Occupational Specialty 94F). The 94F community would handle

the maintenance of the robotic kits, while the 91B (wheeled vehicle mechanic) community is leveraged to support the increased maintenance intensity of driving the trucks for longer shifts. There will be costs associated with increasing man-hours of 94Fs, and potentially also man-hours of the 91Bs, as these vehicles are expected to perform at a higher operational tempo.

Supply Support: ExLF will require maintenance and servicing of parts that are unique to the technology and would not otherwise be required on a standard vehicle.

Additional Parts Storage: Units will maintain a bench stock of parts for the new system. Storage of these new parts will require additional containers or facility square footage as well as any holding costs that go along with that new storage. This bench stock would otherwise not exist with the status quo.

Increased Platform Downtime: Applying ExLF to a vehicle platform introduces one additional system that requires preventive and corrective maintenance. This may increase the overall downtime for whatever platform to which ExLF is applied.

2. Positive Considerations

Accident Avoidance: Accidents involve many costs. While vehicle damage is the most obvious, personnel also risk injury or death which carry costs as well (medical, administrative, lost productivity, etc.). It is estimated that over 90% of vehicle accidents are caused by human error (National Highway Traffic Safety Administration [NHTSA], 2015). Autonomous technology could theoretically recapture 90% of the costs associated with accidents by avoiding the accidents caused by human error. While accidents due to mechanical failure are also possible, driver-assist technology should greatly reduce damage in these instances by removing the chance of human error during a reaction to the failure.

Diagnostic Technology: There is the potential to integrate condition-based-maintenance strategies with diagnostic and health monitoring capability. By providing component readiness and performance status of the host vehicle, this “Health Management System” (HMS) will enable fault detection and appropriate corrective actions. Monitoring vehicle status ensures that performance-based maintenance is scheduled promptly and

efficiently, resulting in the more efficient use of maintenance resources. Preventive maintenance is inherently cheaper and less intensive than corrective maintenance.

C. SURVIVABILITY

Any automation advancement comes with the hope that soldiers will experience fewer casualties. Fewer soldiers in a convoy will necessarily lead to fewer soldier casualties simply because of reduced enemy exposure for the total force. However, because ExLF is not a completely autonomous convoy solution, the personnel survivability effects must be viewed slightly differently.

For the soldiers tasked with manning the lead vehicle in a leader-follower convoy, the chance of casualty will almost certainly increase (assuming no other convoy changes have been made). For example, a convoy of 10 vehicles *without* ExLF technology that is ambushed by the enemy will have at least 20 soldiers on hand for defense (one driver and one truck commander per vehicle). That same convoy *with* ExLF technology will have just two soldiers (one driver and one truck commander for the lead vehicle). Eighteen soldiers have been removed from risk because of ExLF; however, the two remaining soldiers are in significantly increased danger for injury or death at the individual level. Any commander will struggle to justify exposing soldiers to that level of personal risk.

One solution may be to increase the size of the security element that is escorting the supply convoy, and that will certainly decrease the risk. However, commanders must consider what other missions become degraded or infeasible through this reallocation of combat assets.

D. PERSONNEL CONSIDERATIONS

ExLF technology clearly provides some tangible benefits but also comes with significant personnel considerations. In short, ExLF technology allows a unit the ability to do more with less, but this benefit comes at the expense of increased load and unload time required to get a logistics convoy prepared at the origin and off-loaded at the destination. The following example provides a basic illustration of this point.

Take the previous scenario where ExLF is incorporated to its fullest extent for a convoy comprised of 10 vehicles in other words, one manned leader vehicle and nine unmanned follower vehicles. Typically, such a convoy would require between 20 at the most minimal possibility up to near 40 personnel to operate. Meanwhile, ExLF would enable this same convoy to operate with as little as two personnel in the lead vehicle. Now, consider the fact that the personnel assigned to a convoy are also responsible for preparing, loading, and staging of the vehicles. This task moves quickly and efficiently when each vehicle's operators work together to prepare it simultaneously along with the all the other vehicles of the convoy, but would present a significant challenge in the scenario where ExLF is implemented with the minimum number of personnel. Thus, the personnel savings from ExLF comes at the expense of much more effort to handle the convoy's cargo. Therefore, how the *saved* personnel are utilized becomes a consideration of paramount importance to the overall picture of the benefits attained by ExLF.

This scenario provided an illustration of two ways to conduct a 10-vehicle convoy with and without ExLF. The next section further explores alternative forms and levels of implementation of ExLF technology within logistics convoy operations and the effect on both transportation capacity and personnel.

E. FORMS AND LEVELS OF IMPLEMENTATION OF ExLF

ExLF technology provides great flexibility in both the form and level of implementation to augment transportation capacity. This flexibility enables a unit to leverage which type of implementation of ExLF best suits their mission requirements and/or constraints. The next section examines three alternatives of implementation and the resulting effect on capacity, while the fourth explores some options for utilizing the potential excess personnel created from ExLF implementation.

1. Status Quo Capacity with Less Personnel and Equipment

The first option involves the ability of ExLF to maintain current transportation capacity with less personnel and equipment. The amount of personnel and equipment reduction depends on the specific operational context of a given unit; the correct balance will vary from one unit to the next. The increase in utilization capacity for each operator

and truck with ExLF enables this form of implementation. A reduction in the amount of equipment necessary to effectively provide logistics support also results in a reduction in the maintenance requirement as well. However, as noted earlier, further research is necessary to determine the magnitude of this benefit due to the increased operational tempo of each individual truck. The bottom line for this form of implementation is that ExLF provides the ability to provide the same transportation capacity with less personnel and less equipment.

2. Small Capacity Increase with Less Personnel

The second option involves the ability of ExLF to increase current transportation capacity with less personnel but with the status quo equipment. Again, in similar fashion to the previous section, the amount of personnel reduction depends on the specific operational context of a given unit. By leveraging the greater efficiency of each operator and the increased utilization of each truck, a unit can experience an increased logistics transportation capacity while simultaneously considering the available options for alternative uses of the displaced personnel. The bottom line for this form of implementation is that a unit can increase its capacity using their status quo equipment set and simultaneously leverage the personnel savings for other purposes.

3. Large Capacity Increase with More Equipment

The third option involves the ability of ExLF to greatly increase current transportation capacity with status quo personnel and more equipment. The magnitude of equipment increase depends on the specific operational context of a given unit; in some cases, large increases in capacity is unnecessary. This form of implementation leverages the ability of a unit to maximize the capacity of each individual truck operator but requires a substantial investment in additional trucks. A primary consideration of this form of implementation manifests with budget constraints and maintenance. Increasing the number of trucks in a unit is no simple task and will present a significant obstacle, particularly in a likely future of fiscal austerity in response to the growing national debt. Furthermore, an increase in the number of trucks also requires a complimentary increase in the maintenance activity required to support those trucks, resulting in an increase of 91B soldiers, which

manifests an additional expense to consider. Yet, due to ExLF's autonomous capability, the Army would not have to enlist and train additional truck operators, providing a slight counterbalance to these identified expenses. The bottom line for this form of implementation is that it provides the opportunity for the Army to bridge any of the transportation capacity gaps determined worth the increased expense.

4. Alternative Options for Displaced Personnel

One of the greatest benefits of ExLF involves the personnel savings achieved while maintaining or even increasing transportation capacity. Personnel represents one of the most significant investments for the United States military. The amount of time and money required to recruit, train, and maintain a soldier is significant, and it imposes a challenge for the Army to allocate enough trained personnel everywhere in need. Therefore, considering options where the *saved* personnel provide the best utility is a necessary discussion.

Maintainers: Regardless of the chosen form of ExLF implementation, the increased operational tempo of each truck will require more frequent preventive maintenance. Therefore, utilizing some of the displaced personnel to augment the maintenance capacity of a unit provides a logical solution. Cross-training truck operators as mechanics would provide the ability to reallocate personnel if deemed necessary at a latter point, or the unit could be restructured to have fewer truck operators and more mechanics.

Heavy Equipment Operators: Reducing the number of personnel assigned to logistics convoys through the implementation of ExLF creates an increased burden on the task of loading and unloading supply cargo. Therefore, utilizing some of the displaced personnel as heavy equipment (HE) operators⁷ provides a solution to this burden. These soldiers could either be cross-trained for operating both trucks and forklift assets or, eventually, units could be restructured with fewer truck operators and more fully trained HE operators.

⁷ Heavy equipment includes a variety of specialized assets, but those of interest here include various forklift assets used to load and off-load cargo from trucks.

Combat focused: Another area of potential concern regarding the implementation of ExLF involves the survivability of a convoy with reduced personnel. Therefore, restructuring units with fewer truck operators and more combat-oriented occupation specialties would provide the ability to increase the survivability of an ExLF convoy. Total personnel savings on convoy operations would necessarily be reduced in this case, but the inclusion of combat-oriented occupation specialties on convoys would also likely improve the survivability of the convoy above the status quo construct with only truck operators. So, this option provides a commander with a logical solution if ExLF is implemented near the FLOT in contested areas.

Needs of the Army: Limitations on the number of personnel, or force caps, creates a situation where the supply of some occupational specialties falls well short of the demand. Therefore, utilizing the sum of displaced personnel force cap spaces for the recruitment and training of additional occupational specialty areas in high demand could help the Army adjust to personnel shortfalls throughout the force. If ExLF is eventually adopted throughout the entire Army, the number of truck operators displaced would create a significant opportunity for the Army to implement a combination of the above-mentioned options, maximizing the utility gained from the AGR technology.

F. MARINE CORPS ExLF APPLICATION

The Logistics Vehicle System Replacement (LVSR) is the Marine Corps' comparable variant of Army's PLS. The LVSR provides similar capabilities as the PLS and utilizes the same M1076 trailer. Therefore, the ExLF appliqué would easily adapt to the LVSR should the Marine Corps choose to pursue acquisition of this AGR technology. However, in its current state, ExLF may not provide the same tangible benefits for the Marine Corps as the Army.

The Marine Corps and Army share similarities in terms of equipment and capabilities as ground forces, but their differences have significant implications for the application of ExLF to Marine transportation equipment. The Marine Corps intentionally represents a much smaller and more agile force in comparison to the Army due to the mission designated by Title 10 requirements. The Army is well designed and equipped for

dominance in prolonged land-based warfare with robust and lengthy supply lines. In contrast, the Marine Corps is specifically tailored and equipped for expeditionary amphibious operations and self-sustainment for short periods up to one month, depending on the size of the force. Keeping these differences in mind, the potential role of ExLF within the Marine Corps will likely look very different from the Army and may not actually materialize until AGR technology matures.

Marine Corps' missions include raids, assaults, and crisis response operations within the littoral regions of the world. These missions typically result in compressed supply lines much closer to and often within kinetic combat operations, corresponding to a scenario currently more suitable for human operators. The more chaotic an environment, the more the necessity for immediate decisive individual actions becomes for the forces operating within that environment. Therefore, ExLF technology as it exists today most likely cannot provide the same paradigm-shifting impact to logistics support for the Marine Corps' amphibious operations that the Army may experience.

Another important consideration regarding the potential implementation of ExLF concerns the nature of amphibious operations. Marine missions often originate from amphibious ships and utilize ship-to-shore connectors⁸ to get ashore. These connectors require the Marines and vehicles to quickly disembark from the connector upon arriving ashore to limit risk exposure to the forces. This significant requirement further complicates any full-scale integration of ExLF into Marine operations.

One potential solution for ExLF includes a much smaller ratio between leader and follower vehicles utilized within Marine logistics convoys. A logistics convoy with multiple leader vehicles, each with minimal follower vehicles, may provide a sufficient ability for the convoy to conduct defensive maneuvers while still providing some of the aforementioned personnel benefits regarding increasing efficiency. Furthermore, by limiting the number of unmanned ExLF vehicles, the amphibious issue previously identified could be partially mitigated.

⁸ Primary ship-to-shore connectors includes the Landing Craft Air Cushion (LCAC) and the Landing Craft Utility (LCU) vehicles. More information can be found on these vehicles at <https://www.candp.marines.mil/Programs/Focus-Area-3-Naval-Integration/Surface-Connectors/>

The expeditionary and amphibious nature of Marine operations lends itself more favorably to the air and sea autonomous vehicle technology currently being pursued by the U.S. Navy. These platforms are specifically adapted for the areas and terrain where the Marine Corps is designed to operate. Consequently, most of the current investment in autonomous resupply technology for the Marine Corps does not focus on AGR capabilities such as ExLF.

Despite these considerations, as ExLF technology matures and future versions that provide enhanced capabilities come online, the Marine Corps must reevaluate the potential application of this technology to augment its logistics capacity. In the meantime, the Marine Corps should continue to closely monitor the Army's utilization and refinement of their integration of ExLF. The potential benefits of the AGR technology represent a worthwhile capability too promising to dismiss.

G. FUTURE RESEARCH

This project represents a stepping-stone for a multitude of future research possibilities. In order to develop a baseline model for comparison, much of our effort focused on the development of a functioning model to mirror the organic logistics support system of an IBCT. Our model is limited by design but could be easily expanded to support additional research. Some recommended expansions and adjustments include:

1. Enemy Action Incorporation

Our simulation did not consider the possibility of enemy actions taken against a resupply convoy. Future iterations of this research could include a chance that a convoy does not reach the supported unit due to enemy interference. Such consideration would further strain the status quo transportation capacity and increase the benefit of implementing ExLF into logistics support operations.

2. Personnel Survivability Considerations

The survivability of convoys utilizing ExLF to the fullest extent introduces two elements of personnel survivability. First, fewer personnel in a convoy reduces the probability of a soldier getting harmed during an enemy ambush and/or an Improvised

Explosion Device (IED) detonation. Second, this same convoy with reduced personnel are now exposed to substantially more individual risk than in the status quo scenario of a fully manned convoy. Therefore, incorporating this variable into ExLF simulation may provide the ability to explore the optimal number of personnel that balances both components of personnel survivability.

3. Mechanical Failure Considerations

ExLF may actually induce an increase in the number of maintenance failures experienced by the vehicle platform utilized. This decrease in truck availability was not included in our model, but incorporating this variable would more accurately highlight the maintenance considerations of an increased operational tempo for the equipment.

4. Simulation Scope

This simulation is centered on one small portion of the overall theater sustainment operating picture. Expanding the simulation to include resupply convoys, which occur in rear echelons, will help to increase the scope of research. These rear echelon convoys also represent logistics operations done by unit types other than an IBCT and may highlight Army manning and equipping concerns that were not uncovered in our research. Further benefits of ExLF may be realized in a broader application.

5. Prioritization Points Significance

Adjusting prioritization points on a class of supply basis as determined by the mission of the unit will create different results in the distribution plan of the model. Units could be prioritized based on the relative importance of that class of supply given its unique equipment set and/or mission. For example, an Engineer Battalion utilizes much more Class III than any other unit within an IBCT, due in large part to the fuel consumption of the HE equipment they operate. Therefore, Class III may be a higher priority for them than any other unit. A similar relationship could be argued for Class V for the Field Artillery Battalion in comparison to other units of an IBCT. Incorporating this prioritization points adjustment would provide more realism to the model.

6. Organic Lift Gap

We chose to keep the IBCT in a static location for our simulation. Future iterations could strain the capacity of the IBCT further if the variable of units changing their location is integrated. The IBCT would be required to move a large quantity of supplies that are otherwise static in our model (e.g., personnel, tents, generators, etc.). Incorporating this variable introduces an additional level of realism to the model.

7. Other AGR Systems

This model can be adapted to simulate the difference between the status quo and any AGR technology. The model does not need to be limited to studying only ExLF. With the growing interest in AGR throughout the DoD, adjusting this model to fit alternative technology to measure against the status quo may provide many opportunities for further research.

H. CONCLUSION

The model developed in this research serves as an important launching point for additional research. While the conclusions and analysis we have provided are valuable, future research has the potential for leaps in understanding that the limited nature of our work has not achieved. AGR technology shows promise for the future of logistics support operations and will likely provide numerous additional research opportunities as this capability matures.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A. INFANTRY 1—SIMULATED CONSUMPTION

CRYSTAL BALL SIMULATED CONSUMPTION				
DAY	Class I	Class III	Class V	All Other
1	1,944.79	1,344.58	0.00	14.82
2	1,828.35	1,583.89	0.00	18.59
3	1,900.70	1,412.50	0.00	16.09
4	1,536.07	1,594.02	0.00	14.95
5	2,136.93	1,470.51	0.00	18.61
6	2,317.15	1,493.25	0.00	15.12
7	1,928.15	1,553.94	0.00	19.46
8	2,174.76	1,721.39	0.00	17.65
9	2,055.17	1,523.75	0.00	15.09
10	1,918.61	1,542.58	0.00	18.87
11	2,183.99	1,343.27	0.00	17.36
12	1,921.05	1,702.88	0.00	15.71
13	1,658.62	1,337.06	0.00	15.21
14	2,036.94	1,509.10	0.00	17.87
15	1,764.32	1,478.07	0.00	16.69
16	1,747.14	1,555.40	0.00	15.72
17	1,765.35	1,408.23	0.00	18.51
18	1,990.74	1,467.37	0.00	17.45
19	1,763.52	1,291.23	0.00	19.04
20	2,144.62	1,608.07	0.00	17.62
21	1,868.76	1,481.71	0.00	18.35

AVERAGE CONSUMPTION FOR ONE DAY				
	Class I	Class III	Class V	All Other
Average	1959.93	1486.00	145.00	17.00

SIMULATED CONSUMPTION IN DOS				
DAY	Class I	Class III	Class V	All Other
1	0.99	0.90	0.00	0.87
2	0.93	1.07	0.00	1.09
3	0.97	0.95	0.00	0.95
4	0.78	1.07	0.00	0.88
5	1.09	0.99	0.00	1.09
6	1.18	1.00	0.00	0.89
7	0.98	1.05	0.00	1.14
8	1.11	1.16	0.00	1.04
9	1.05	1.03	0.00	0.89
10	0.98	1.04	0.00	1.11
11	1.11	0.90	0.00	1.02
12	0.98	1.15	0.00	0.92
13	0.85	0.90	0.00	0.89
14	1.04	1.02	0.00	1.05
15	0.90	0.99	0.00	0.98
16	0.89	1.05	0.00	0.92
17	0.90	0.95	0.00	1.09
18	1.02	0.99	0.00	1.03
19	0.90	0.87	0.00	1.12
20	1.09	1.08	0.00	1.04
21	0.95	1.00	0.00	1.08

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B. INFANTRY 2—SIMULATED CONSUMPTION

CRYSTAL BALL SIMULATED CONSUMPTION				
DAY	Class I	Class III	Class V	All Other
1	2,169.75	1,686.37	0.00	17.36
2	1,948.98	1,623.60	0.00	15.71
3	2,103.60	1,321.25	0.00	15.21
4	2,132.29	1,557.23	0.00	15.24
5	1,893.71	1,633.74	0.00	14.98
6	1,771.64	1,503.21	0.00	14.93
7	1,911.91	1,525.91	0.00	19.19
8	1,672.69	1,657.06	0.00	17.06
9	1,778.06	1,690.44	0.00	17.31
10	1,663.21	1,627.95	0.00	18.50
11	2,168.31	1,582.33	0.00	18.41
12	1,679.95	1,392.79	0.00	16.90
13	1,929.39	1,322.89	0.00	16.73
14	2,024.07	1,658.56	0.00	17.99
15	2,197.76	1,551.61	0.00	17.33
16	1,871.80	1,758.05	0.00	17.70
17	2,296.58	1,596.77	0.00	19.03
18	1,867.07	1,621.91	0.00	16.51
19	1,768.59	1,603.72	0.00	16.25
20	1,902.01	1,773.37	0.00	17.33
21	1,974.04	1,458.35	0.00	18.27

AVERAGE CONSUMPTION FOR ONE DAY				
	Class I	Class III	Class V	All Other
Average	1959.93	1486.00	145.00	17.00

SIMULATED CONSUMPTION IN DOS				
DAY	Class I	Class III	Class V	All Other
1	1.11	1.13	0.00	1.02
2	0.99	1.09	0.00	0.92
3	1.07	0.89	0.00	0.89
4	1.09	1.05	0.00	0.90
5	0.97	1.10	0.00	0.88
6	0.90	1.01	0.00	0.88
7	0.98	1.03	0.00	1.13
8	0.85	1.12	0.00	1.00
9	0.91	1.14	0.00	1.02
10	0.85	1.10	0.00	1.09
11	1.11	1.06	0.00	1.08
12	0.86	0.94	0.00	0.99
13	0.98	0.89	0.00	0.98
14	1.03	1.12	0.00	1.06
15	1.12	1.04	0.00	1.02
16	0.96	1.18	0.00	1.04
17	1.17	1.07	0.00	1.12
18	0.95	1.09	0.00	0.97
19	0.90	1.08	0.00	0.96
20	0.97	1.19	0.00	1.02
21	1.01	0.98	0.00	1.07

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C. INFANTRY 3—SIMULATED CONSUMPTION

CRYSTAL BALL SIMULATED CONSUMPTION				
DAY	Class I	Class III	Class V	All Other
1	1,726.41	1,521.61	0.00	16.42
2	1,925.77	1,521.59	0.00	17.40
3	1,794.86	1,383.91	0.00	17.58
4	2,120.61	1,486.65	0.00	17.80
5	2,121.87	1,773.69	0.00	16.75
6	2,051.54	1,679.09	0.00	13.95
7	1,962.92	1,297.55	0.00	15.77
8	2,127.52	1,790.68	0.00	16.41
9	1,931.38	1,579.13	0.00	16.24
10	1,866.96	1,467.17	0.00	14.33
11	1,894.36	1,508.28	0.00	16.88
12	1,842.77	1,593.97	0.00	17.22
13	1,809.10	1,589.86	0.00	16.58
14	1,683.09	1,617.72	0.00	17.28
15	1,844.67	1,502.22	0.00	18.40
16	1,845.15	1,680.59	0.00	16.49
17	1,803.99	1,538.84	0.00	17.62
18	1,611.75	1,409.36	0.00	16.55
19	2,241.33	1,622.90	0.00	17.44
20	2,221.87	1,566.40	0.00	16.29
21	1,732.07	1,531.28	0.00	18.79

AVERAGE CONSUMPTION FOR ONE DAY				
	Class I	Class III	Class V	All Other
Average	1959.93	1486.00	145.00	17.00

SIMULATED CONSUMPTION IN DOS				
DAY	Class I	Class III	Class V	All Other
1	0.88	1.02	0.00	0.97
2	0.98	1.02	0.00	1.02
3	0.92	0.93	0.00	1.03
4	1.08	1.00	0.00	1.05
5	1.08	1.19	0.00	0.99
6	1.05	1.13	0.00	0.82
7	1.00	0.87	0.00	0.93
8	1.09	1.21	0.00	0.97
9	0.99	1.06	0.00	0.96
10	0.95	0.99	0.00	0.84
11	0.97	1.01	0.00	0.99
12	0.94	1.07	0.00	1.01
13	0.92	1.07	0.00	0.98
14	0.86	1.09	0.00	1.02
15	0.94	1.01	0.00	1.08
16	0.94	1.13	0.00	0.97
17	0.92	1.04	0.00	1.04
18	0.82	0.95	0.00	0.97
19	1.14	1.09	0.00	1.03
20	1.13	1.05	0.00	0.96
21	0.88	1.03	0.00	1.11

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX D. FIELD ARTILLERY—SIMULATED CONSUMPTION

CRYSTAL BALL SIMULATED CONSUMPTION				
DAY	Class I	Class III	Class V	All Other
1	2,418.11	3,222.16	22,487.32	16.10
2	2,185.26	3,405.14	22,519.19	16.31
3	2,507.04	2,985.01	22,500.85	16.73
4	2,496.80	3,069.81	22,558.92	15.10
5	2,222.28	3,385.19	22,498.04	17.31
6	2,617.74	3,053.35	22,521.33	16.16
7	2,603.72	3,426.25	22,487.84	17.67
8	2,371.45	2,871.10	22,508.60	14.59
9	2,466.33	3,192.25	22,509.33	14.60
10	2,309.67	3,180.74	22,485.31	16.65
11	2,180.69	3,427.22	22,533.20	18.35
12	1,849.27	3,047.87	22,530.05	18.33
13	2,522.11	3,257.62	22,478.23	17.68
14	2,189.52	2,867.41	22,499.14	19.01
15	2,202.99	2,952.18	22,521.26	17.73
16	1,823.52	3,163.60	22,506.81	18.86
17	2,332.77	3,474.57	22,508.78	17.88
18	2,494.58	3,544.33	22,533.69	18.61
19	2,534.44	3,309.92	22,493.47	19.00
20	2,594.10	3,453.12	22,554.07	17.09
21	2,131.44	3,324.68	22,518.02	18.94

AVERAGE CONSUMPTION FOR ONE DAY				
	Class I	Class III	Class V	All Other
Average	2374.12	3126.00	22509.00	17.00

SIMULATED CONSUMPTION IN DOS				
DAY	Class I	Class III	Class V	All Other
1	1.02	1.03	1.00	0.95
2	0.92	1.09	1.00	0.96
3	1.06	0.95	1.00	0.98
4	1.05	0.98	1.00	0.89
5	0.94	1.08	1.00	1.02
6	1.10	0.98	1.00	0.95
7	1.10	1.10	1.00	1.04
8	1.00	0.92	1.00	0.86
9	1.04	1.02	1.00	0.86
10	0.97	1.02	1.00	0.98
11	0.92	1.10	1.00	1.08
12	0.78	0.98	1.00	1.08
13	1.06	1.04	1.00	1.04
14	0.92	0.92	1.00	1.12
15	0.93	0.94	1.00	1.04
16	0.77	1.01	1.00	1.11
17	0.98	1.11	1.00	1.05
18	1.05	1.13	1.00	1.09
19	1.07	1.06	1.00	1.12
20	1.09	1.10	1.00	1.01
21	0.90	1.06	1.00	1.11

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX E. CAVALRY—SIMULATED CONSUMPTION

CRYSTAL BALL SIMULATED CONSUMPTION				
DAY	Class I	Class III	Class V	All Other
1	1,412.40	1,802.56	0.00	13.95
2	1,531.87	2,630.16	0.00	13.56
3	1,264.64	2,411.25	0.00	15.37
4	1,366.94	2,358.02	0.00	15.07
5	1,525.05	2,041.22	0.00	17.64
6	1,551.21	1,948.62	0.00	11.07
7	1,240.92	2,874.97	0.00	13.22
8	1,357.85	2,354.37	0.00	11.09
9	1,750.61	2,010.36	0.00	11.26
10	1,392.40	1,338.53	0.00	13.20
11	1,672.28	2,049.19	0.00	12.57
12	1,269.02	2,447.40	0.00	12.43
13	1,731.41	2,170.48	0.00	12.71
14	1,292.84	2,431.92	0.00	11.82
15	1,586.08	1,132.00	0.00	11.83
16	1,391.29	1,865.50	0.00	13.07
17	1,638.79	1,479.07	0.00	12.62
18	1,507.41	2,168.39	0.00	11.93
19	1,553.77	2,805.40	0.00	11.29
20	1,493.27	2,119.80	0.00	13.43
21	1,595.09	2,204.23	0.00	12.41

AVERAGE CONSUMPTION FOR ONE DAY				
	Class I	Class III	Class V	All Other
Average	1464.61	1833.00	80.00	14.00

SIMULATED CONSUMPTION IN DOS				
DAY	Class I	Class III	Class V	All Other
1	0.96	0.98	0.00	1.00
2	1.05	1.43	0.00	0.97
3	0.86	1.32	0.00	1.10
4	0.93	1.29	0.00	1.08
5	1.04	1.11	0.00	1.26
6	1.06	1.06	0.00	0.79
7	0.85	1.57	0.00	0.94
8	0.93	1.28	0.00	0.79
9	1.20	1.10	0.00	0.80
10	0.95	0.73	0.00	0.94
11	1.14	1.12	0.00	0.90
12	0.87	1.34	0.00	0.89
13	1.18	1.18	0.00	0.91
14	0.88	1.33	0.00	0.84
15	1.08	0.62	0.00	0.85
16	0.95	1.02	0.00	0.93
17	1.12	0.81	0.00	0.90
18	1.03	1.18	0.00	0.85
19	1.06	1.53	0.00	0.81
20	1.02	1.16	0.00	0.96
21	1.09	1.20	0.00	0.89

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX F. ENGINEER—SIMULATED CONSUMPTION

CRYSTAL BALL SIMULATED CONSUMPTION				
DAY	Class I	Class III	Class V	All Other
1	2,142.70	5,380.72	0.00	19.45
2	1,821.69	5,487.94	0.00	22.72
3	2,352.58	5,214.76	0.00	18.88
4	1,918.67	4,965.25	0.00	16.53
5	2,369.08	4,879.97	0.00	19.74
6	2,623.29	4,904.63	0.00	21.59
7	2,372.00	5,225.48	0.00	22.64
8	2,125.72	5,220.00	0.00	19.56
9	2,241.74	5,424.40	0.00	19.61
10	2,269.65	5,198.67	0.00	17.08
11	2,219.68	4,954.53	0.00	15.43
12	2,208.65	5,153.01	0.00	15.94
13	2,144.20	4,882.51	0.00	14.99
14	2,156.05	5,352.81	0.00	14.62
15	2,164.28	4,916.02	0.00	15.23
16	2,739.65	5,201.94	0.00	16.10
17	2,322.42	5,141.92	0.00	14.78
18	2,437.15	5,379.09	0.00	15.96
19	2,087.76	5,084.30	0.00	15.00
20	2,255.12	5,158.87	0.00	15.18
21	2,027.00	5,003.17	0.00	14.93

AVERAGE CONSUMPTION FOR ONE DAY				
	Class I	Class III	Class V	All Other
Average	2275.91	5156.00	68.00	20.00

SIMULATED CONSUMPTION IN DOS				
DAY	Class I	Class III	Class V	All Other
1	0.94	1.04	0.00	0.97
2	0.80	1.06	0.00	1.14
3	1.03	1.01	0.00	0.94
4	0.84	0.96	0.00	0.83
5	1.04	0.95	0.00	0.99
6	1.15	0.95	0.00	1.08
7	1.04	1.01	0.00	1.13
8	0.93	1.01	0.00	0.98
9	0.98	1.05	0.00	0.98
10	1.00	1.01	0.00	0.85
11	0.98	0.96	0.00	0.77
12	0.97	1.00	0.00	0.80
13	0.94	0.95	0.00	0.75
14	0.95	1.04	0.00	0.73
15	0.95	0.95	0.00	0.76
16	1.20	1.01	0.00	0.80
17	1.02	1.00	0.00	0.74
18	1.07	1.04	0.00	0.80
19	0.92	0.99	0.00	0.75
20	0.99	1.00	0.00	0.76
21	0.89	0.97	0.00	0.75

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX G. SIMULATED TRUCK AVAILABILITY

DAY	TRUCKS AVAILABLE		ROUNDED DOWN	
	LHS (28)	Fuel (5)	LHS	Fuel
1	22.99	3.75	22.00	3.00
2	23.25	3.87	23.00	3.00
3	22.75	4.15	22.00	4.00
4	22.88	3.89	22.00	3.00
5	22.95	3.85	22.00	3.00
6	24.47	3.90	24.00	3.00
7	21.27	4.39	21.00	4.00
8	23.42	4.22	23.00	4.00
9	22.08	4.25	22.00	4.00
10	23.45	3.72	23.00	3.00
11	22.29	4.30	22.00	4.00
12	22.71	3.96	22.00	3.00
13	22.87	4.32	22.00	4.00
14	23.20	4.45	23.00	4.00
15	23.78	4.01	23.00	4.00
16	19.93	4.41	19.00	4.00
17	21.51	3.89	21.00	3.00
18	24.31	3.78	24.00	3.00
19	22.26	4.00	22.00	3.00
20	23.63	4.05	23.00	4.00
21	23.32	3.96	23.00	3.00

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX H. PRIORITIZATION POINTS TABLE

Scale priority of each level of supply relative to other levels

Priority of each class of Supply Relative to the other classes.

Priority of each unit relative to the other units.

Supply Level (DOS)	INF 1 (ME) 100%				INF 2 95%				INF 3 95%				FA 90%				CAV 85%				ENG 75%			
	Class I	Class III	Class V	AO	Class I	Class III	Class V	AO	Class I	Class III	Class V	AO	Class I	Class III	Class V	AO	Class I	Class III	Class V	AO	Class I	Class III	Class V	AO
100%	100	50	70	30	95	48	67	29	95	48	67	29	90	45	63	27	85	43	60	26	75	38	53	23
95%	95	48	67	29	90	45	63	27	90	45	63	27	86	43	60	26	81	41	57	24	77	38	54	23
90%	90	45	63	27	86	43	60	26	86	43	60	26	81	41	57	24	77	38	54	23	72	36	50	22
85%	85	43	60	26	81	40	57	24	81	40	57	24	77	38	54	23	72	36	51	22	68	34	48	20
80%	80	40	56	24	76	38	53	23	76	38	53	23	72	36	50	22	68	34	48	20	64	32	45	19
75%	75	38	53	23	71	36	50	21	71	36	50	21	68	34	47	20	64	32	45	19	60	30	42	18
70%	70	35	49	21	67	33	47	20	67	33	47	20	63	32	44	19	60	30	42	18	56	28	39	17
65%	65	33	46	20	62	31	43	19	62	31	43	19	59	29	41	18	55	28	39	17	53	26	37	16
60%	60	30	42	18	57	29	40	17	57	29	40	17	54	27	38	16	51	26	36	15	49	24	34	15
55%	55	28	39	17	52	26	37	16	52	26	37	16	50	25	35	15	47	23	33	14	45	23	32	14
50%	50	25	35	15	48	24	33	14	48	24	33	14	45	23	32	14	43	21	30	13	41	21	29	12
47%	47	24	33	14	45	22	31	13	45	22	31	13	42	21	30	13	40	20	28	12	38	19	26	11
44%	44	22	31	13	42	21	29	13	42	21	29	13	40	20	28	12	37	19	26	11	35	18	25	11
41%	41	21	29	12	39	19	27	12	39	19	27	12	37	18	26	11	35	17	24	10	33	17	23	10
38%	38	19	27	11	36	18	25	11	36	18	25	11	34	17	24	10	32	16	23	10	31	15	22	9
35%	35	18	25	11	33	17	23	10	33	17	23	10	32	16	22	9	30	15	21	9	29	14	20	9
32%	32	16	22	10	30	15	21	9	30	15	21	9	29	14	20	9	27	14	19	8	26	13	18	8
29%	29	15	20	9	28	14	19	8	28	14	19	8	26	13	18	8	25	12	17	7	24	12	17	7
26%	26	13	18	8	25	12	17	7	25	12	17	7	23	12	16	7	22	11	15	7	22	11	15	7
23%	23	12	16	7	22	11	15	7	22	11	15	7	21	10	14	6	20	10	14	6	20	10	14	6
20%	20	10	14	6	19	9	13	6	19	9	13	6	18	9	13	5	17	8	12	5	17	8	12	5
18%	18	9	13	5	17	9	12	5	17	9	12	5	16	8	11	5	15	8	11	5	15	7	11	4
16%	16	8	11	5	15	8	11	5	15	8	11	5	14	7	10	4	14	7	10	4	14	7	10	4
14%	14	7	10	4	13	7	9	4	13	7	9	4	13	6	9	4	12	6	8	4	12	6	8	4
12%	12	6	8	4	11	6	8	3	11	6	8	3	11	5	8	3	10	5	7	3	11	5	7	3
10%	10	5	7	3	9	5	7	3	9	5	7	3	9	4	6	3	8	4	6	3	9	4	6	3
8%	8	4	6	2	8	4	5	2	8	4	5	2	7	4	5	2	7	3	5	2	7	3	5	2
6%	6	3	4	2	6	3	4	2	6	3	4	2	5	3	4	2	5	3	4	2	6	3	4	2
4%	4	2	3	1	4	2	3	1	4	2	3	1	4	2	3	1	3	2	2	1	4	2	3	1
2%	2	1	1	1	2	1	1	1	2	1	1	1	2	1	1	1	2	1	1	1	3	1	2	1
0%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

- Cummings, M. (2017). *Artificial intelligence and the future of warfare*. London, England: Chatham House.
- Defense Science Board. (2016). *Summer study on autonomy*. Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology and Logistics.
- Defense Science Board. (2018). *Task force on survivable logistics*. Washington, DC: Department of Defense.
- Garamone, J. (2004, January 29). Army to restructure, will grow by 30,000. *Department of Defense news*. Retrieved from <https://archive.defense.gov/news/newsarticle.aspx?id=27416>
- Gordon, J., Matsumura, J., Alter, A., Boston, S., Boyer, M., Lander, N., & Nichols, T. (2015). *Comparing U.S. Army systems with foreign counterparts: Identifying possible capability gaps and insights from other armies*. Santa Monica, CA: RAND.
- Goure, D. (2018, October 4). *Winning future wars: Modernization and a 21st century defense industrial base*. Washington, DC: The Heritage Foundation.
- Hatfield, S. (2018, May/June). Shaping modernization to address autonomy and force capability. *Armor and Mobility*. 13-16.
- Headquarters, U.S. Army. (2018, March 28). *Inventory management: Supply policy below the national level* (Army Regulation 702-10). Washington, DC.
- Hunter, A., & McCormick, R. (2017). *The Army modernization imperative: A new big five for the twenty-first century*. Washington, DC: Center for Strategic and International Studies.
- Ivanova, K., Gallasch, E., & Jordans, J. (2016). *Automated and Autonomous Systems for Combat Service Support: Scoping Study and Technology Prioritisation*. Edinburgh, South Australia: Australian Government Department of Defence Land Division.
- National Highway Traffic Safety Administration. (2015). *Traffic safety facts*. Washington, DC: NHTSA's National Center for Statistics and Analysis.
- North American Treaty Organization. (2015). *Autonomous systems: Issues for defense policy makers*. Norfolk, VA.
- Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. (2018). *Unmanned systems integrated roadmap: 2017-2042*. Washington, DC

- Oshkosh Defense. (2019, October 3). Support the mission with versatility, performance and reliability. Retrieved from <https://www.oshkoshdefense.com>.
- Pendleton, John H. (2019). *Army readiness: Progress and challenges in rebuilding personnel, equipping, and training* (GAO-19-367T). Washington, DC: Government Accountability Office.
- Training and Doctrine Command. (2018). *Training and doctrine command pamphlet 525-3-1*. U.S. Fort Eustis, VA: Training and Doctrine Command.
- U.S. Army. (2008a). *Water planning guide*. Fort Lee, VA: U.S. Army Combined Arms Support Command. Retrieved from <https://quartermaster.army.mil>
- U.S. Army. (2008b). *Supply Policy Below the National Level* (AR 710-2). Washington, DC: Headquarters, Department of the Army.
- U.S. Army. (2015). *Brigade Combat Team* (FM 3-96). Washington, DC: Headquarters, Department of the Army.
- U.S. Army. (2019, September 20). *FDD—Planning Data Branch (PDB)*. Fort Lee, VA: U.S. Army Combined Arms Support Command. Retrieved from https://cascom.army.mil/g_staff/cdi/fdd/mld/planning_data_branch.htm
- Van Howe, P. (2019, April 1). The challenges of multi-domain sustainment. Retrieved from https://www.army.mil/article/219078/the_challenges_of_multi_domain_sustainment

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California